BATTERY MANAGEMENT SYSTEM FOR ELECTRIC RACING CARS

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To my parents.

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Abstract

With the introduction of the electrics cars into the market new technologies regarding the battery are being developed and new problems to be solved, one of them the battery management system because each type of cell requires a specific way of handling. This research is done using the active research method to find out the actual problem on this subject and features a BMS should have, understand how they work and how to develop them applied to the purpose on this work. Once the features the BMS should have are clarified, it's possible to develop a BMS for an electric racing car. The decisions are made taking into consideration the nature of the vehicle being developed. After the project done it's clear to see that what was developed was not only the BMS itself but all the other factors around it, such as CAN communication, safety control, diagnostics and so on.

Keywords

Battery Management System, dSpace, CAN communication,

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Abbreviations

BEV	–	Battery Electric Vehicle
BMS	–	Battery Management System
BOM	–	Bill of Materials
CAD	–	Computer Aided Design
CMOS	–	Complementary Metal Oxide Semiconductor
DMOS	–	Diffused Metal Oxide Semiconductor
ECU	–	Electronic Control Unit
EMI	–	Electromagnetic Interference
ESF	–	Electrical System Form
FCEV	–	Fuel Cell Electric Vehicle
HV	–	High Voltage
HVD	–	High Voltage Disconnect
ICV	–	Internal Combustion Vehicles
IMD	–	Isulation Monitoring Device
LV	–	Low Voltage
NN	–	Neural Network
PCB	–	Printed Circuit Board
PHEV	–	Plug-In Hybrid Electric Vehicle

RFI – Radio Frequency Interference

RTDS – Ready-To-Drive-Sound

SOC – State of Charge

SPR13e – Student Project Rüsselsheim 2013 Electric

TSAL – Tractive System Active Light

EMF – Electromotive Force

FET – Field-effect Transistor

DBC – DataBase Container

ESF – Electrical Safety Form

FSG – Formula Student Germany

AMS – Accumulator Management System

GLVS – Grounded Low Voltage System

GRP – glass-reinforced plastic

POM – Polyoxymethylene

PE – Polyethylene

POM – Polyoxymethylene

1. INTRODUCTION

After 125 years of the existence of the electronic mobility seems like only in the current days the electric car is being seen as a suitable concurrent for the traditions internal combustion vehicles (ICV).

Alternatives for the conventional internal combustion vehicles are becoming very popular in the last years, they are either hybrids or electrics. In the case of the electrics ones they can have their batteries charged in any place with a regular electricity plug with 230 volts, parking places, garages, gas stations on the highways are already implementing charging spots to satisfy that need. However the relative small range of an electrical cars and the higher initial price are still disadvantages.

In this document both factors are going to be studied in the theoretical part as well as the focus of this document that is going to be the battery management system which in Scuderia-Mensa is totally self-developed, last year for example the team member David Brandt developed all by himself but this year he developed the slaves boards that measure temperatures and voltages of the cells and via Controller Area Network (CAN), the master which contains the algorithm that evaluates the data from slaves and take the proper action e. g. in case of emergency open the contactors disconnecting the battery from the rest of the system.

1.1. BACKGROUND

The electric mobility is not something from the modern days, during the event *"125 Jahre Elektromobilität"* that took place in Rüsselsheim in 27th and 28th of April, I had the opportunity to see the first German electric car called *"Flocken"* as shown in Figure 1. The car has a similar appearance when compared to the conventional cars of its time. The batteries used by that time were Lead-acid and appeared in the market in 1890, they were reliable and last long, the first batteries worked continually for 16 years, they had an energy density of 27 Wh/kg and where responsible for 100 Kg of the 450 Kg total weight of the complete car [1].

Figure 1- Flocken Elektrowagen 1888

Factors like cheap oil and mass production made the combustion car to be predominant on the streets by the year 1920.

The next relevant appearance of the electric cars happened more than 100 year after that, in 1996 when General Motors (GM) introduced the EV1 that by that time was the first mass-produced electric vehicle followed by Honda EV Plus and Toyota rav4 EV and others. The EV1 was produced between 1996 and 1999 in total was produced 1117 units the latest versions with better batteries had a range of 120 miles, approximately 193 kilometers. In 2002 against the willing of the drivers that had access to the car through leasing program without option to purchase the cars. In the beginning of 2002 GM notified the drivers that the EV1 would be removed from the roads in 2003 with the excuse that would not be possible to sell enough cars to make the EV1 profitable [2, 3]. There are a lot of discussions regarding the real reason for the EV1 being taken out of the roads but this issue is not part of the scope here addressed. Fact is that in the previous years some factors such as political instability of the countries that produces oil, worries about how much oil is left in the world as well as the quality of the air gave a bread new breath to the alternatives to the ICV e.g. Fuel Cell Electric Vehicle (FCEV), Battery Electric Vehicle (BEV) and Plug-In Hybrid Electric Vehicle (PHEV).

Helping to solve the pollution problems caused by the emission of gasoline-powered engines and as the batteries few years ago was considered not good enough, the hybrid cars were presented as the step between ICV and BEVs and due to the success of the Toyota Prius introduced worldwide in 2000, others car manufactures invested in their own hybrid vehicle and later on the electrics show up again, Nissan Leaf introduced in the end of 2010 and brought back the confidence in electric cars being the best-selling all-electric car reaching 50 thousands units by the middle of February 2013 [4, 5].

Sport cars also gained relevance in the electric mobility world, a good example of that is the Tesla that was created in 2003 but only after 10 years registered profit [6, 7]. That shows that the market now has acceptance to electric cars and even sportive electric cars, to increase this statement nowadays there is also Plug-in hybrid luxury sports such as Fisker Karma and Porsche Panamera.

1.2. PROBLEM

The batteries are present all around us, every car, ship, airplane has at least one battery, electronics devices are also supplied by batteries, in the case of pure electrical systems as the system became more complex and require more energy, the battery also became bigger and more complex, this requires a more effort to make a proper management to make the battery behave as expected and in safety conditions.

We are in a moment which the cells are responsible for an important part of the introductions of new ways of mobility and due to that in the latest years nanotechnology make it possible for some new technologies regarding the cells types and the problem associated to this is that we are still not sure about what can happen in non-common operation situations, for example, accidents, long term storage, hurricanes, water overflow and so on after all the safety is the main issue of the batteries.

A consequence of failures due to non-common operation situations is shown now. The Hurricane Sandy that took place in October, 2012 and had devastating consequences in the American continent and brought destruction also for the automotive industry, and the safety of electric cars were one more time discussed. In this situation the cars were submerged under between 5 and 8 feet seawater for several hours.

In this situation 10000 vehicle were damaged. Toyota had 4000 vehicle parked at Port Newark during the storm and more than 220 of them were hybrids or plug-in models, one Prius burned on this situation, not a bad scenario when compared to what happened to the Fisker Karma, behind the label of being the first car to burn underwater, Fisker saw 16 units of its $ 100.000+ just burned, how it happened it’s not clear, it’s possible that the salt water caused short circuit that led to a fire, and another doubt is if all 16 units had its own spark or if the fire spread from one to another [8], Fisker said that the problem was a low-voltage Vehicle Control Unit that was corroded by the salt water. In this situation Fisker had more than 300 of its cars damaged. In the Figure 2 it’s possible to see the face of the destruction.

Figure 2 – Burned Fisker Karma plug-in Port Newark [9]

Due to the amount of electronics the electric cars became very expensive and complex from the operational point of view, as we are going to see in more detail in the next chapter where the state of the art is described in detail. Next a brief description of problem for the penetration in the market by the BEVs.

Backward compatibility can be also a problem, in the combustion car, we still can find parts that should be changed often e. g. filters, battery, belts and many other parts even if the car is a few decades old. In the electric cars we still don't know if for instance we need after 10 years to change the battery, if it's just exchange for a similar one, of if some more systems will need to be changed as well in order to ensure the correct operability.

Range anxiety is another argument people often talk about regarding electric cars, although the largest part of the people don't drive more than 100 km per day, seems like a range of 200 km Nissan Leak it's still a problem for people with range anxiety.

Walk home is the situation when the car get broken or run out of gas/energy and the driver is not anymore able to drive it, in case of system failure there is not much to do but when the problem is the car running out of gas/energy, there is a big difference between ICVs and BEVs, while in a ICVs the driver just need to find a gas station and get some fuel just enough for the car run until the gas station, in the case of the BEVs that is not possible, in this case a BEV running out of energy can be considered as a failure, and failures make the consumer lose faith in the car and consequently in the brand. Regarding this issue Opel Ampera has a great advantage by being a PHEV, that means the batteries get energy from 2 different sources, the electric plug and a small combustion engine that is used to produce energy for the batteries, so, even if the car runs out of energy still it's possible to get gas and make the car run again.

In the latest years nanotechnology make it possible for some new technologies regarding the cells types [10].

Big losses caused by battery problems are not only present in the automotive industry, recently Boeing was forced to see their bread new fleet of 50 Boeings 787 Dreamliner on the ground due to a problem after charging a battery on a Nippon Airways flight. After 3 months of work, more than 200.000 engineering hours and more than 100000 hours of testing, Boeing has found an approved solution, the actions taken passes through manufacturing improvements, design enhancements and enclosure system. The work requires about 5 days per airplane, skills include advisors, engineers, quality inspectors and mechanics and capabilities include diagnosis, repair, logistics, parts procurement, warranty and certification. [11]

1.3. PURPOSE

The overall aim of this research is to develop a BMS for different needs and performance regarding the competition. The competition has 4 dynamic events; Skidpad worth 50 points and measures the capability of the cornering of the car, the driver has to complete 2 right-hand laps immediately followed by 2 left-hand laps, the faster it is done, better; Autocross worth 150 points and consists in a track which the driver should drive as fast as possible keeping in mind possible penalties for knocked cones for example; Endurance worth 300 points the car should be able to run 22 km and this event has additional 100 points for efficiency, e. i. running the event spending the least amount of energy.

Specifically, within the context of the BMS, the objectives of this research are to:

1. Identify the main features and functions that a BMS should have in order to run a racing car.

2. Evaluate critically the options available to implement each function of the BMS.

3. Formulate the studied solutions and implement the function and thus built the BMS.

4. Analyze the behavior and performance of the system and implement adjustments if necessary.

To have a good performance in all of this events, it's important to have a good State of Charge (SOC), a balancing algorithm that makes sure the battery has the maximum amount of energy possible after being charged, and other features to ensure that the whole system works properly, e. g. cell failure detection, signal acquisition, contactor control, pre-charging control, discharge control, thermal management and charge communication. All of this features that are going to be developed and implemented will be in described in detail in this document.

An individual research objective is to take some lessons from the point of view of the project management, as an Industrial Management student this is a great opportunity to get familiar with a real world project implementation and common problems that normally are faced such as communication problems and application of work methodologies e. g. Concurrent engineering which is based on the parallelization of tasks.

1.4. RESTRICTIONS

It's very common to see others teams of the formula student electric with between 10 and 20 members just for the electric team, that happens due to the large amount of work that must be done during the whole project, a good example of this is the Electrical System Form (ESF). The following electrical systems must be described and explained in detail when filling in the document: Shutdown Circuit, Isolation Monitoring Device (IMD), Inertia Switch, Brake Plausibility Device, Reset / Latching for IMD and BMS, Shutdown System Interlocks, Tractive System Active Light (TSAL), Measurement Points, Pre-Charge Circuitry, Discharge Circuitry, High Voltage Disconnect (HVD), Ready-To-Drive-Sound (RTDS), Accumulator, Energy meter mounting, Motor controller, Motors, Torque encoder, Additional LV parts interfering with the tractive system, Overall Grounding Concept and Firewall.

All these parts of the car must have a document that must be handed in time under the punishment of being disqualified from the competition.

In my case I wrote the document regarding the BMS with the help of Mathieu Bacquet that made the computer-aided-design (CAD) of the battery and therefore know physical attributes of the battery and David Brandt that built the slaves and know details about the temperature sensors that are being used and other issues regarding the measurement.

During the elaboration of this document some content of the ESF file is going to be used to explain some details of the concept such as system overview, schematics, CAD images of the battery container, CAD images of the slaves positioning in the container, and so on.

A structural restriction is the fact that the master of the BMS is all done by software using Matlab Simulink, that happens because in the car we are using the MicroAutoBox ii from dSpace which is a real-time system for performing fast function prototyping in fullpass and bypass scenarios. It operates without user intervention, just like an Electronic Central Unit

(ECU). The whole digital programming of the vehicle is on the dSpace device as well as the BMS programming and this become a restriction in case the BMS has to be implemented in another context without a similar device, in this case, the programming should be done in another device e. g. a micro controller.

Time is always a restriction that should receive special attention, moreover when there are important milestones ahead in time, that is to avoid the classic problem of the last minute solutions, another important issue is the intercompatibility of the project. In a project like this there are a lot little groups working in different parts of the car e. g. suspension, body, frame, battery, motor and so on, and as time goes by a specific group need another part to be done before can go on with its work, for example, the suspension team is not able to finish their work if the frame is not ready, in my case I was just able to work with the battery 2 days before an important milestone, the roll-out, and with this short period of time it was just possible to run the car with the basics safety functions and no performance features that could have been implemented if the battery was ready before.

Manpower is a big problem in another formula student teams as well, I had the opportunity to be in contact with some other teams like TU Darmstadt in their roll-out event and the team from Wolfsbug in Hannover Messe, and during brief conversation with the members it was clear that not only Scuderia-Mensa has difficulties to find electric people to join the team. The electric team started the season with only 4 members, but in the lasts months of activities we were 6 persons and that seemed to be enough because although the team was small, it was composed by very committed people.

1.5. TIMESCALE

I soon I got in contact with the team and David, who is the person with more knowledge about what have to be done in the project due to the fact of being in the Racing Team previously, the team set up some meeting in order to organize all the tasks and assign every task among our electric team. The result of those meetings I prepared a MS project file which allow the team members to see clearly the evolution, the time available and the incoming milestones. The project timescales can be seen in Figure 3.

The main problem of the timescale was in the first part of the project, until the roll out, that happened because the mechanical part was not ready, so that, the electric team was not able to implement and mount the devices on the car.

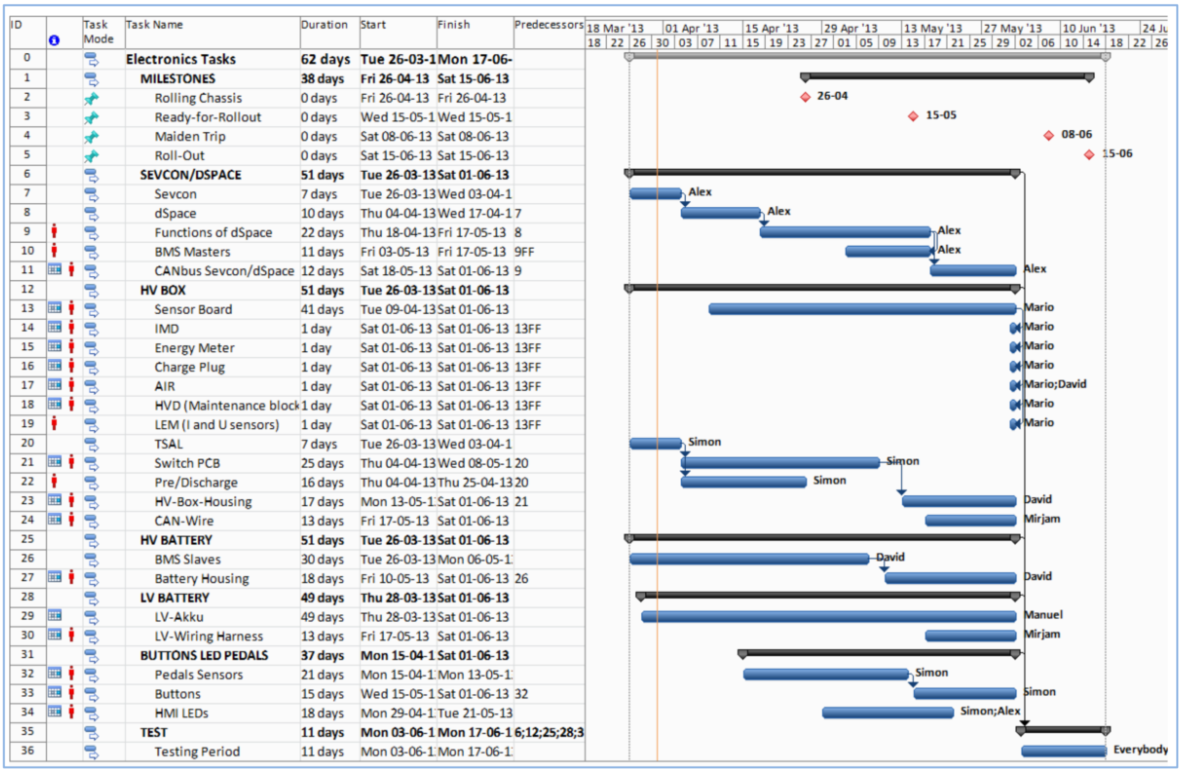

Figure 3 – Timescale for all electronics tasks in the beginning of the season

A Gantt chart with the project timescale development can be seen in Figure 4. The tasks have been sorted in three represented by the colors representing:

- Purple – Preparation and consolidation of the knowledge obtained during research through deeper study of particular aspects for the development stage;
- Green – Development stage including, programming and tests of the software.
- Blue – Writing of the Thesis document.

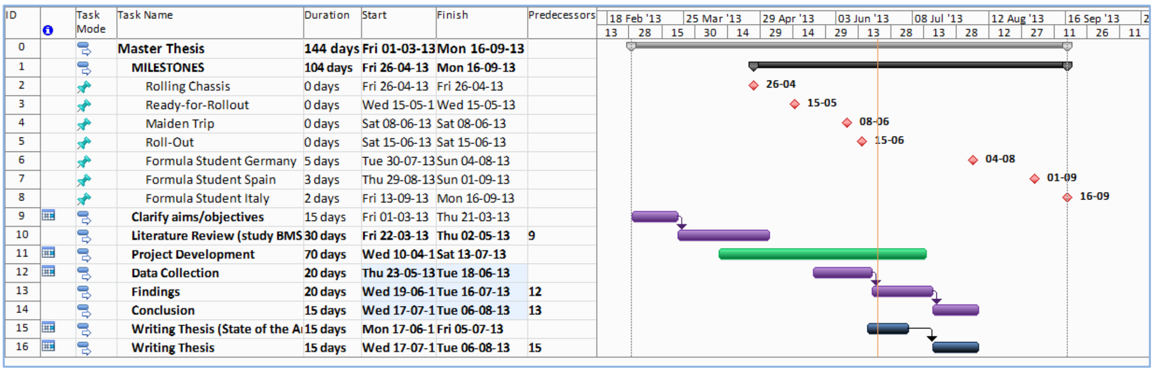

Figure 4 - Timescale for the thesis activities

1.6. OUTLINE OF THE THESIS

In this first chapter the context and contents of the document are briefly described as well as the organization, proposed research aim and individual research objectives.

In the second chapter is presented the State of the Art of the BMS in a global scenario, the actual BMS used in Opel Ampera (Chevy Volt) in detail. Information regarding battery pack and its composition, safety systems, management and controlling and room for improvements are supplied as well as a brief comparison with the Toyota Prius.

In the third chapter is presented the Literature Review where some basic features of a BMS are studied mainly SOC, balancing and safety limits operation, in order to be self-developed later on.

The forth chapter describes the Research Methods used in this research and the reason why this choice was made in comparison with others methods. It's also justified why this is a qualitative research and why the action research is the proper suitable way to do it.

In the fifth chapter the findings of the project are shown and justified, decisions made and lessons learned. It's one of the largest chapter of this work, the main developments of the BMS are shown and explained as well as the monitoring and testing possible because dSpace has a great real time application.

In the last chapter of this work are presented the conclusions of this work, where is checked if all the objectives of this work are full filled. The discussion presents some decisions and situations that happened during the semester and how they affected the results of the car on the competitions. To conclude some advices are provided on the future work section.

2. STATE OF THE ART

Reverse engineering is a very common practice in the industry moreover when some new product shows up full of technology innovations. In May 2012 In United States of America, a group formed by John Scott-Thomas, UBM TechInsights' product-marketing manager, and Al Steier, Munro & Associates' senior associate and "design prophet" did a product teardown or simply called teardown of a Chevy Volt 2012. A teardown is the act of disassembling a product to identify its component parts and functions. Such act besides being interesting for hobbyists can be useful to estimate the bill of materials (BOM) which consists in a list of the raw materials, needed to manufacture an end product.

The objective of this teardown was to see how the car was build and the systems that make part of it and how the designers put everything together. Over three days the Volt was disassembled as shown in Figure 5 and the people involved could learn many things about the vehicle and the most relevant ones for this document are going to be described here but the whole article about it can be found in the following references [12, 13, 14].

Before the teardown took place some safety actions were done. The team left the system on to drain the battery before taking the car apart, but during this process the software started the gas engine to prevent deep discharge of the battery. Then the team decided to drain the tank and then leave the lights, radio and other systems on in order to drain the 12 V battery.

The HV system recharged the battery overnight, an interesting fact is that the system did not allow the battery to be completely discharged but only at a level at the car could still travel 35 miles, approx. 53 Km. Concluding the preparation of the car for the teardown a company specialized in electric vehicle drained the battery using a power resistor across the terminals.

Figure 5 – Chevy Volt teardown [12]

The battery pack is composed by 288 lithium-ion cells separated into four modules that together built a T shape that fits below the rear seat and in the space between the front seats. The battery configuration is 96S3P meaning that there are 288 cells from the South Korean-based company LG Chem, 96 series of 3 cells in parallel with 170 Kg weight and producing 360 V with a capacity of 16 KWhr, the battery can be seen in detail in Figure 6. To reduce electrical stress on the cells and prolong the battery lifetime, it is never fully charged or discharged so it uses only 10 KWhr of the battery energy which represents approx. 60%. Once the battery reach a specific minimum value the 1.4 L Austrian made gasoline engine kicks in and runs a generator that provides enough energy to both run the car and recharge the battery.

Figure 6 – Volt battery pack [13]

Chevy Volt has four cooling systems each one with its own controller and radiator module. The systems supplied with a cooling system are: Internal combustion engine, the two electric motor/generator inverters, the power-line plug-in charger's power converter and finally the battery pack. In the case of the battery cooling system, if the battery is operating at a lower temperature than the optimum operating temperature, then the fluid heated by an 1800 W heater heats the battery to operating conditions and then cools again to avoid overtemperature all this care with the temperature of the cells are to maintain the targeted 10 year lifetime of the pack. Another interesting feature is that even if the car is not operating, the control electronics activate the coolant loop to avoid overheating the battering during warm weather or overcooling in case of cold weather. So that keeping the Volt on its external charger when the car is not in use it's a good idea because prevents the battery of being drained in such conditions.

By the components and inspections marks present on Volt, the team responsible for the teardown was able to take good conclusions about the manufacturing process, for example, in the battery pack coolant loop was connected using hose clamps, and so that they concluded the car is a limited production vehicle because in a higher production volumes brazed joints would have been used. The bolts clamping together the pack each have three inspectors paint marks, and this shows that the assembly is carefully inspected to ensure quality and function of the $ 8000 in components that together are the heart of the Volt.

The teardown revealed a very complex battery pack and equally a sophisticated control and monitoring for the whole car. Scott-Thomas observes that 40% of the value of the vehicle is in its electronics, typified by the nearly 100 onboard microcontrollers. Approximately 10 million lines of code control this electronic suite make this car with more code than it takes to control the Boeing 787 Dreamliner, at 8 million lines. Obviously all this complexity reflects on the final price of the car.

The control software of the battery pack makes sure that the battery life goes as far as possible, because of the care about the temperature and the algorithm provides the balancing of the cells to ensure all the cells ages at the same rate and also spot differences in manufacturing and other variables that influences the aging process. During the charging process to ensure every cell with the same amount of energy, when a cell reaches the capacity early than the others the balancing resistor is shunt and this prevents that cell to be overcharged while the others reach the same level, this is an important stage because a proper cell balancing can improve the maximum charge and/or lifetime of the battery up to 10%. The car's controllers monitor the battery pack voltage and temperature with 500 diagnostics tests are done 10 times a second, with control activity even when the car is not operating.

The control is achieved by 5 boards on the battery pack, the main battery control board has a Freescale dual core microprocessor (Part MPC5516EAMLQ48), this board is the main interface between the pack and the rest of the vehicle.

Each battery interface module unit is able to read data from the cells, the components that populate the printed circuit board (PCB) are from Freescale, LG Chem and STMicroelectronics, the LG Chem and STMicro chips use bipolar complementary metal oxide semiconductor (CMOS) diffused metal oxide semiconductor (DMOS) technology.

In the Figure 7 we can see a battery interface PCB and is also possible to see the quality checks that take place during the manufacturing process.

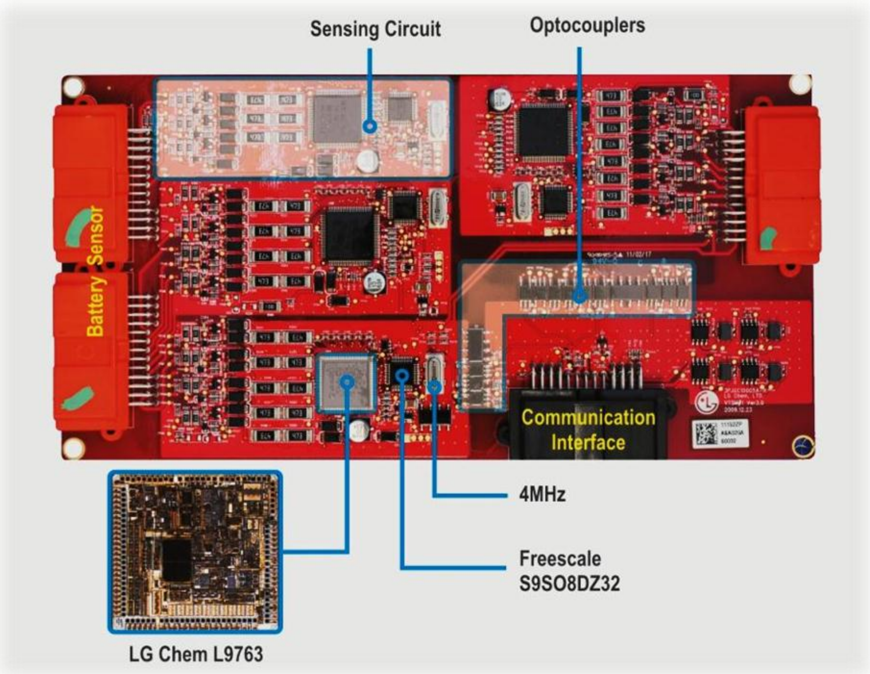

Figure 7 – Battery Interface PCB [13]

The PCB layout requires a large amount of attention because issues like layout, trace design, ground planes and voltage-isolation technique in order to get the right measurement. Other issue to keep in mind is the flexibility and modularity of the system, in case the car need to receive new cells or battery packs, electronics or controls, the whole system should work without problems so that the car design is a work in process.

During the teardown the team discovered one unexpected battery-related module in the car, in addition to the standard onboard-diagnostics port under the driver’s side dashboard, they also found a sealed and potted module under the front passenger seat. This module stores data regarding the battery and hybrid operation and it has a connection for an appropriate cable for a technician to access them.

The charging system besides using regenerative braking, the battery pack stores energy by charging from the power grid, the charger is so sophisticated that the charging process only starts if the user plug respects the restrictions regarding the grounding circuit. The charger was also disassembled in order for its features get known and the charger presented itself very robust and with very good isolation protection, stable and mechanically redundant.

The brain of the car is considered to be the PCB which controls the traction, generator, and the clutch. The PCB responsible for controlling the power train as well as defining the operating state of the drive and the regenerative braking system can be seen in Figure 8.

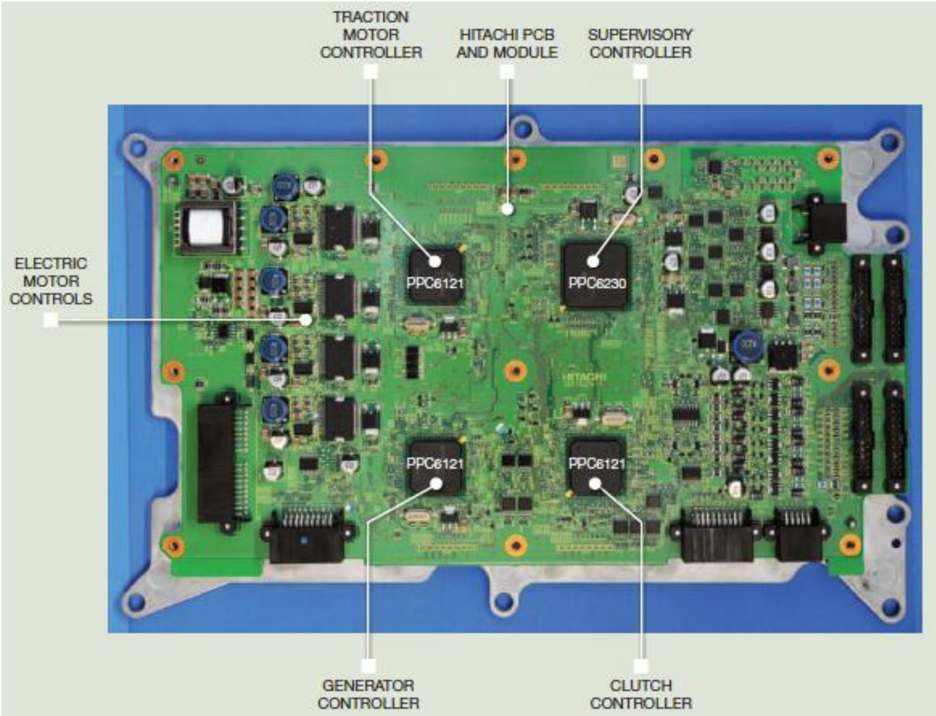

Figure 8 – Motor/generator inverter module [12]

In the upper part of the PCB is located the Hitachi module which includes four 32-bit Freescale Qorivva microcontrollers. One of the four controllers has the function of supervising reading the input such as wheel speeds, acceleration, throttle, braking and battery state, then decide which state is the most efficient. The decisions to be made can also include choosing the best combination of outputs from the traction motor and when combustion engine generator to operate, when to activate regenerative braking, and to what extent to recover energy. This supervising controller is the largest on of the four microcontrollers, with 3 Mbytes of flash memory, and using half of the space of the matrix. The controller also endeavors to run the electric motor at lower rotation rates increasing the efficiency. The other three Freescale microcontrollers control the traction motor, the combustion engine driven generator and the clutched planetary gear set.

In general those are the electronic parts that are not found in a conventional ICV, the rest of the electronics pretty much the same as a conventional car. A general view of all the electronic modules can be seen in Figure 9. An air-cooled dc/dc converter, with PCBs from

TDK and a Renesas microcontroller, takes the place of an alternator to provide 12 V for running standard auto systems, such as doors, lights, navigation, radio and to charge the auxiliary 12 V battery.

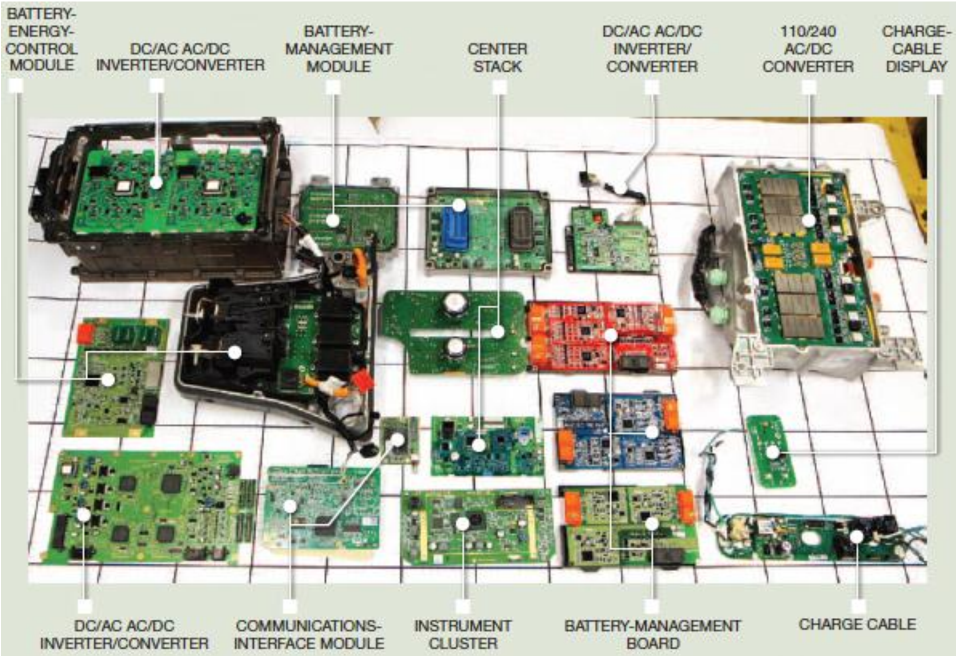

Figure 9 – All 18 electronic modules in the Volt [12]

The Volt is designed with quality and attention to safety and detail while allowing improvements and upgrades. As these kind of vehicle start to be more present on the streets, the mass production increases and the costumers gain experience takes place, it will be interesting to see the evolution of the systems of the PHEV and how fast all this evolution process will happen.

The team member Steier that had previously taken apart a Toyota Prius Hybrid found some differences between the Prius and the Volt. The battery is the first difference, Volt uses lithium-ion battery which is safer, cheaper, more durable and can store two to three more energy than a nickel-metal-hydride battery used in the Prius, another difference is due to the fact that Volt is a PHEV and because of it has an extra inverter module for charging. Differences were found on the thermal management, Volt uses liquid cooling while Prius uses air cooling. The last difference found stated by Steier was regarding the electronic components supplier, Volt has a more diverse supplier base while Prius primarily uses

Toyota technology. What both cars has similar is the safety features of wiring and disconnects that are comparable in both vehicles [15, 16].

In this chapter the topics addressed was how the Chevy Volt works and the systems that make part of it, like the battery pack and its composition, safety systems, management and controlling and room for improvements, now that is known the functions and systems of the car consulting the literature will make it possible to understand how those functions were implemented as well as supply me with useful information for the development of the BMS that is going to be used on the Scuderia-Mensa 2013 car called Student Project Rüsselsheim 2013 Electric (SPR13e).

3. LITERATURE REVIEW

This Literature review will explore all the subjects surrounding a BMS but the focus in going to be the lithium-ion batteries because this kind of cells are the ones that are going to be used in the project. The study within this review of literature focuses on objectives 1 and 2 as set out in sub-section 1.3 of the introductory chapter, the third objective will be met through the development of the project and the final objective is derived as a result of the findings from the objective 3.

1. *Identify the main features and functions that a BMS should have in order to run a racing car*.
2. *Evaluate critically the options available to implement each function of the BMS*.
3. Formulate the studied solutions and implement the function and thus built the BMS.
4. Analyze the behavior and performance of the system and implement adjustments if necessary.

By exploring the above areas of literature, a significant contribution will be made to this research.

The main advantage of using a BMS is that it provides a fault-tolerant capability and battery protection. A BMS is relatively simple in low-power application e. g. cell phones, laptops, gps, digital cameras and so on, and, thus, a large amount of integrated solutions are available [17]. In those devices previously quoted the difference is that the quantity of cells that needs to be monitored are small, in a laptop battery for example there is normally 6 cells. However, in high-power systems, long battery packs with high-capacity increase the risk of failure as well as the repair costs.

3.1. OPERATION IN NOISE ENVIRONMENTS

The printed circuit board must be designed in a specific way that the signal should not be affected by ground noise, electromagnetic interference (EMI) and radio frequency interference (RFI), because the measurement accuracy of the battery cell voltages must be of few millivolts or tenths of millivolts, to achieve that multilayer PCBs are a good option once they shield the analog signal path and allows more efficient high current paths.

3.2. PROBLEMS EXCEEDING THE LIMITS

The lithium-ion batteries are not very tolerant to overcharging that if happens leads to electrolyte oxidation and decomposition and overdischarging that results in cathode structural changes, so that, reduces considerably the cycle life of the battery. An accurate voltage monitoring is required in order to not exceed those limits [18]. The temperature is also a variable that should be under control, that’s because if the battery operates out of the safety temperature range, that can damage the cells.

3.3. BALANCING

In order to obtain the maximum energy storage, the cells must be balanced individually during the charging operation.

Different algorithms of cell balancing are often discussed especially when multiple cells in series are being used in a battery pack. The most common solutions perform the cell balancing through by-passing some cells during the charge process and in specific cases even during the discharge process, that by-passing consists on connecting external loads parallel to the cells through controlling corresponding Field-effect Transistor (FET).

The cells voltages are used to characterize a situation of unbalance when the cells voltages are different between themselves, those differences are corrected either instantaneously or gradually through by-passing the cells with the higher voltage.

However the reason for the voltage differences on the level of the cells chemistry and discharging kinetics are not widely understood, therefore the goals of a balancing process during the charging process cannot be taken for granted that brings more good than harm. So that it's common to see packs of batteries with balancing schemes being more unbalanced than the packs without any balancing.

3.3.1. BATTERY CELL UNBALANCE TYPES

- State of Charge Unbalance – When the cells capacity is referenced to the SOC of the whole pack. The unbalance state remains constant during the discharge process until near to the end of discharge where the voltage difference between the cells increases.

- Capacity differences – Can happen that the cells have different chemical capacity, and the pack get limited by the worst cell of the pack, because that cell is the one which reaches the maximum voltage during the charging process.

- Impedance differences – The internal impedance differences between the cells can be expected to be approximately 15% per production batch. These unbalances are not perceptive when measuring the OCV, however they will be noticed during the discharge process. There is no balancing algorithm that can help against the resistance imbalance. What can be done is an online monitoring of the cells voltages and decide which cell need to pass more charge through, in this case the one with higher voltage, but still this may not be the best action, because the difference in cell voltage can have another origin e. g. can be also due to differences in the SOC.

The balancing process should only take place at the end of the charging process because by that time the current of charging is small so the drop of the cell voltage has a small impact on the battery voltage. When the balancing is done during the discharge process, there is a risk of resulting in even more unbalance, that because there is no low-rate phase during the discharge.

In a case where a cell has less capacity than the others, this cell during the charging process is going to be more time exposed to a high voltage and this makes causes a faster degradation of that cell, even worst is the fact that this degradation is auto-accelerating, because this degradation makes the cell with less and less capacity and this leads to a runaway circle. This is a problem especially to the Li-ion batteries because this kind of battery store almost all the energy that it's delivered, other kind of batteries e. g. Lead-acid, NiMH and NiCd are relatively tolerant to overcharge because they can respond to increased voltage by internal shuttle reactions that are equivalent to a chemical short-circuit inside the cell. In the case of the NiMH battery oxygen and hydrogen generated after the end of charge recombine inside the cell building water. This causes extensive heating because all the energy of the charger is converted to heat rather than stored.

The need for cell balancing has to be evaluated in conjunction with rate capability, cooling and other properties of charging system.

Regarding safety hazards, Li-ion batteries have a high energy density and the highly reactive chemicals in close proximity makes this battery dangerous. Overcharging and overheating of the battery can causes reaction of the active components with electrolyte and with each other and in extreme situation can causes explosion and fire.

With a good hardware and software it's possible to make a good balancing algorithm that not only optimize the energy capacity of the battery pack but also increase the lifetime of the pack, bypassing the low cell during the discharge process can increase the battery useful discharge time, but to be effective it requires a high-rate capable by-pass capability which is expensive to implement.

3.4. BALANCING METHODS

3.4.1. CURRENT BYPASS

The simplest and cheapest ways of implementing the balancing are through the current bypass, this consists of a FET places in parallel with each cell and controlled by a comparator for simple voltage based algorithms that turn-on the bypass FET during the onset of voltage differences or by microcontroller for more complex algorithms. The general schematic is shown in Figure 10.

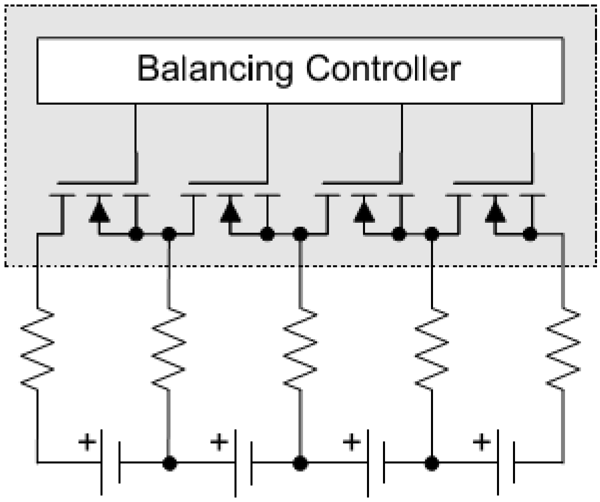

Figure 10 – By-pass FET cell balancing [19]

3.4.2. CHARGE REDISTRIBUTION

The main disadvantage of that is the energy wasted during the balancing process, this can be acceptable if the balancing is done during the charging process and so that the battery is connected to the power grid. A solution that transfer the energy from the higher cell to the lower ones instead of just threw it away through a by-pass resistor is also possible, this can be done simply by placing a capacitor between the higher voltage cell and the lower voltage cell as show in Figure 11, but depending on the number of the cells, this solution would became more complex from the point of view of the hardware implementation.

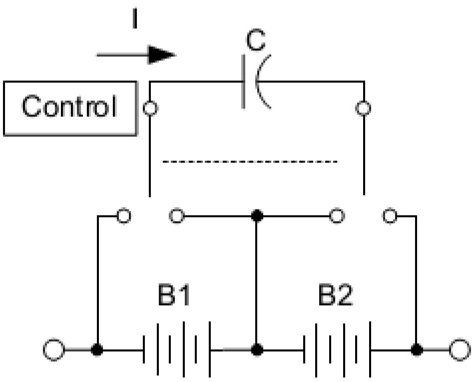

Figure 11 – Capacitor-based cell balancing [19]

For more complicated implementations it’s possible to connect not only the cells nearby, but also cells far away in the stack for faster balancing but as mentioned before can make the hardware development more complex in size matters. A schematic of cells is shown in Figure 12.

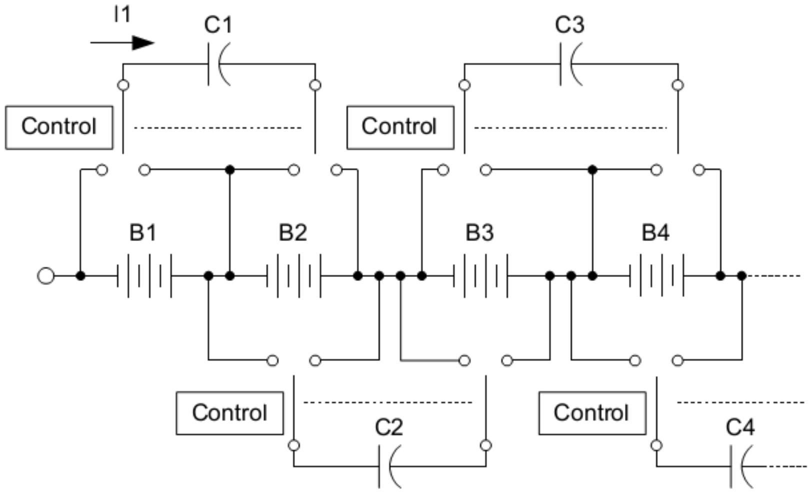

Figure 12 – Capacitor-based for multi cell balancing [19]

The main disadvantage of this method is that a considerable amount of energy is lost during the capacitor charging, so that the maximum efficiency of this method is 50%. Another problem is that this method only becomes efficient near to the end of the discharge state that happens because the transfer rate is proportional to the voltage differences so the total amount of unbalance that can be removed during one cycle is low.

3.4.3. INDUCTIVE CONVERTERS

This method doesn't have the disadvantages other methods has, e. g. small voltage differences between cells decreasing the balancing rate is implemented by transferring pack energy into single cell by directing pack current through a transformer which is switched to one of the cells that needs additional charge.

The efficiency of the converter is limited and the need of a transformer increases the price and the size of the overall solution. The author states that by the time of his research in 2001, no commercial implementation of this system in portable devices was successful, according to him the area where it could be practical are high-power systems e. g. BEV and PHEV. The schematic of this method is shown in Figure 13.

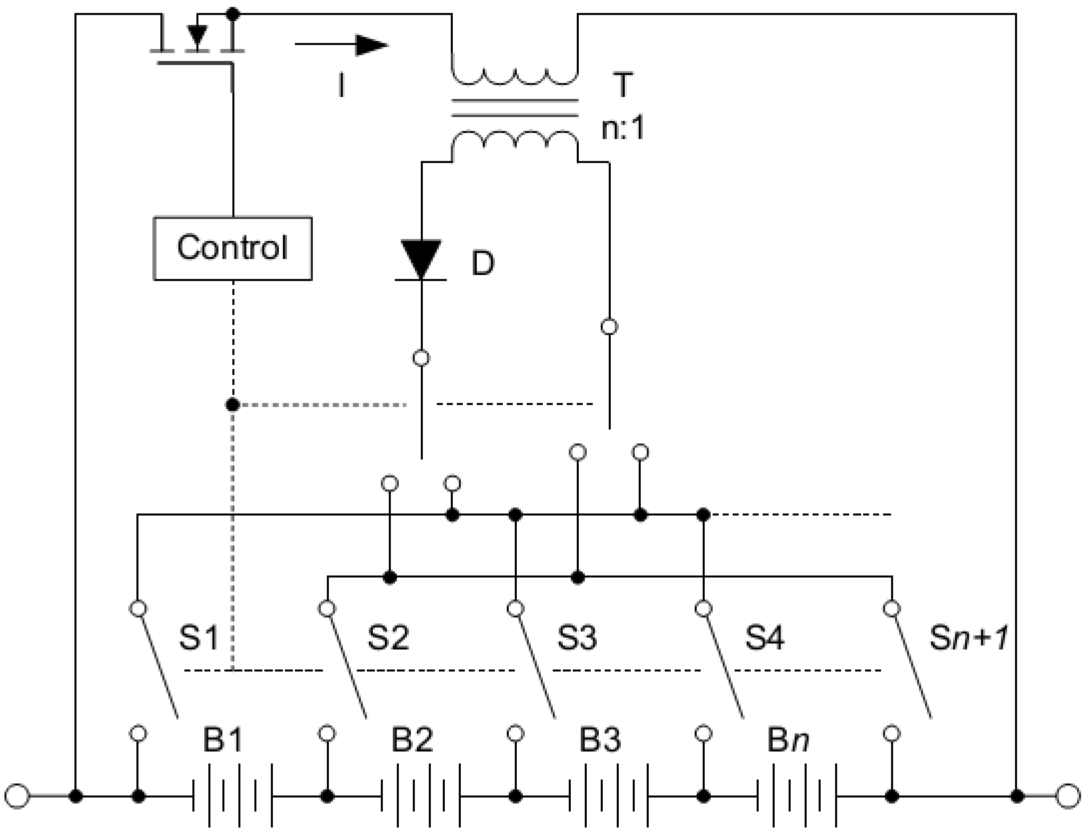

Figure 13 – Inductive converter cell balancing [19]

There are some solutions that can be adopted the most common ones with their advantages and disadvantages are described on Table 1.

Table 1 – Balancing methods – advantages and disadvantages [20]

Method	Advantage	Disadvantage
Switched Capacitor	Simple Circuit Elements	Low balancing capability
Variable Analog Cell Shunting	Good balancing capability, constant voltage model.	Complex power electronics. Thermal management. Energy efficiency (90%)
Switched Resistive	Good balance capability. Simple electronics. Low power requirements	Thermal management. Energy efficiency (90%)

Switched Resistive Inductor	Energy efficiency (99%)	EMI

3.5. State of Charge

The battery is of the weakest parts of a BEV, limited autonomy and recharge facilities are some of the main drawbacks. For this reason the full control and knowledge about the battery is important and this requires an accurate of the State of Charge (SOC) of the battery. The knowledge of the amount of energy that can be extracted from the battery is a key element in order to optimize the system performance. To reach an accurate SOC is not an easy task, some options are available to get there e. g. circuit models, empirical models, statistical or artificial-intelligence-based models [21, 22, 23, 24]. Bellow the SOC estimation is divided in 2 big groups, direct measurement and Book-keeping systems.

3.5.1. Direct measurement

Classical methods for SOC estimation should get the measurements of the extracted charge, the battery internal impedance or resistance and the battery Open Circuit Voltage (OCV). None of these provides acceptable results, so a hybrid method, that measures the internal impedance or resistance, extracted charge and OCV can achieve a better result measuring the SOC.

There are a lot of methods that can be used to determine the SOC of a battery, in early days inexpensive fuel gauges were used simply measuring the battery voltage, but this method is highly inaccurate because factors like, temperature, age and discharging rates changes the battery capacity. Other well-known method uses impedance measurement to determine the SOC, the measurements were compared with previously generated standard curves. Those methods are far too simple and no accurate enough.

Estimating the SOC only by the battery voltage is not accurate enough for 2 reasons, first because the voltage level depends on the discharge rates, that means, let suppose we have a 1000 mAh battery, if the current of discharging is 1000 mA then this means a discharge rate of 1 C but, if instead the current of discharging is 500 mA then the discharge rate is

0,5 C. The second reason why the voltage is not an accurate enough is because the voltage is not linear as the battery is getting empty, both factors can be clearly seen in Figure 14.

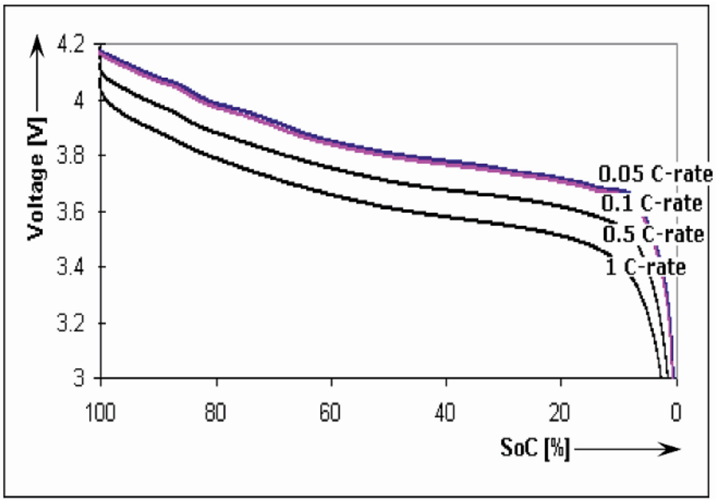

Figure 14 – Li-ion battery voltage curves at different discharge rates [25]

An important point of the SOC is to define when the battery is fully discharged, this can be set as the point where it can’t provide anymore the power needed by the system to operate properly. The procedure of fully discharging a battery is most of the times impractical because of the large amount of time required to do that. The author’s assumption is that the SOC decreases linearly with time if discharge occurs with a periodical current profile. This approximation was supported by laboratory tests. From this point on, the authors proposed a neural network (NN) based procedure that allows an estimation of the SOC using a function of the OCV, internal impedance and the extracted charge. A NN would be very useful if well implemented not only to estimate the SOC but also to estimate the operation in different conditions because the model can compensate the non-linear behavior of the battery [26].

A similar result is obtained a function uses the battery voltage (V), battery impedance (Z) and voltage relaxation time (τ) are used. As the temperature (T) always has an important influence regarding batteries it also in the model to indicate that should also me measured. All this can be summarized by the basic principle of SOC indication shown in Figure 15.

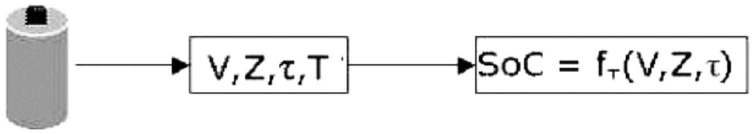

Figure 15 – Basic principle of a SOC indication [25]

The electromotive force (EMF) is a method that uses the internal driving force for providing energy to a load. The EMF principle can be deducted from thermodynamic data and the Nernst equation. It can also be obtained from linear interpolation. This method consists in calculating the average battery voltage at the same SOC measured during two consecutive discharge and charge cycles using the same conditions such as current and temperature. An example this method is presented in Figure 16. The EMF can also be determined based on the value of the voltage relaxation. In this case the battery voltage will relax to the EMF value after current interruption. For this a lot of time is required especially if the battery is almost empty, if the experience is done at low temperatures or if a high discharge rate was used [25].

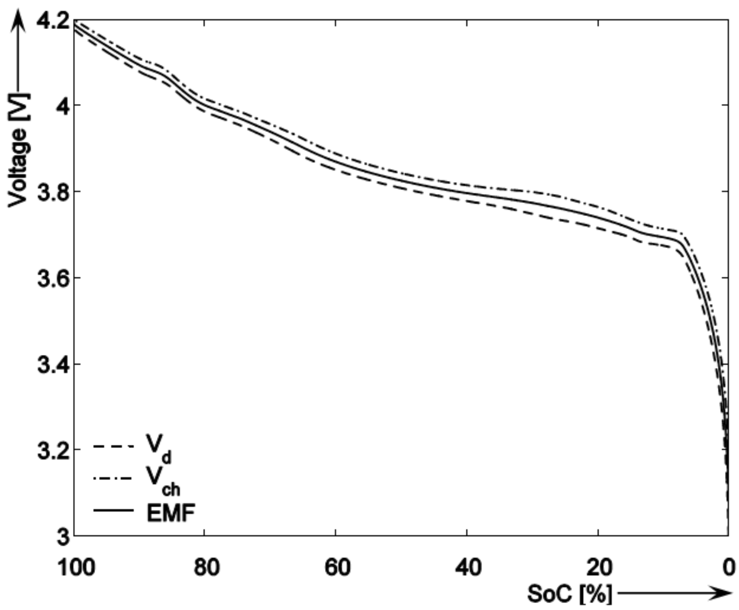

Figure 16 – EMF curve obtained using linear interpolation method [25]

The EMF method in a Li-ion battery showed to be a good way to measure the battery SOC, e. i. the relationship between the EMF and the SOC does not change during the cycle of the battery when the SOC is expressed relatively to the capacity.

The most common ways of estimating the SOC when using the EMF are through a look-up table, the accuracy depends on the number of measurement points, the more it has, more accurate but also more expensive than other approaches. The other way is using piecewise linear function, this method is similar to the one using look-up table, the difference is that instead of specific values, there are intervals of linear functions [25].

3.5.2. BOOK-KEEPING SYSTEMS

In this method to measure the current flowing either in (charging) or out (discharging) of the battery, besides measuring the current it also integrates this current over time in order to determine the capacity of the battery. The integration of current is referred as coulomb counting [25]. Not only the current is used the SOC indication, other factors such as self-discharge rate, temperature, charge/discharge efficiency, number of cycles can and should also be used as input for an accurate SOC indication. Some of these factors will be explained bellow.

Discharging efficiency – Regards the charge inside a battery that can actually be retrieved. What determines this efficiency are reaction kinetics and diffusion processes, both are temperature dependent. This feature can be noticed when a battery seems empty after it has been discharged with a relatively high current and can still be discharged further after a rest period and/or with a lower current. Temperature has influence because it changes the charge/discharge current and the aging has influence because of the increasing internal resistance.

Self-discharge – When a battery is stored for a long time, it loose charge. The Coulomb counter can’t measure this discharge because there was no current flowing through the battery terminals. This self-discharging effect is influenced by the temperature and the SOC.

Capacity loss – The fact that the battery capacity in Ah decreases as time goes by. The aging is not the only factor that contributes for that, misused through overcharging or overdischarging on a regular basis leads to loss of capacity.

3.5.3. ADAPTIVE SYSTEMS

Designing an accurate SOC by itself is already an complicated task, the unpredictability of the behavior of both batteries and users make this task even more complicated, for this reason more than one method simultaneously are intended to be used in order to improve the SOC accuracy [25].

The use of the Kalman filter works with a parameter estimation to determine the SOC. The basis of the filter is a numeric battery model description. The voltage of the battery is estimated based on the current and temperature measurements and then the results are compared with the voltage measured value. This filter is very complex to implement and has the disadvantage that requires very reliable measurements because the results are based on the measurements.

The fuzzy logic can also be used to estimate the SOC, the method uses fuzzy logic mathematics to analyze data obtained by impedance spectroscopy and/or coulomb counting techniques. This technique is also complicated to implement but the accuracy it's around 5%.

3.5.4. SUMMARY

A number of methods to determine the SOC are possible but previously presented were the most popular ones. The important lesson from here the data we should collect to implement a SOC indicator, such as, voltage, current, temperature and even the time are important in order to accurately predict the SOC. In the Table 2 the SOC determination methods are summarized along with application, advantages and disadvantages.

Some methods for estimation of the SOC are going to be described with respective advantage and disadvantage of each of them.

Table 2 – SOC Determination – advantages and disadvantages

Method	Application	Advantages	Disadvantages
Discharging test	Beginning of life determination	Ease, accurate, independent of SOH	Offline, time demanding, modifies battery state, loss of energy

Coulomb counting	All battery systems	Accurate if, available re-calibration and good current measurements	Need of re-calibration and sensitive to parasite reactions Depends on initial SOC
OCV	Lead, Lithium, Zn/Br	Online, cheap, voltage prediction	Requires long rest time
EMF	Lead, Lithium	Online, Cheap, EMF prediction	Requires long rest time
Fuzzy logic	All battery systems	Online	Requires a lot of memory in real-word application
Kalman filter	All battery systems	Online	Difficult to implement the algorithm

The SOC is a very important component of the BMS and in order to get a good SOC determination variables like, voltage, impedance, current and temperature should be inputs of the system and in an algorithm should be well processed to give accurate status information of the system. More than one method should be used in order to reach the wanted accuracy.

The accuracy of the coulomb counting method depends on the accuracy of the current measurement device in both stages, charging and discharging. Normally this measurement is done by a shunt resistor connected in series to the battery system and converts the measured voltage into a current, but in our case we have 2 ways of measuring the current, through a proper device in the HV box, and the Sevcon does it as well. In case of a need of a resistor, the features that the resistor must have are, lower value and high power dissipation rates because the low resistance of the shunt results in a small voltage drop across the shunt which must be measured in order to determine the smaller charge and discharge currents in the battery system.

Features that are required for an ideal battery: high energy density, high output power (density), long life, high charge-discharge efficiency, wide range of use from low temperature to high temperature, minimal self-discharge, good load characteristics, good temperature storage characteristics, low internal resistance, no memory effects, fast charging, high degree of safety, high reliability, low cost and good recyclability [27, 28]

4. RESEARCH METHODS

This research study has a number of inter-related objective set within the context of developing a BMS.

1. Identify the main features and functions that a BMS should have in order to run a racing car.

2. Evaluate critically the options available to implement each function of the BMS.

3. Formulate the studied solutions and implement the function and thus built the BMS.

4. Analyze the behavior and performance of the system and implement adjustments if necessary.

A valuable aspect to this research work relates to Objective 2 where the options are studied and evaluated in order to check which decisions fits better the proposed application.

The Objective 1 were initially addressed in the previous section, in the form of a review of literature in the field of the battery features.

This section will provide the details of the research strategy adopted to address the research issues identified previously, together with the means of collecting data for analysis, including the analysis approach to be adopted taking into account that the project has a real world application in this case only for racing cars but some with a few more algorithms would fulfill the requirements for commercial electric cars, since the components being used on the project can also be implemented in an everyday car.

A BMS is not a new issue in our society, since the popularization of the portable electronics devices e. g. cell phones, mp3 players, digital cameras, etc. The battery receives special attention, but, in those cases the battery is compound for one single cell, so that the management is much simpler.

The introduction of more complex system such as electric cars, and the need for more powerful batteries, the need for more complex BMS came together and since this project has a specific focus on an racing formula student car, the research method here applied was an qualitative research is more adequate than a quantitative research, since no analysis of numerical data is conducted. The method used was action research, this method was used because the market already has some solution regarding the problem here studied, the difference is that in this case just research what features a BMS should have is not enough, the features has to be really understood in order to be self-developed.

The data collected is presented is the previous chapter where some features of a BMS, such as SOC estimation and Balancing are presented, other features e. g. CAN communication, limits monitoring and power control were totally self-developed based on the knowledge gained during the period which the project were being developed and the researcher getting more familiar with the battery behavior as a whole.

The empirical research in this study is necessary because the more we get familiar with the behavior of the system, improvements can be done to make the whole system works as we desire. A little bit of historical research was also conducted to understand the evolution of the material and methods used as well as the influence of the digital electronics on the controlling systems. Experimental research was also conducted in order to improve the behavior of the system, fortunately I had the opportunity of use a Simulink model which simulates the battery behavior during both charging and discharging process, and this model was very useful to develop the charging algorithm. Survey-research is inappropriate in this context because this is a qualitative research therefore no opinions and statistical data were needed.

The research presented some limitations, e. g. not many sources with proper explanation of how the features a BMS should have are implemented, however the good point was that the few sources with enough information agreed between then when describing the features.

In the next chapter the data collected will be discussed and the decisions taken will be justified.

5. FINDINGS

In this section some of the lessons learned from this semester project, this knowledge acquired encompasses not only subjects regarding the BMS but also the whole project itself.

5.1. SYSTEM OVERVIEW

A good starting point is to show the system overview, the information bellow is also on the ESF (Electrical Safety Form) which are files that should be fulfilled with information regarding the electrical safety, e. g. the datasheet of the components used must be presented that the parameters are within the safety limits, e. g. the isolation voltage of the components present at the slaves and therefore handle both low and high voltages should be higher than the maximum voltage that the system can reach.

This year the FSG (Formula Student Germany) called the BMS, AMS (Accumulator Management System), so that in the schematic bellow we see AMS.

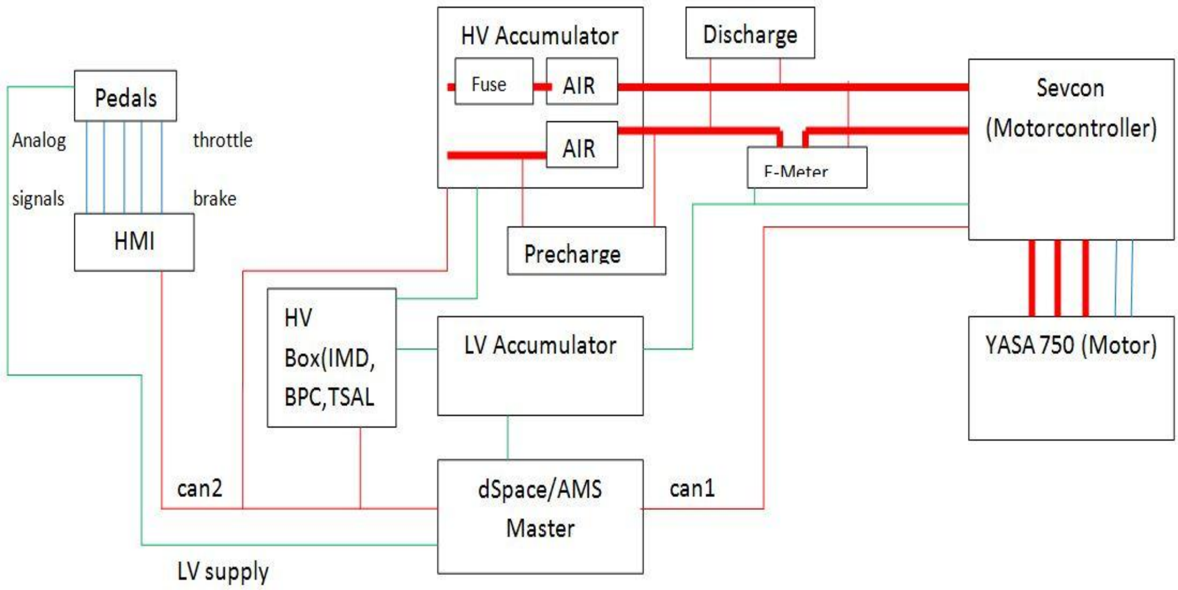

Figure 17 – System Overview

The system is made of self-developed AMS and Accumulator case. There is also a case housing for the energy meter and other electrics components.

As shown in the previous Figure 17, we have the whole electric system schematic but we are going to focus only in the parts regarding the AMS:

- HV – Accumulator which is the accumulator box and in it we have the cells, slaves (6 slaves monitoring 16 cells each), AIRs, pre-charge and discharge resistors.
- HV – Box which has the relays, transistors, sensors and others devices responsible for the safety and controlling.
- dSpace – Responsible for all the controlling including, drive control, AIR control and AMS master.

The Table 3 contains useful information regarding the specifications of our system:

Table 3 – General Parameters

Maximum Tractive-system voltage:	345.6VDC
Nominal Tractive-system voltage:	316.8VDC

GLVS voltage:	13.2VDC
GLVS supply:	LiFePO4
Accumulator configuration:	96s1p
Total Accumulator capacity:	20Ah
Motor type:	Permanent excitated synchronous motor
Number of motors:	1
Maximum combined motor power in kW	100kW

The data in the Table 3 refers to the project but in the case of the GLVS (Grounded Low Voltage System) the documentation is not agreeing with the reality, at least for the first competition, FSG. In Hockenheim the LV battery instead of being the stated one, we used a regular motorcycle 12 V battery with 20 Ah capacity, that performed well since the car in full operation including the oil pump drains 7 A so that battery is enough for let the car run at least for 2 hours. The reason why we didn't use the stated one is because it was not ready by Hockenheim, moreover it requires one slave and we didn't have time to test it.

In Figure 18 it's possible to see the electric system overview, it's clear the division between low voltage and high voltage. In this schematics it's possible to see the connections and regarding the charging points unfortunately the energy meter is well located when the car is in the discharge mode, but it's by passed during the charging mode, that is not the best choice for the location of the energy meter since it should operate during both modes charging and discharge. The right position for the energy meter should be at the same line as the AIR, that way it would measure in both operations, the difference between the way it is and the way it would be is that if properly mounted, would be very helpful for a more accurate SOC estimation, since my initial idea was to measure the energy going in through coulomb counting method, subtract the losses due to the chemical reactions and heat which is around 3% and when the car is on operation mode the energy going out is measured and subtract of the total energy of the battery, but since the energy meter is by passed during the charging, an estimation of the total energy of the battery is proceeded based on the cell voltages.

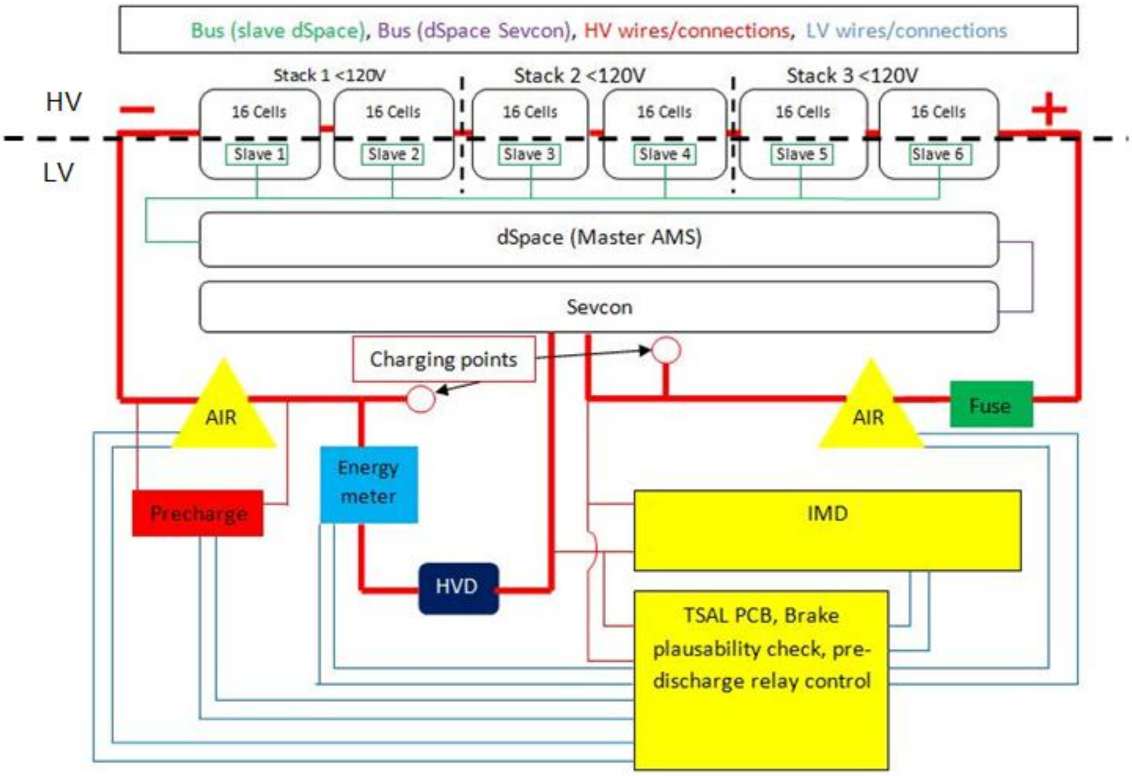

Figure 18 – Electric System Overview

A CAD picture of the HV accumulator container can be seen in Figure 19 followed by its parameters shown in Table 4.

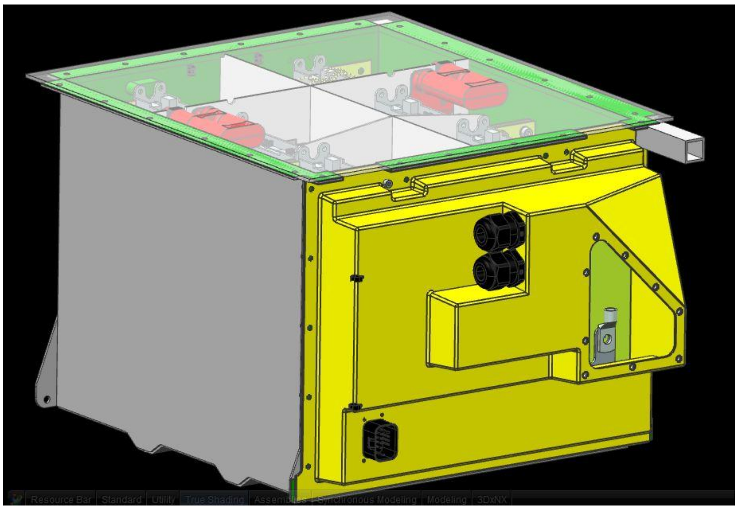

Figure 19 – Accumulator Container

On the figure above you can see the accumulator container. There is only one in the car. It consists of two cases. One is made of aluminum and GFK. In this one there are the cells and in red the maintenance plugs. You can also find the slaves inside the first container.

The second container consists of GRP (glass-reinforced plastic) laminated cover 2mm strong. Under this cover there are the AIRs, the fuse and a self-made PCB which bunches all LV wires e.g. AIRs, Pre-charge relay and send them through an automotive connector from Ampseal to the HV box located above to accumulator.

Table 4 – Main Accumulator Parameters

Maximum Voltage:	345.6VDC
Nominal Voltage:	316.8VDC
Minimum Voltage:	240VDC
Maximum output current:	300A for 10s
Maximum nominal current:	240A
Maximum charging current:	40A
Total numbers of cells:	96
Cell configuration:	96s1p
Total Capacity:	22.46 MJ
Number of cell stacks < 120VDC	3
Number of cell stacks < 6 MJ (if applicable)	6

5.2. CELL DESCRIPTION

On Figure 20 can be seen one of six stacks in the accumulator. One stack consists of 16 cells, one slave (AMS), two copper lugs, one printed Polyethylene **(**PE) profile with a GRP plate on the ground and one Polyoxymethylene **(**POM) profile on the top. The cell lugs are ultrasonic welded. The sense wires are made of OILFLEX HEAT cables with fuses. Two of these stacks represents a <120 VDC/ <12 MJ respecting what states on the rules that says that the battery should be divided in 3 sections and each of them should have a voltage under 120 VDC and a capacity under 12 MJ. In our case, since we have 6 stacks, to divide the battery in 3, two of our stacks should be 1 group and respect the voltage and capacity requirements.

It's also possible to see the sense wires going from the slave to the cell lugs. The cell lugs have a die cut hole where the terminal is attached to by using a rivet.

The NTC temperature sensors are connected to the slaves by molex pico blade connectors and are inserted between two cells.

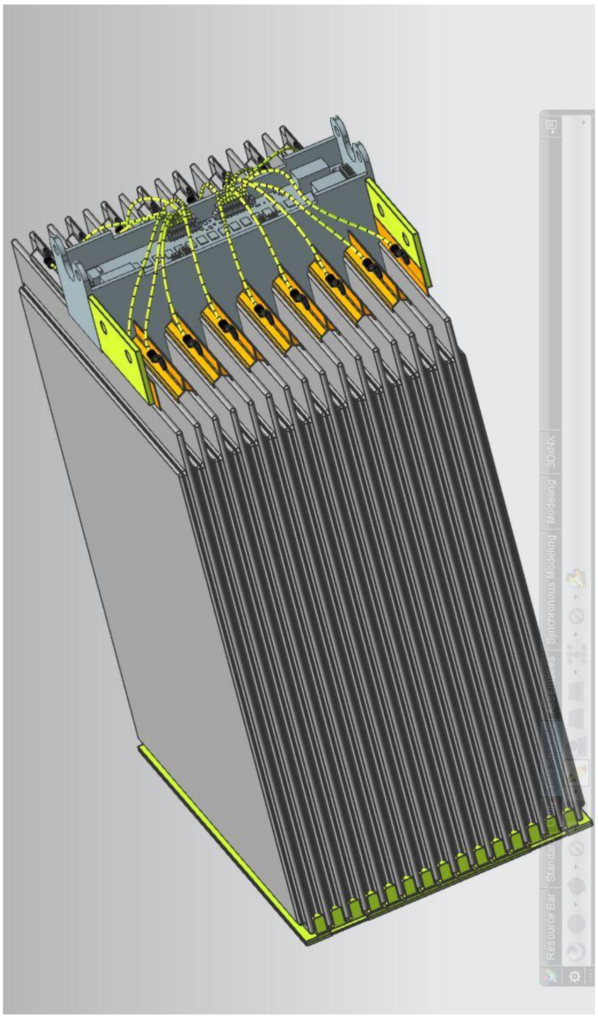

Figure 20 – Cell Stack

Table 5 – Cell Specification

Cell Manufacturer and Type	A123Systems Inc Gen 1.5 cells AMP20
Cell nominal capacity:	16.4 Ah
Maximum Voltage:	3.6 V
Nominal Voltage:	3.3V
Minimum Voltage:	2.5V

Maximum output current:	16C for 10s
Maximum nominal output current:	12C
Maximum charging current:	2C
Maximum Cell Temperature (discharging)	55°C
Maximum Cell Temperature (charging)	55°C
Cell chemistry:	LiFePO4

5.3. WIRING DESCRIPTION

From the last slave to the master the can bus wire is going as shown in red to a PCB board with an ampseal automotive connector. From there it goes through the wiring harness to the dSpace, our master.

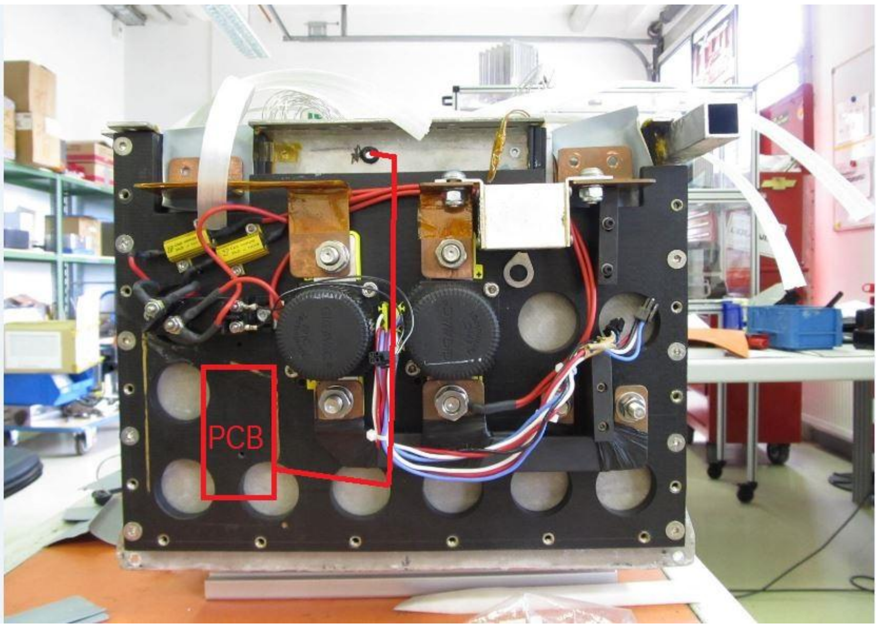

Figure 21 – Accumulator Wiring

The wiring between the slaves is done by regular CAN wires already described earlier, all the slaves are connected in series, in the first slave is connected the termination 120 Ω resistor, the other resistor is located inside dSpace. Details of the connection between the slaves can be seen in the red circle in Figure 22.

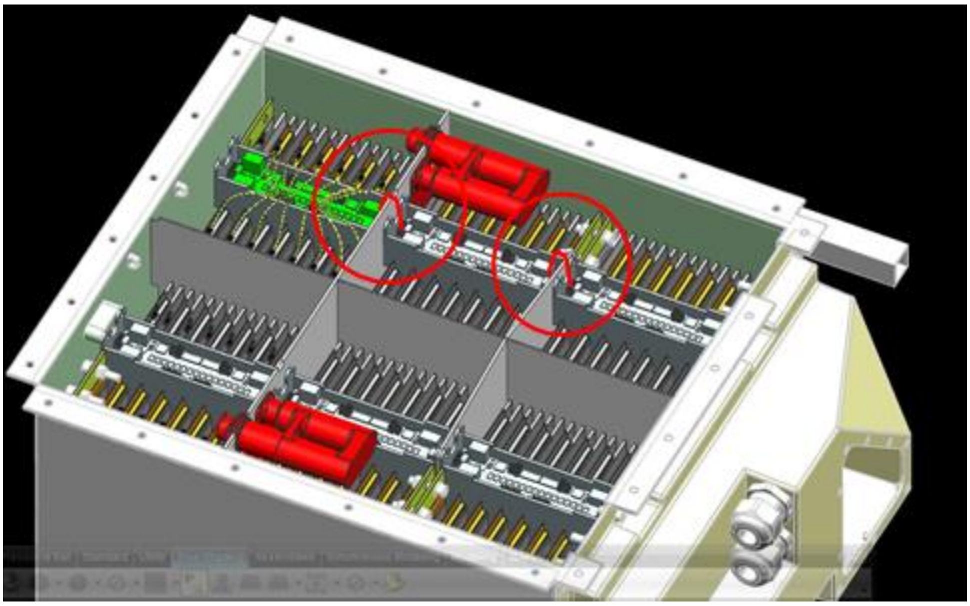

Figure 22 – Slaves Wiring

5.4. LOCATION

The location of the devices is a important issue in the cars, if not properly done, the car can have grounding or EMI problems, in our case that we handle an electric car this issue gain even more relevance, so that, when determining the location of the devices in the car those aspects were taken into consideration, therefore dSpace which has not only the master of the BMS but also the motor controller, sensors inputs and contactors outputs, is located far from the main battery and the motor. The location is under the knew of the driver as shown highlighted in green in Figure 23, and by far no problems regarding grounding or EMI show up.

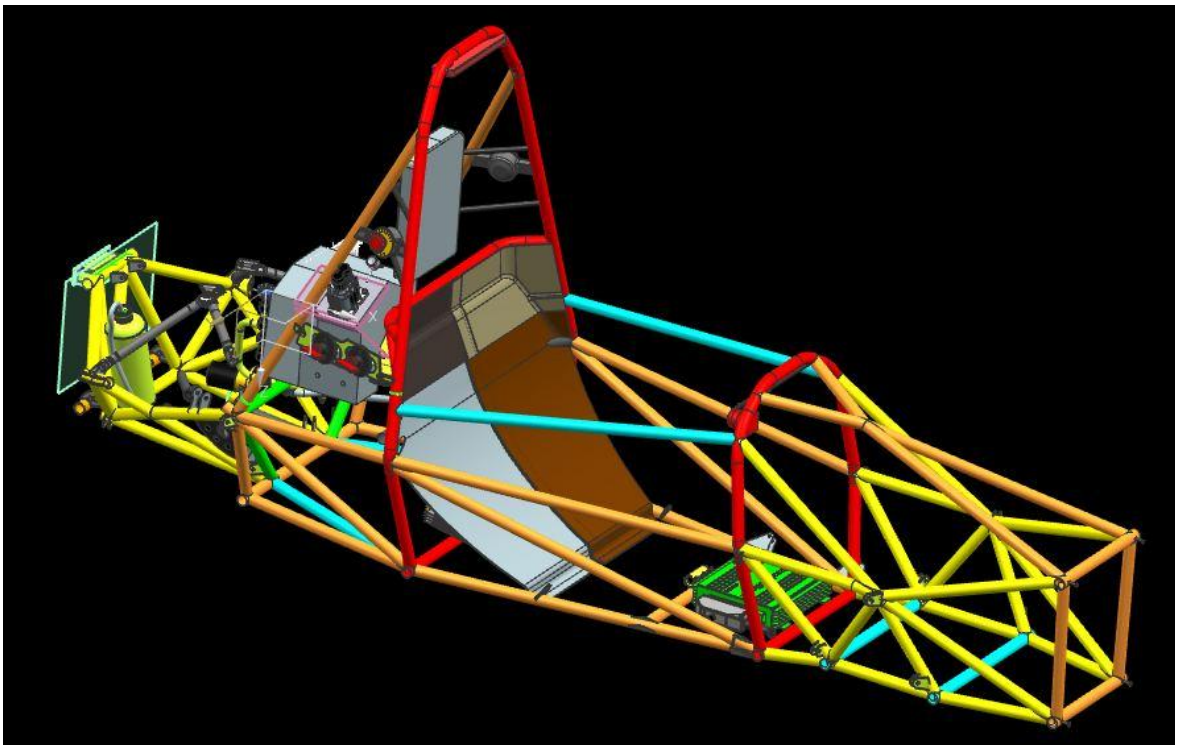

Figure 23 – dSpace location in the car

5.5. PCB LAYOUTS

In this section the layout of the slaves are supplied as well as the isolation. Our PCB, totally developed by David Brandt, has 4 layers which are presented now from the bottom to the top.

In Figure 24 it's clear to see the separation between HV and LV, the black line represents it that distance between LV and HV on the PCB is 4mm.

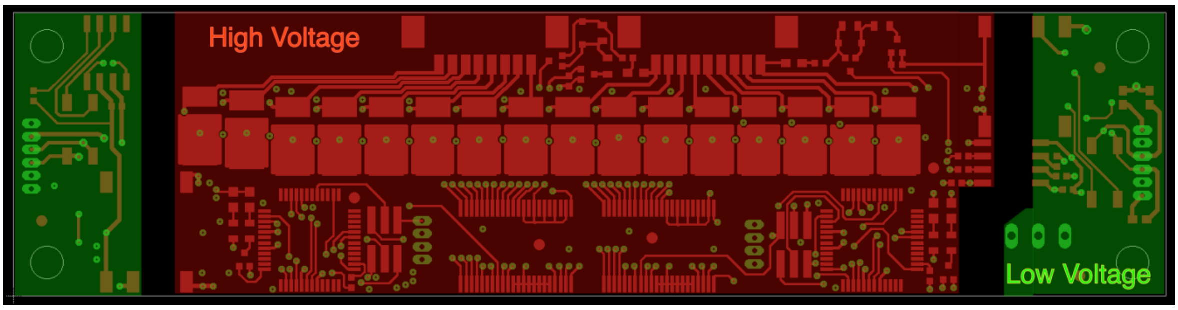

Figure 24 – Slave PCB (top layer)

There are 6 of these boards in the main battery, one for each stack, every board has 2 microcontrollers and each microcontroller is able to measure 12 cells, but in our case is measuring 8 cell voltages. Eight of this board were built and the first six that were integrated to the battery worked fine, but during the first tests we realized that one of the then had an intermittent failure, this failure only show up when we actually drove the car and what happened was that one microcontroller of one slave simply stop sending data and due to that errors show up on the BMS, first the low voltage limits because when it stops sending data the dSpace understand as zeros, and after 5 seconds the timeout error. Because of the potentialities of the dSpace, it was easy to spot the error because there is tools that let us see what error happened even if the error is gone by the time we are looking for it.

5.6. CAN COMMUNICATION

To establish a proper connection through the CAN bus, it's mandatory that both devices agree about the messages going back and forward, in order to obtain that a DBC (DataBase Container) file was created to handle all the messages flowing on the bus, as well as IDs, and offset values. Since the company Vector is one of our sponsors and so that we had the opportunity of working with the Vector CANcaseXL which is a device that we use in the car for logging the messages passing through for future analysis and improvements of the performance of the car as shown later on in this document. That device came with the software Vector CANdb++ Editor which was used to create our DBC file.

The first step is to set the signals that going to be inside the messages, the parameters that should be choose for each message are: Name of the signal, length, variable type, factor, offset, minimum value, maximum value and unit as shown in Figure 25. Those values were agreed between me and David Brandt since he programmed the slaves, during test of the communication we had a small problem that was the data I got at the master was not right, but the communication was working properly, we realized that the problem was the order of the bits, i. e. the most significant bit was not in the position which David had programmed on the slaves, that happened for the cell voltage and temperature, David solved the problem by re flashing all the slaves with the right order of the word.

Name	Leng...	Byte Order	Value Type	Initial Value	Factor	Offset	Minim...	Maxi...	Unit	Value Table
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Balancing_slav...	12	Intel	Unsigned	0	1	0	0	4095		<none>
Cell_temp_01_04	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_05_08	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_09_12	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_13_16	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_17_20	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_21_24	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_25_28	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_29_32	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_33_36	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_37_40	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_41_44	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_45_48	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_49_52	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_53_56	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_57_60	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_61_64	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_65_68	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_69_72	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_73_76	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_77_80	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_81_84	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_85_88	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_89_92	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_temp_93_96	8	Intel	Unsigned	0	0.5	-27.5	-27.5	100	°C	<none>
Cell_volt_01	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>
Cell_volt_02	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>
Cell_volt_03	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>
Cell_volt_04	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>
Cell_volt_05	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>
Cell_volt_06	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>
Cell_volt_07	12	Intel	Unsigned	0	1.5	-768	768	6910.5	mV	<none>

Figure 25 – DBC file creation (Signals)

Once the signals are all configured the second step is to create the messages that are the group of signals that are grouped together and sent under an ID. We need 3 messages to handle every 8 cells, i. e. the first message sends the cell voltages of the first 4 cells of that slave, the temperature of the chip and the status of the slave (0 – no error; 1 – error), this last 2 signals are not being used on the master program, the chip temperature because it's not expected that the chip operate in a high temperature environment because as soon the cells reach 50ºC the system shut down and the other signal regarding the status of the slave, an algorithm for error was developed covering all the possible failures, same massages being send constantly, no data being send and microcontroller turning of or restarting by itself. The second message sends the last 4 cells voltages and the temperature of this first pack of 8 cells. The third message regards the balancing command, so this one goes from the master to the slaves while the first and second goes from the slave to the master. In Figure 26 the messages names and ID as well as the signals inside the messages.

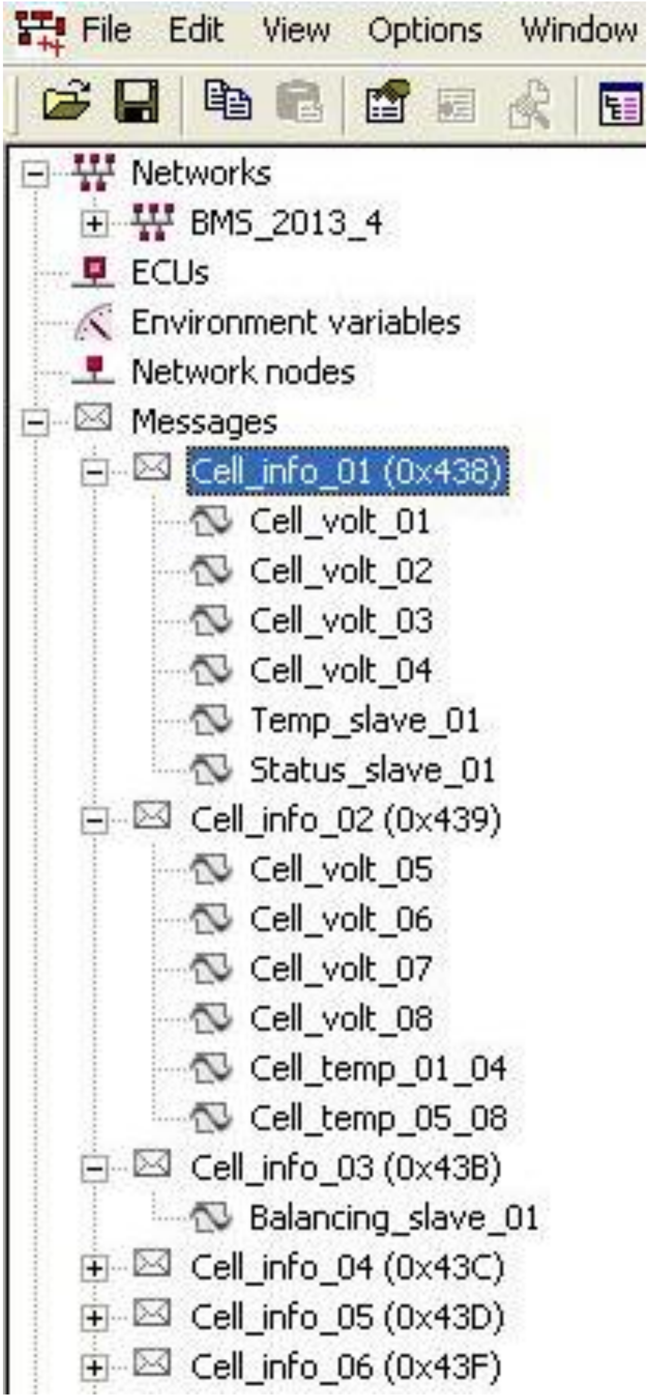

Figure 26 - DBC file creation (Messages)

In Figure 27 is shown the main BMS CAN block, each block refers to 1 micro controller where the information that should be sent to the slaves e. g. balancing command goes in and where the information coming from the slaves e. g. cell voltages are taken, unfortunately in the picture is not very clear but there is 2 signals going in, the balancing command and a upper cell indication that are going to be explained later in this document. Coming out and being used there are the signal referring to cells voltages, cells temperature and timeout error.

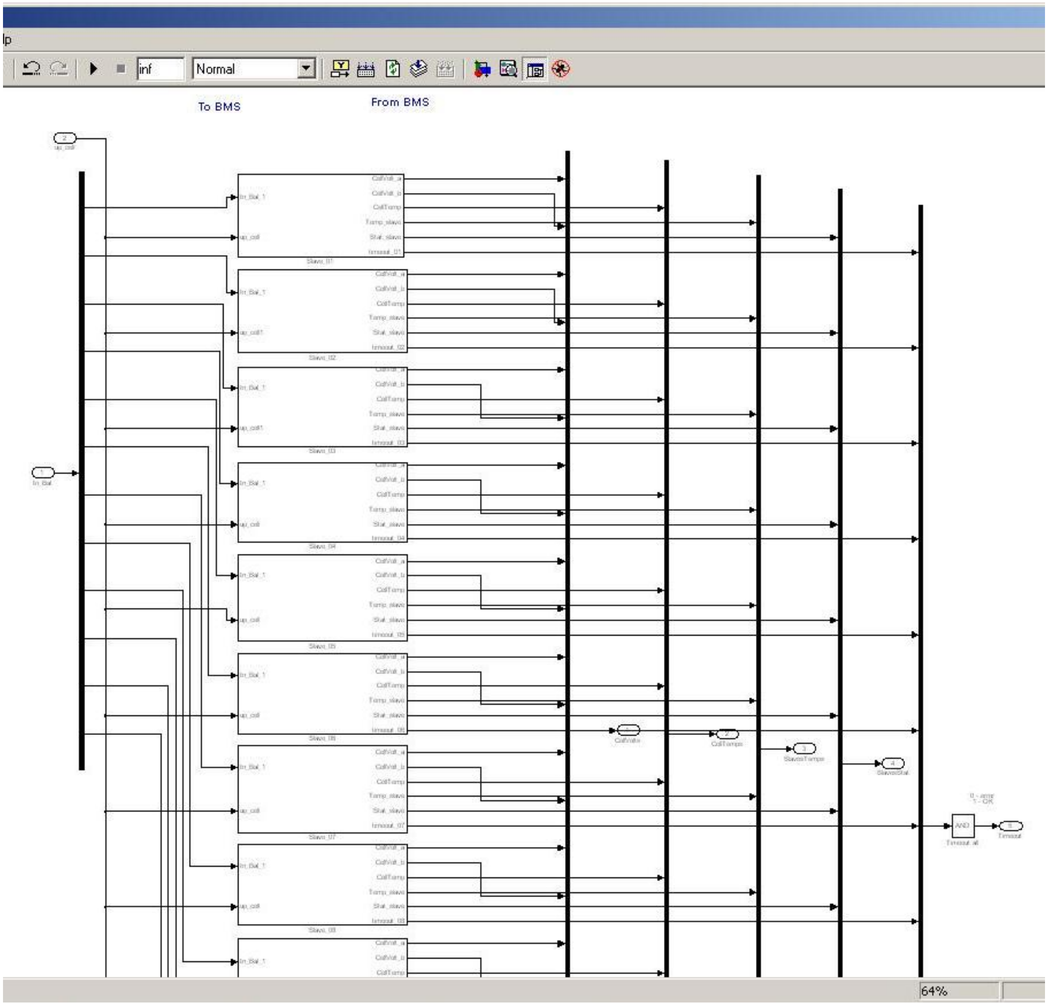

Figure 27 – BMS CAN block

Inside of each of the block there are the block which receives and send the messages according to the ID, inside of the blocks we set the ID of the message and the block automatically generates the inputs and outputs according to the DBC file, then the signals need to be addressed. In Figure 28 the first block on the left refers to the balancing command, the one in the middle is the first received message and the last one to the second received message. The group of block in the down side refers to the upper cell indication that is going to be used on the Control Desk which is the dSpace software.

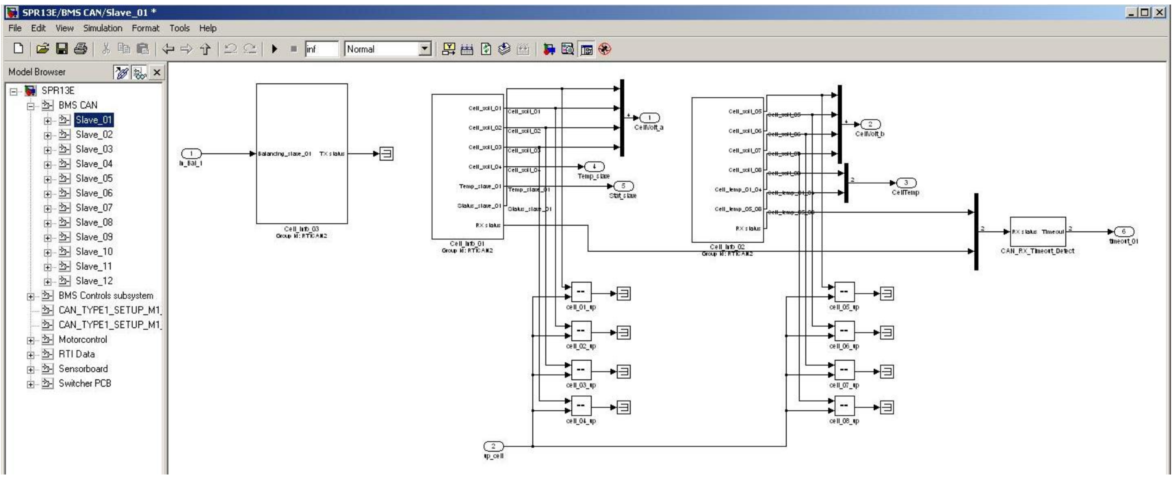

Figure 28 – BMS CAN block (inside)

5.7. Cell Voltage

To make it simple to work and to avoid the need of converting data everywhere it is needed it was useful to get from the cell voltages the other outputs as can be seen in Figure 29, with the max bock we get the highest cell of the battery, with the min block the lowest one, the voltage of the battery is obtained both by the sum of all the cell voltages and by the information that comes from Sevcon.

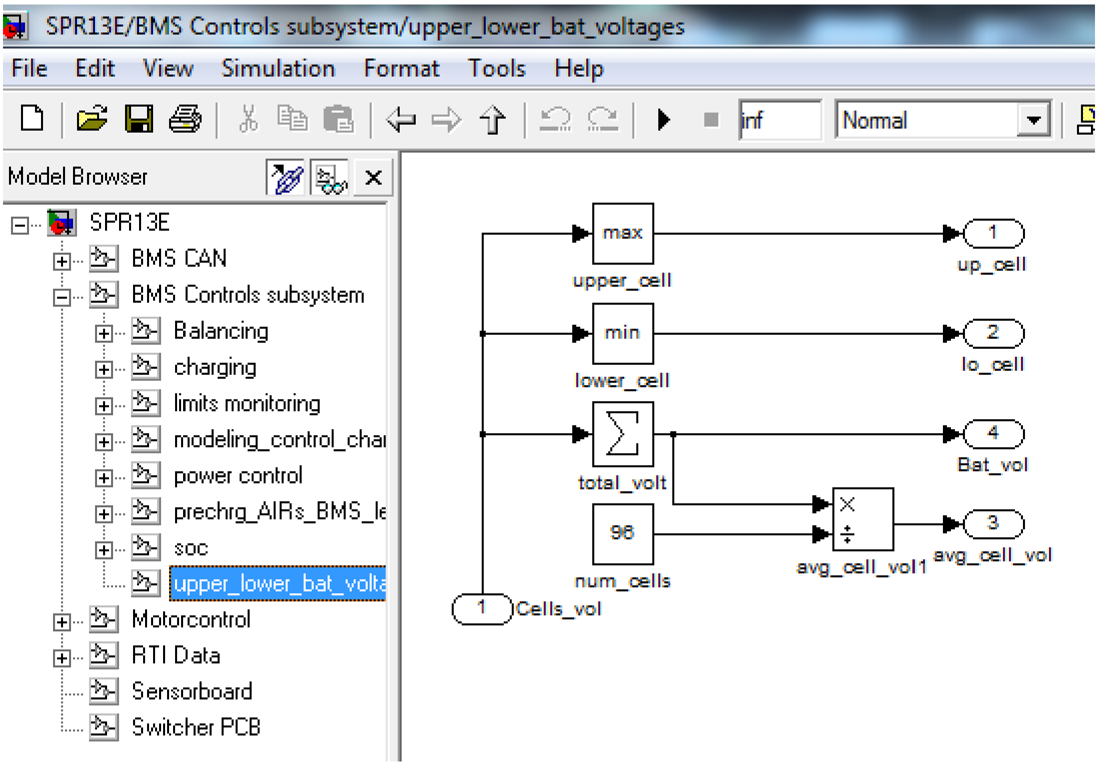

Figure 29 – Cell voltage Information

5.8. BALANCING

For balancing the algorithm should get the cell voltage of each cell, that is done by the demux on the left, then it goes to 12 mux of 8 inputs, from those mux it goes to the blocks that are explained in Figure 31. This Figure 30 is just to show the data acquisition like all the cell voltage, charging on information, lowest cell voltage and manual balancing command. On the output there is a mux that put all the information of the slaves in one line and a data converter to convert the data into a format that the slaves “understand”.

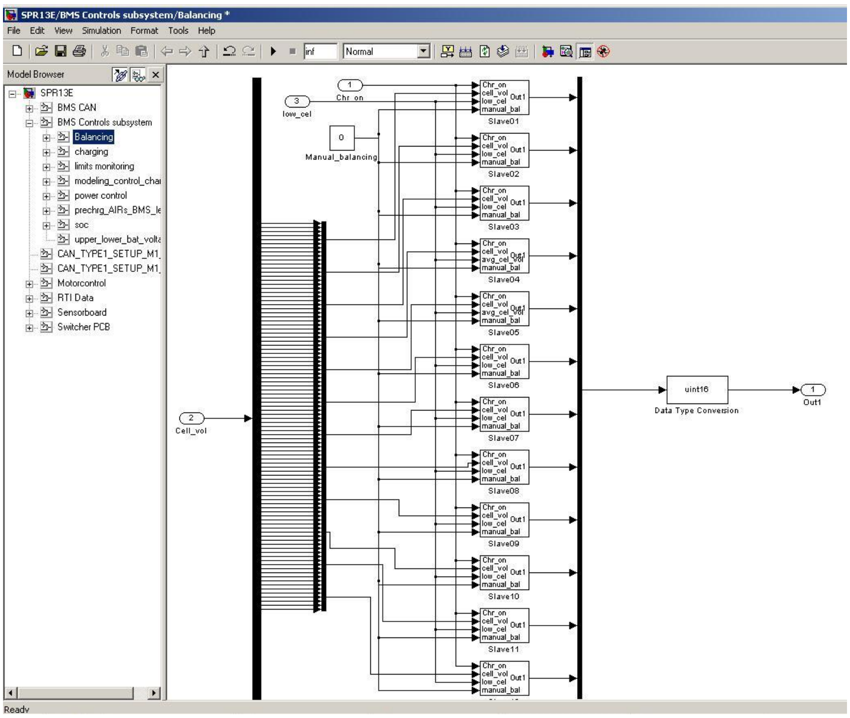

Figure 30 – Balancing Algorithm (data acquisition)

The balancing algorithm is shown in Figure 31, and described here, the algorithm is going to be explained from the left to the right. The cells voltage regarding the respective slave comes through the demux and goes into one port of a comparator on the other side of the comparator the input is the value of the lowest cell added by 10 mV, so, when one cell has its voltage higher than 10 mV comparing to the lowest one that comparator sends 1. That signal just goes forward when the lowest cell is higher than 3.35 V (near to the end of charge) AND the charging process is taking place. It is possible also to start the balancing process manually even if the battery is not being charged and it is also possible to balance each cell manually using the Control Desk, that can be done through the OR block in the right side of the algorithm. In the right side of the window there is the sum which add all the data on the input, and before that there is a gain for each cell, that is because the slave expect a 12 bits word, that is a number between 0 and 4095, the way I found to have that on the output was to add a gain for every cell, the least significant one has a gain of 1, while the most significant one, in our case the eight because each chip handle just 8 cells instead of 12, receive a gain of 128. With this by the sum on the output the slave knows what cells should be balanced. The same process is used for all the other 11 microcontrollers as can be shown on the root on the left hand side.

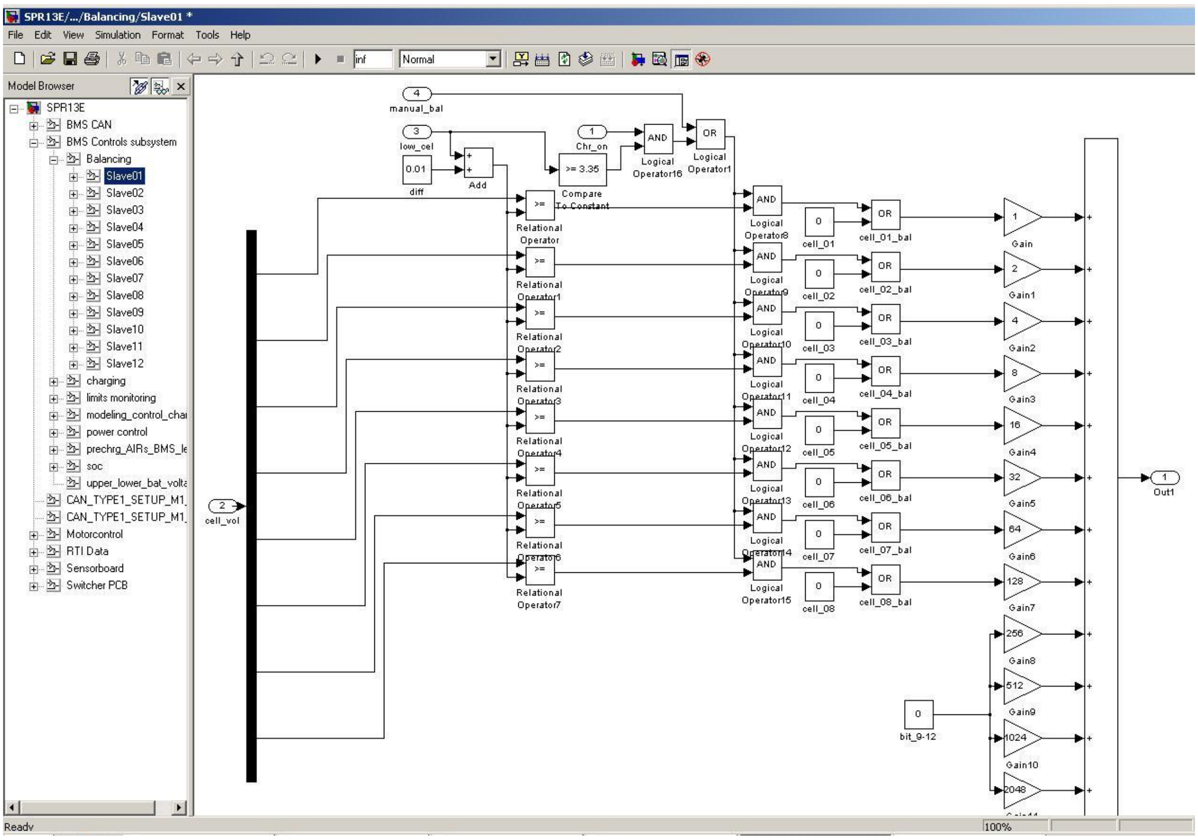

Figure 31 – Balancing Algorithm

5.9. LIMITS MONITORING

This is one of the most important sections of the whole project, this subsystem makes sure the cells are keep under safe conditions regarding voltage, temperature and current.

In the appendix section there are the documents supplied by Opel which the algorithm was based on, appendix 1 contains battery limits, appendix 2 contains cells datasheet, appendix 3 contains cable datasheet, appendix 4 contains safety datasheet.

In Figure 32 the limits monitoring algorithm is presented. On the left side there are the 3 necessary inputs, cell voltage, temperature and current. Regarding the cells voltages, according to the document that Opel supplied, it can be higher than 3.6 V for 10 s, so the upper limits are exceeded when the voltage reaches 3.8 V or 3.6 V for more than 10 s. The lower voltage limits follow the same logic, it can be lower than 2.0 V for 30 s, so the lower limit are exceeded when the voltage reaches 1.6 V or 2.0 V for more than 30 s. There are other blocks just after the input but there were used just to test the algorithm.

Regarding the temperature the algorithm is simple, if some temperature reaches more than 50 ºC then the temperature limit is exceeded. There are other blocks on that line but it's just for the signal conversion.

Finally the current limits, one more time following the documents given by Opel, it is stated that the battery can supply up to 200 A for 30 s, up to 250 A for 20 s, up to 300 A for 10 s, but if those conditions are exceeded or the current exceeds 300 A then the limits has been exceeded, this last conditions are stated on the rules of the Formula Student, during the competition an energy meter supplied by the competition is applied to the car and if the car drains more than 300 A for more them 100ms then the team is disqualified.

On the right side there is a NOR logic gate that has 1 on it output while all inputs are zero, and just before that, there is one flip-flop for each input of the gate, that way it is possible to see what limit was exceeded even if the variable has changed for an acceptable value again. Using this technique we could realize that one of the slaves stop working because the error was the lower cell voltage. Later on this document a screen shot of the Control Desk will be presented to show where we can see the error.

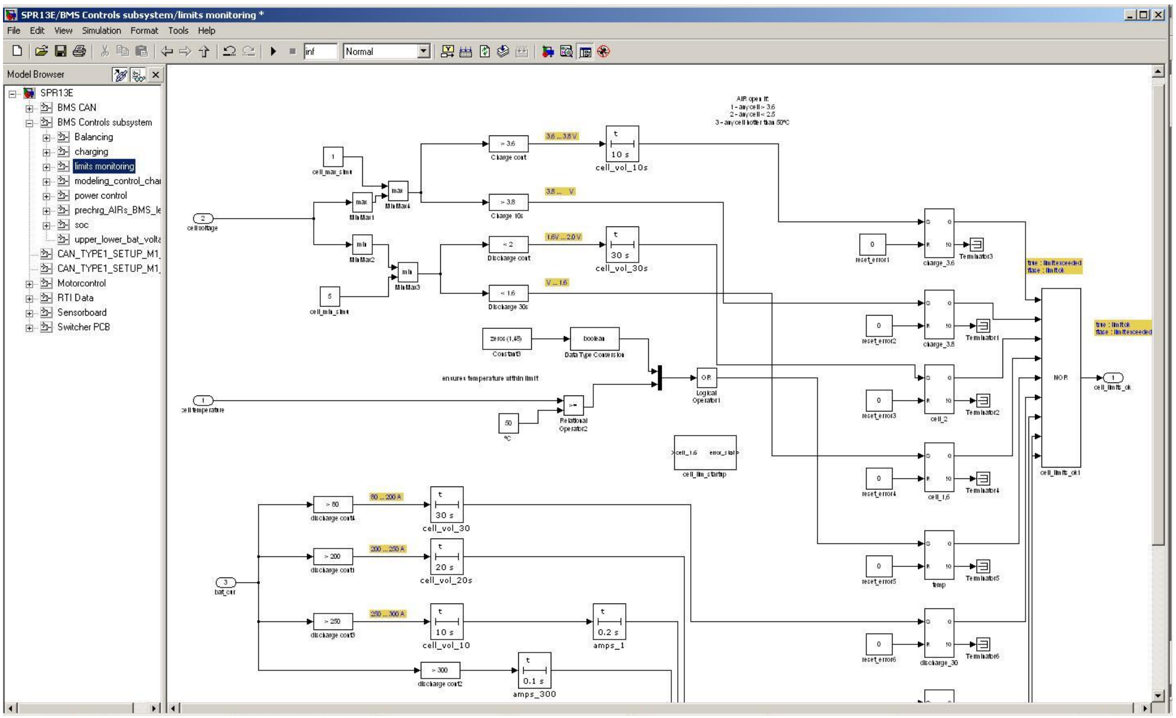

Figure 32 – Limits Monitoring

5.10. CONTACTORS COMMAND

This subsystem in Figure 33 is responsible for closing and opening the AIRs as well as the pre-charge resistors. This subsystem receive the state of the car as an input, for example, the state of cells, if the car it's on the operation mode, and others external errors that may happen, for example the IMD or the emergency buttons.

The subsystems inside that subsystem are mainly to let the car operate properly and to respect the rules, for example, the rules says when the car is turned on, one of the two AIRs and the pre-charge should be closed and the other can only be closed when the voltage level at the controller is equal or higher than 90% of the battery voltage. That is done by comparing the battery voltage by the sum of all cells and the voltage the Sevcon receives.

Regarding the well operation of the car, it was needed to be implemented some startup delays. What happened was that during the startup of the system the slaves takes longer to transmit valid data than the dSpace takes to start to operate, so, when the system is turned on, the dSpace receives zero on the cell voltages and goes in error mode, due to that, some subsystem just make the system wait 2 seconds after the car is turned on before being able to go on an error mode. Another implementation done here is, when the BMS goes on error mode, it opens the AIRs protecting the battery from the rest of the system, but to open the contactors when a high current is passing through is not good because through the time the detrition of the contactors may cause malfunctioning, so that when the error happens, the controller receives a message to stop working and after 0,5 s the contactor are opened.

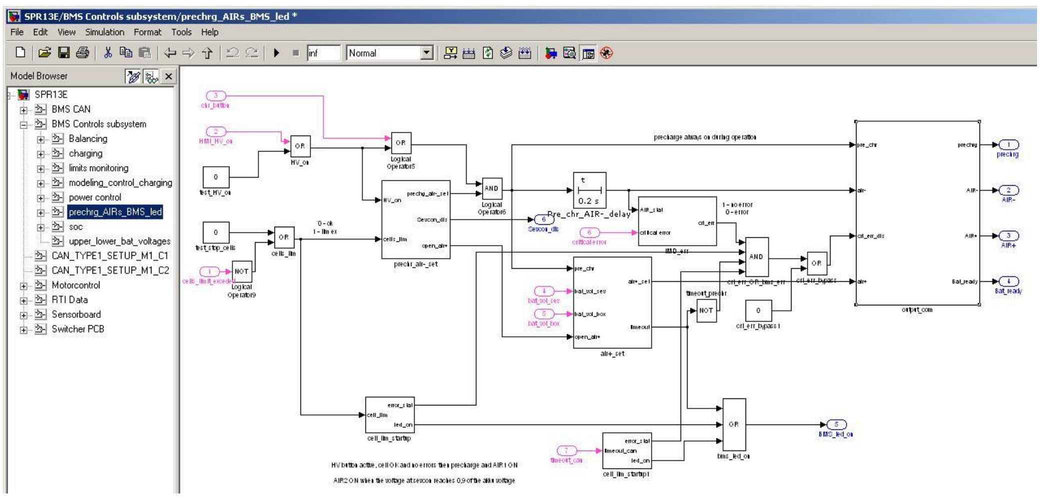

Figure 33 – Contactors Control

5.11. POWER CONTROL

This subsystem was developed in order to make the car run for longer in case that is needed e. g. the dynamic event Endurance.

The system has 4 inputs, cell voltage, whole battery voltage, SOC and temperature.

The logic here used is simple, if the battery is close to the end of discharge mode than an output limits the energy that can go out of the battery on that moment.

The output varies between 0 and 1, zero for 0% that means the battery is over and one for 100% the car can run as the driver wants.

In Figure 34 it's possible to see in detail the first variable handling, it is the cell voltages, just after the raw value of the cell voltage it's used a lowpass filter with the objective of let the car operate smoothly even in a situation that a high current is drained and the cell voltage drops and the power is not limited, without that filter the car would have an unexpected behavior when the driver demands a lot of energy, because the voltage drops, then the algorithm limits its power, then the voltage rises again, power is demanded and voltage drops again and so on.

In the graphic it's shown how the power control is done, the voltage curve of the cells is very flat, the nominal voltage is 3.3 V but when that value is reached and measured in a OCV that means that the SOC is already in 50%, so based in another documents supplied by Opel and present in the appendix 5 of this document, when the SOC of the battery reaches 30% the output power is equivalent to 50% but as can be seen in the graphic the change happens gradually in order to minimize the perception of the driver, that way he will recognize that the battery is almost in the end of the discharge. Afterward as the battery keep on going down the power follow the same behavior and less and less power is delivered, the minimum power the system deliveries is 20% which is enough for the car to run.

Good to remember that this whole subsystem is just useful for the endurance because the other dynamic events are not long enough to bring the battery to a low level.

Cell voltage, Battery voltage and SOC follow the same rules, the temperature is different but still simple, since the system goes off when the cells reaches 50 ºC, the power start to be limited when the temperature reaches 40 ºC the idea here is to not let the car goes down because of the temperature, so that power limit has the objective of not letting the battery get even warmer.

All this signals goes into a Min block which let the lowest one go forward e. i. the worst case. The signal comes to the controller that convert the number in a valid value for limiting the torque.

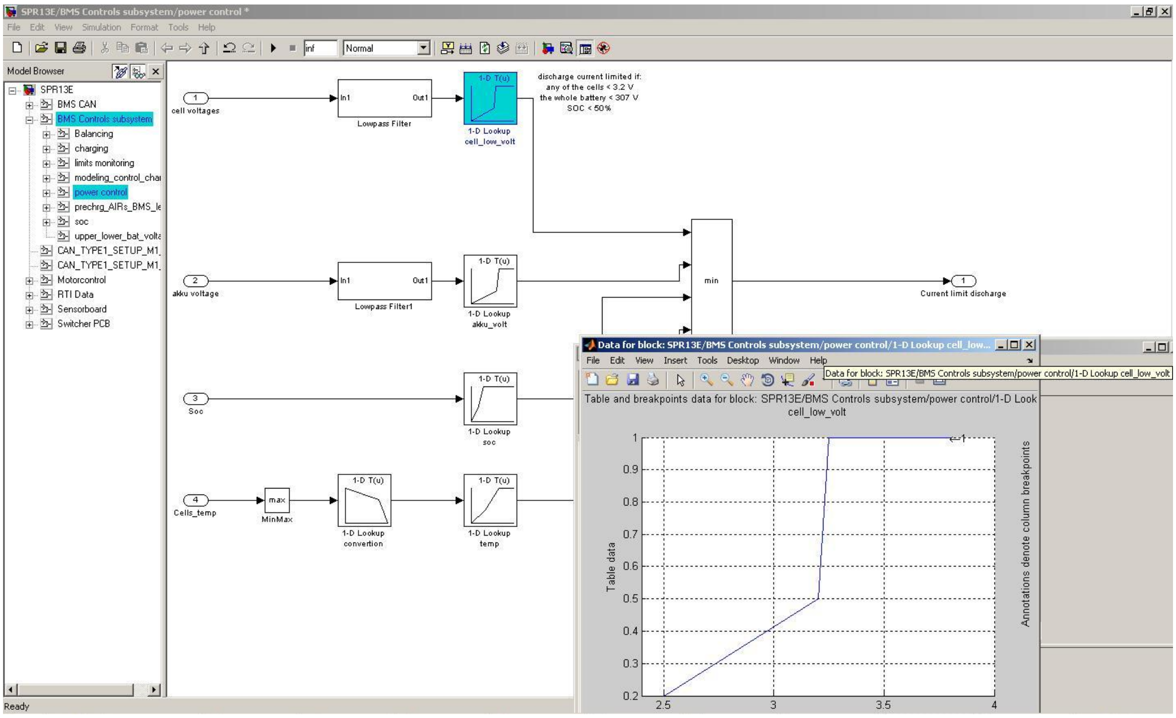

Figure 34 – Power Control

5.12. SOC

This is one of the most complex algorithms developed in this work. As stated in the literature review section, it is possible to get a SOC estimation using only one method but that is not accurate enough, so, in order to have a trustable enough SOC estimation, two methods are being used.

First the simplest one, which is the OCV, that is accurate when the battery has a rest time of at least half an hour, e. i. because after using the battery when the system is turned off the cell voltages rises for an amount of time, after half an hour it's almost stabilized so it's enough to get a good estimation, since the OCV method has this feature it is used to measure the initial SOC of the system, later when the car starts to run then the Coulomb Counting method takes place and make the SOC estimation from this time on.

The subsystem in Figure 35 has 3 inputs average cell voltage which is the battery voltage divided by the 96 cells of the battery pack, the button command which puts the car in the ready to drive mode and the current flowing out of the battery.

The average cell voltage is used for the initial SOC estimation, the 2 seconds delay is here present as well to avoid the use of wrong data during the estimation. That value goes to the lookup table and a value is determined, when the car goes to the ready to drive mode that value is not taken into consideration anymore. As the car starts to run and the current flows the actual energy of the battery starts to be subtracted through a group of block that works as an integrator, a simple integrator block could not be used because of the sample time of the system which is called “ts” on the system. That method was tested using Simulink, we simulated a full battery with approx. 6 KW (after the loses) and since the capacity of the cell are 20 A we simulated for 1 hour with a drained current of 20 A, after the simulation time has finished the SOC indicated exactly 0%, the only problem that can appear is the variations between the sample time, but since we are using 0,005 seconds, we believe that differences should not have major relevance.

The last part of this subsystem is the storage of the data, for the next time the system is started up the estimation comes from the last Coulomb Counting method because is more accurate than the OCV. That part unfortunately is not fully implemented because the storage of the data should be the last action to be done, because after that the car is not able to drive anymore, that happens because the storing data process take some milliseconds and during that time the program doesn’t run and due to that the CAN communication crashes. To be perfectly implemented the car should have a button that should be pressed just before the main key is turned off, that would allow the dSpace to store data to be used the next time the system goes on.

The SOC is implemented but is not having a relevant work on the car because we didn’t have the opportunity to test it properly, that happened because mechanical problem has shown up and are more important for the functioning of the car because influences directly in the situation of the car, running or not.

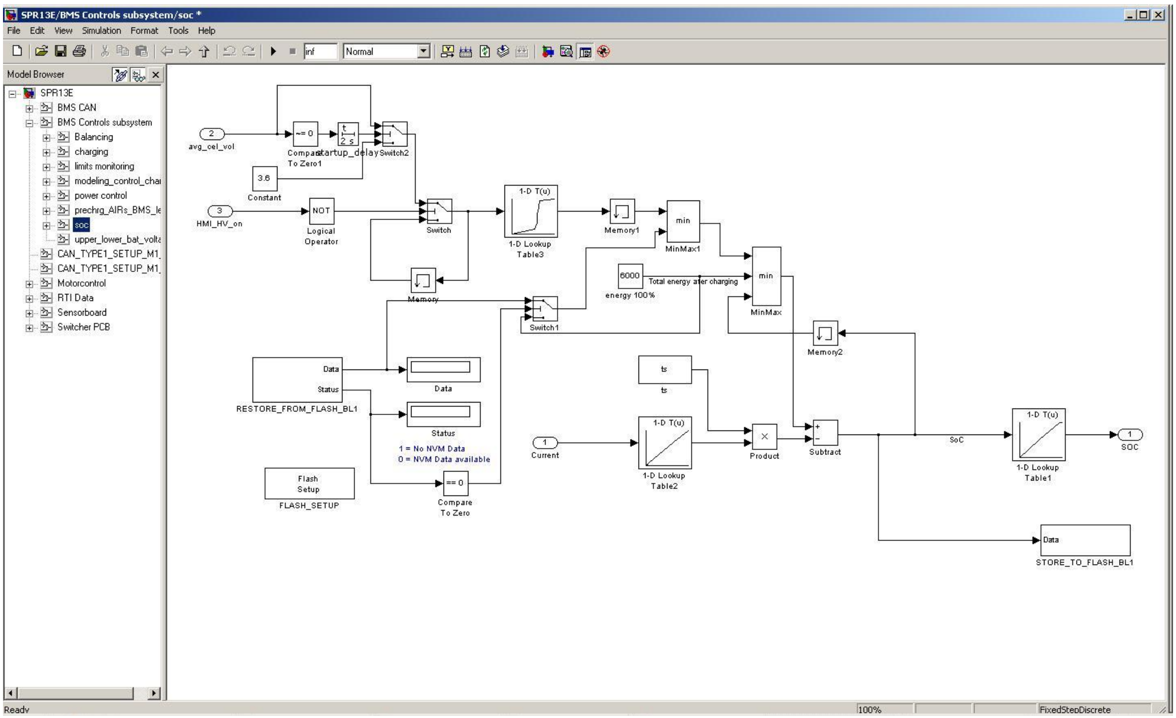

Figure 35 – SOC Estimation

5.13. CHARGING

The charging process deserves a special attention because of the hysteresis effect. In another document supplied by Opel present in the appendix 6 of this document it is presented the difference of the cell voltage related to the energy in the cells both during the char and the discharge process.

The cells datasheet states that the maximum charging current should be 40 A but in order to extend the life span of the cells we charge using maximum 20 A, and only if the battery is totally discharged.

A problem that was faced is that the communication with the power supply is not working properly, last year the power supply had some failures so that could have caused the damage on the communication, we tried to communicate via RS232 and Serial, but in both cases it was not possible to send information to set the voltage and the current. Due to that problem a screen was developed in order to the operator to know which mode the charging process is, Voltage or Current, and the set point of each of those variables.

First let’s describe the charging algorithm, as the charge process begins we use the Current mode, that means we change the current set point, only in the end of the charge when the current is already low e. g. 1 A then we change the voltage.

During the charging process it’s good to keep an eye on the cells because when they reach 3.4 V they go up very fast, so from the beginning of the charge until they reach 3.4 V takes a long time, if the battery is totally discharged and we use 10 A to charge, that process takes almost 2 hours then when they reach 3.4 V the current of charge is decreased the voltage drops a little bit and then as time goes by goes up again, when it reaches 3.4 V again the current is decreased one more time, the process is repeated until the current reaches the minimum which is 1 A when that happens the algorithm changes to voltage mode and from that point on only the voltage is changed.

In Figure 36 is shown the algorithm it starts with 20 A and the factor of division is 1.4, so when the highest cell reach 3.4 V the current is divided and becomes 14.28 A then 10.2 A, 7.28 A, 5.2 A, 3.71 A, 2.65 A, 1.89 A, 1.35 A and finally 0.96 A. after all those steps the current reaches its minimum and from this point on the voltage becomes our set point, but for that point on there is no algorithm developed because the power supply doesn’t receive data anyway.

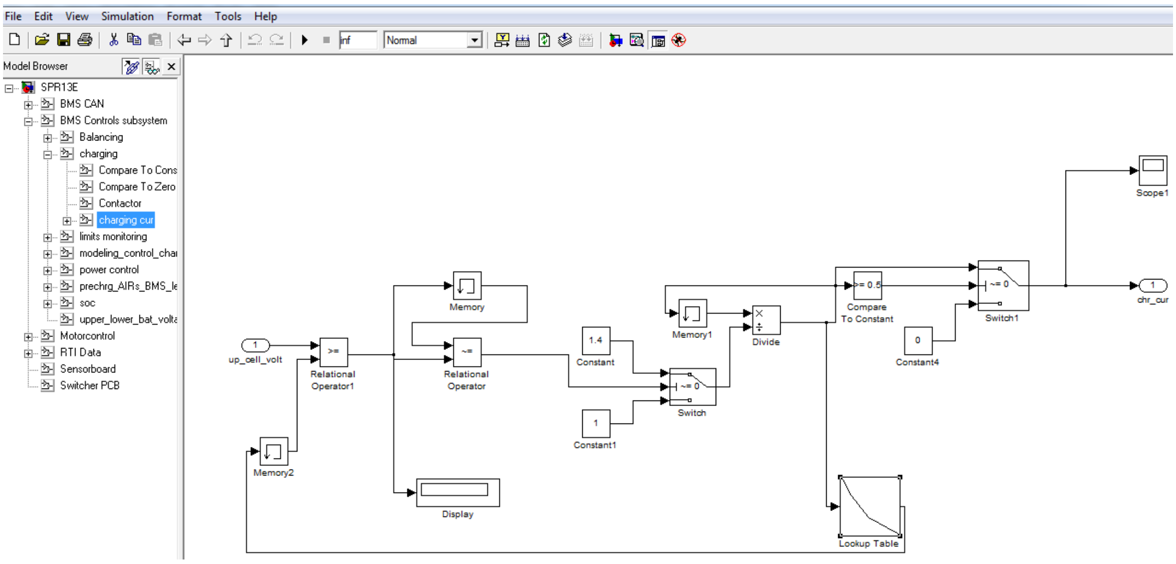

Figure 36 - Charging

On Control Desk it was developed a panel to show the operator in which mode the charging is taking place through the red LED as well as the set point that should be through the display. That panel is only possible because even if the power supply doesn't get the data we sent to it, it can still send the data referring to the voltage and current.

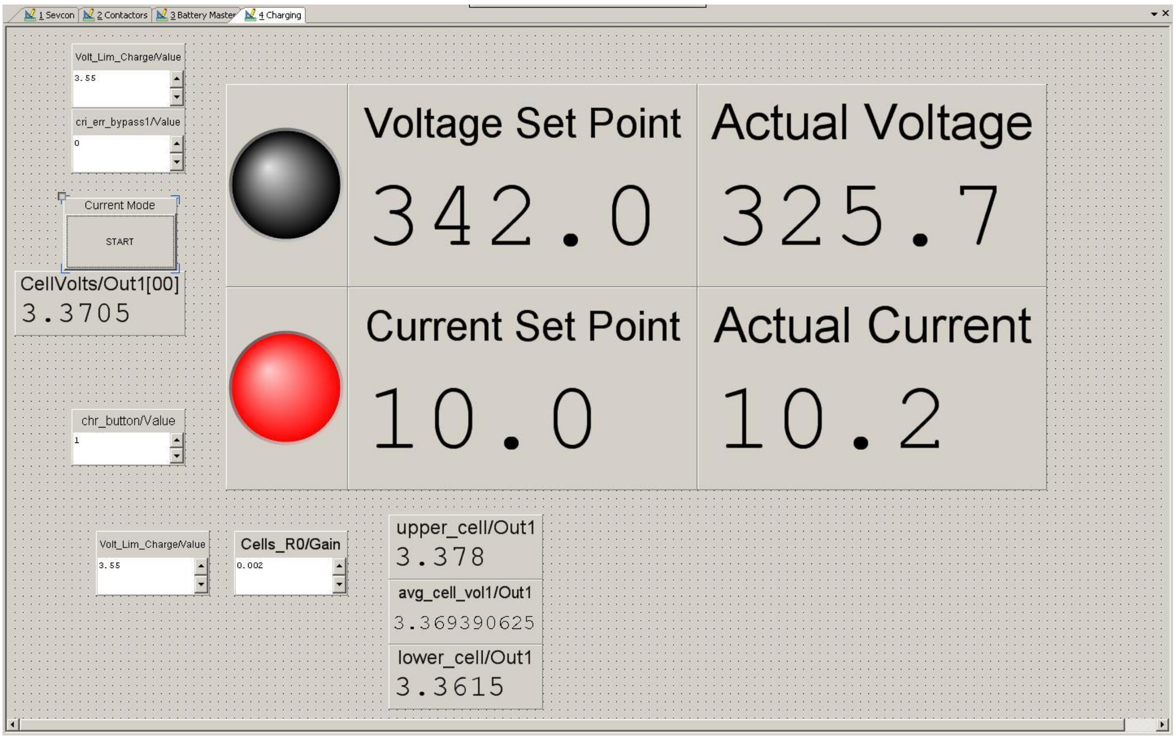

Figure 37 – Charging panel at Control Desk

5.14. CONTACTORS CONTROL AND ERRORS MONITORING

A tab on Control Desk was created with the intention to have an overview about what is going on the car regarding errors and the state of the contactors, that screen can be seen in Figure 38.

On that screen is possible to see, on the top right, the voltage of the battery through 2 ways, the cells voltage sum as well as the voltage at the motor controller (Sevcon), we can see a difference between both voltages, about 2 V which is not a big deal for the algorithm, and the current the motor controller is draining from the battery.

On the top left the manual switch of the contactors can be done, as well as the bypass of some error that normally doesn't allow the contactors to close, but for testing purposes it's useful to have a bypass option.

When both AIRs closes a signal called "bat ready" is sent to the motor controller program to let the algorithm know that the car is ready to go to the ready to drive mode.

On the bottom left side is presented the errors that may happen and in that case as already said, the algorithm sends a message to the controller to stop and after 0,5 seconds the contactors are opened. Those errors are: IMD, Cells limits, Pre charge timeout and CAN timeout.

IMD is the isolation device that measures the isolation between LV and HV, Cells limits were already described in Limits Monitoring, pre charge timeout is an error that occur when we turn on the car and the pre charge and one of the AIR are closed and it's expected that the second AIR closes after 7 seconds that is the pre charge time, but if some error occur, e. g. the controller is in an error mode, and so that doesn't send the voltage information and without that error the pre charge would be active forever, so the timeout avoid that to happen, it counts the time of the pre charge, if it reaches 9 s then the error occurs and the contactors open. The CAN timeout makes sure the communication between slaves and master are happening properly, the error occurs if no message or if the same message is transmitted for 5 s.

On the right side in the middle we can monitor the cells limits errors, is through this part that when an error happen we can see exactly which one it was.

Finally on the bottom right part is the SOC estimation, the memory2 block indicates the energy after the Coulomb Counting and the block under it indicates the percentage of charge of the battery for that energy, e. i. 3951 KW indicates our battery is at 65,8% of the SOC, the other display with the value 6020 KW, is the value of the energy when the car was turned on until the beginning of the operation mode, that value was estimated using OCV but as soon the car runs that value froze and the other value (memory2) is used to indicate the SOC.

All the others blocks that we can put a value are used for testing purposes, such as bypass, error simulation and button pressed simulation e. g. the power down button is the one which saves the SOC on the non-volatile memory.

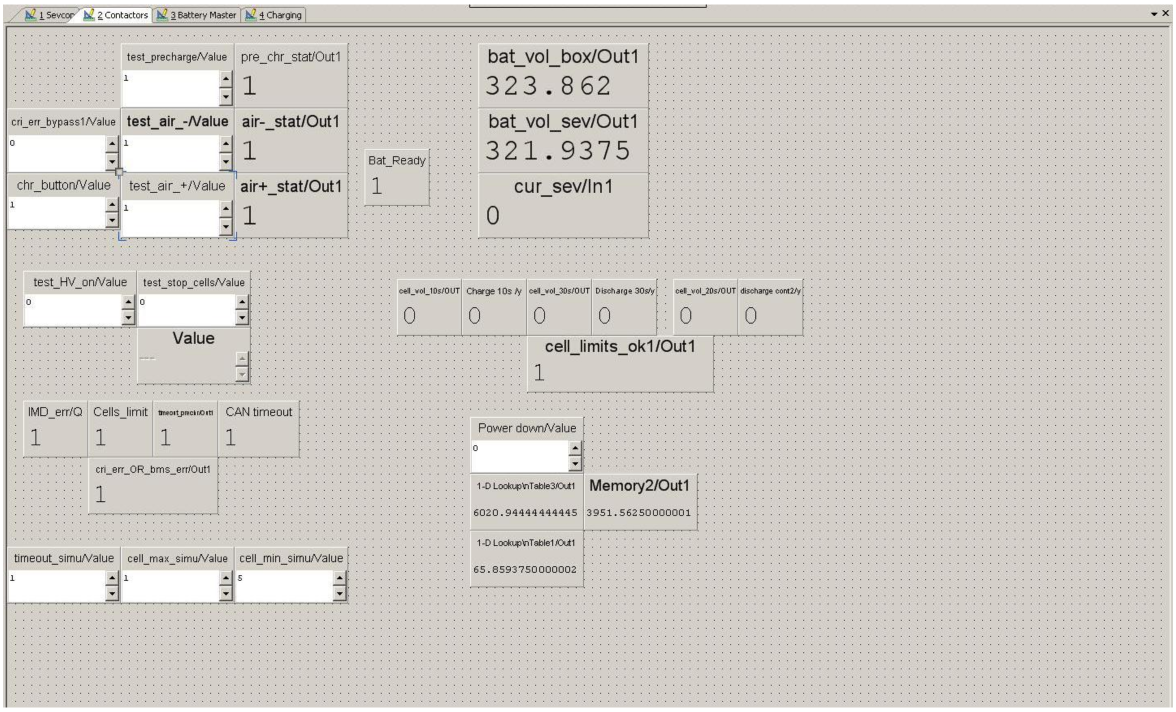

Figure 38 – Contactors control and errors monitoring

5.15. CELLS VOLTAGES AND TEMPERATURE MONITORING

The most important screen regarding the battery is this one presented in Figure 39.

In this screen is possible to see the state of each cell, each line corresponds to one microcontroller messages, e. i. the 8 cells voltages and 1 temperature. In total there are 12 lines with all 96 cells of the battery pack. On the right hand some general information as the upper cell, average value of the cells voltage and the lower cell of the battery pack, as well as the total battery voltage. Bellow that 2 buttons, one to tell the system the charging is taking place and the other to start the balancing process manually without the need to wait until the end of charge for it to take place.

Each cell has 2 LEDs indicators, the left one (red) indicate which cells are the ones with the highest voltage. The screen bellow was taken after charging and the battery and wait the rest time so we only see 1 cell as the highest one actually the one that limited the charging process, but when the battery is not in the end of charge point is normal to see 5 or 6 cells as the highest ones, during the charging that happens as well, that indicator was placed to check during the charging process if the charging is limited by only one cell or more than one, in our case it always the cell 86 that limit the charging process. The other led on the right (green) indicates which cells are being balanced, remembering that the balancing happens when any cell is higher 10 mV comparing to the lower one. So in the end of charge it's common to see the majority of the cells being balanced.

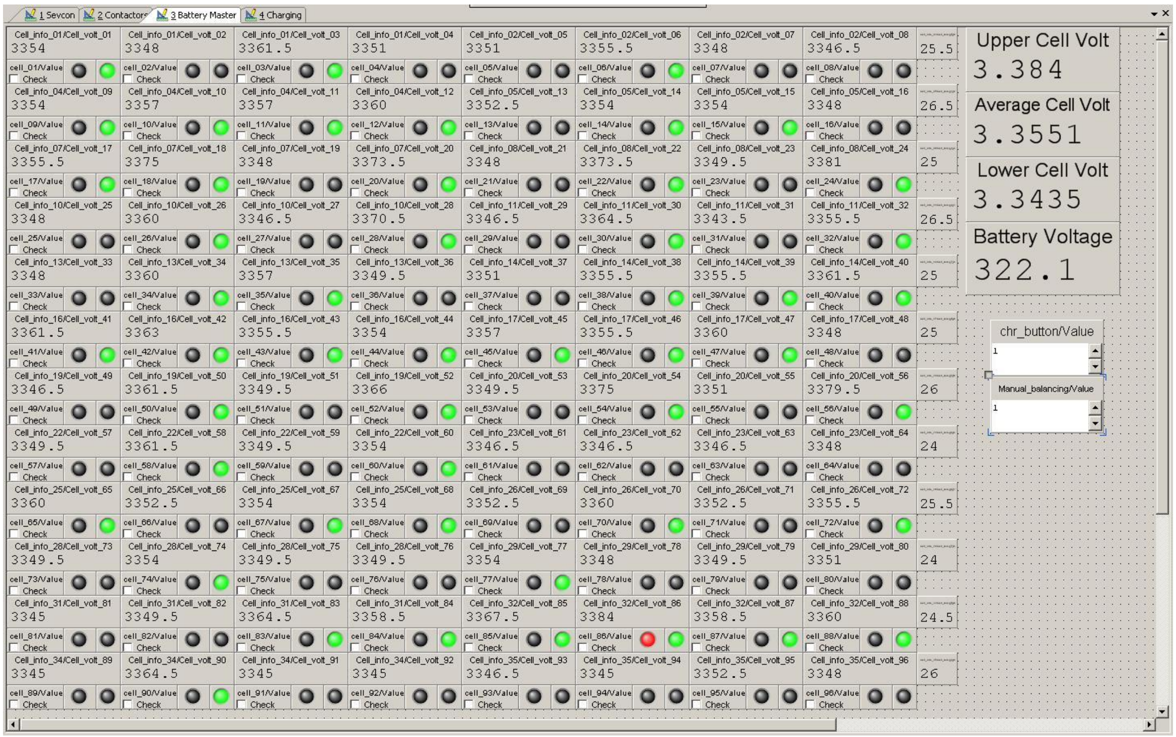

Figure 39 – Cells voltages and temperature monitoring

5.16. DATA FROM TESTS ANALYSIS

Our car is equipped with a data logger which is quite useful to check what is going on since we don't have telemetry.

In Figure 40 is presented the graphic configuration window, there we set how do we want out variable to be presented on the graphic by changing values as offset, division, minimum and maximum.

In this first graphic 4 variable are analyzed, which are, battery current, battery voltage, the current actually going to the motor (Iq) and the velocity of the motor.

In Figure 41 the battery current was not properly adjusted so we can't see the highest value that the current reaches, but that figure is not useless, it is useful to see the battery voltage dropping when the velocity goes up. In that test the battery voltage was 310 V and when the driver speed up fast the voltage drops to 280 V. That is a very useful information regarding the power control, this 30 V the battery drops it's ok for the actual program, if the voltage drop was higher than implementations on the program should have been made, but like this it’s working properly.

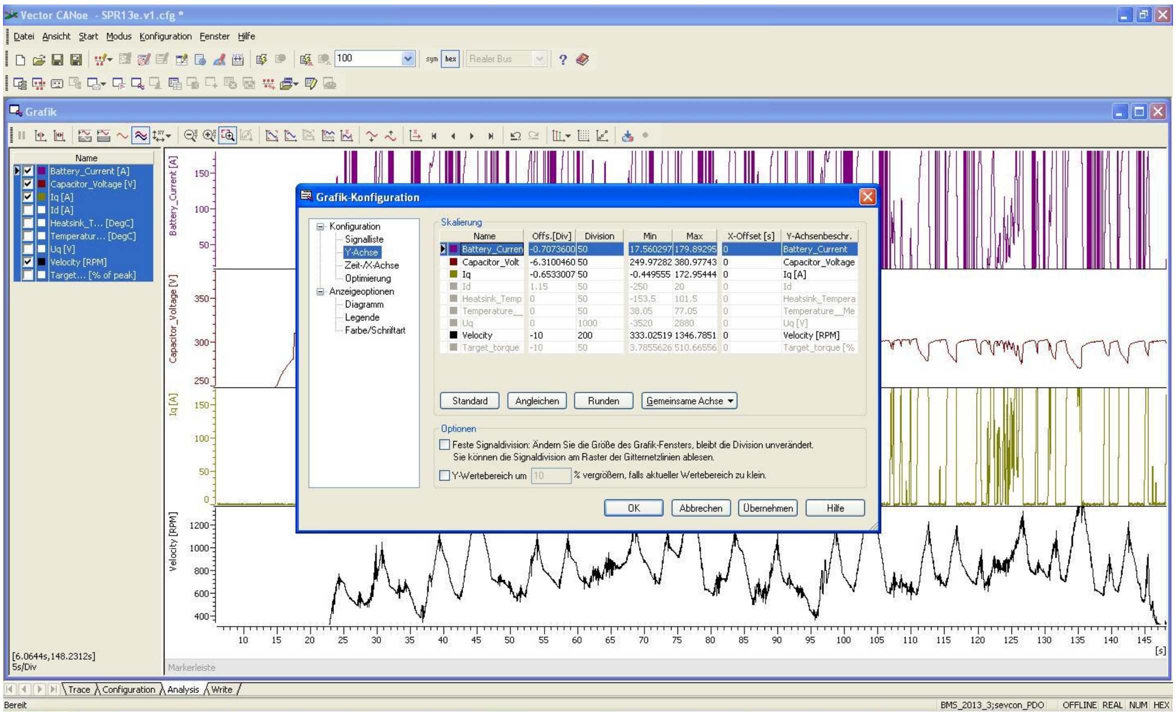

Figure 40 – Data analysis (variable configuration)

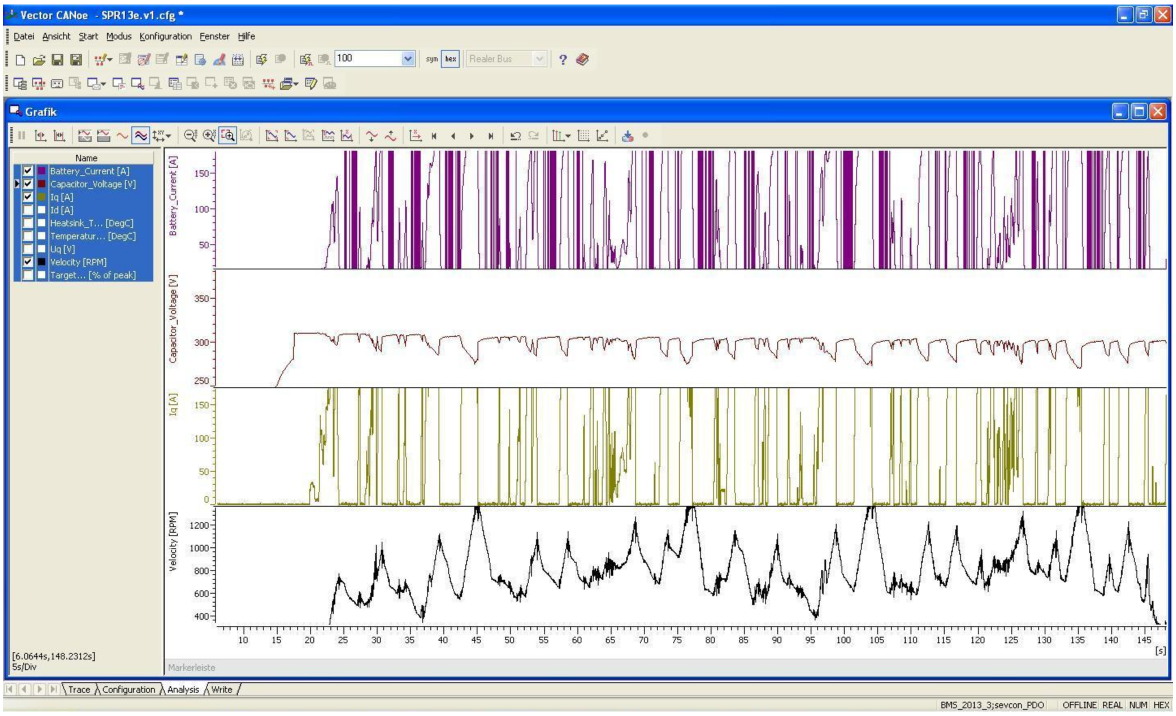

Figure 41 – Data analysis (graphic study)

In another test conducted by us we analyzed 3 variables, battery current, motor velocity and the torque value that is direct connected with the throttle pedal the Figure 42 shows the graphic of that test.

This test was important to check the highest current value the car can reach, in almost 6 minutes of testing we had 3 pulses that reached 300 A and that is not good to happen, but that is what the test is for. Since we find that issue we worked to avoid that situation to happen during the competitions, the simplest way to solve that problem is to limit the torque to a level that the current never reaches 300 A.

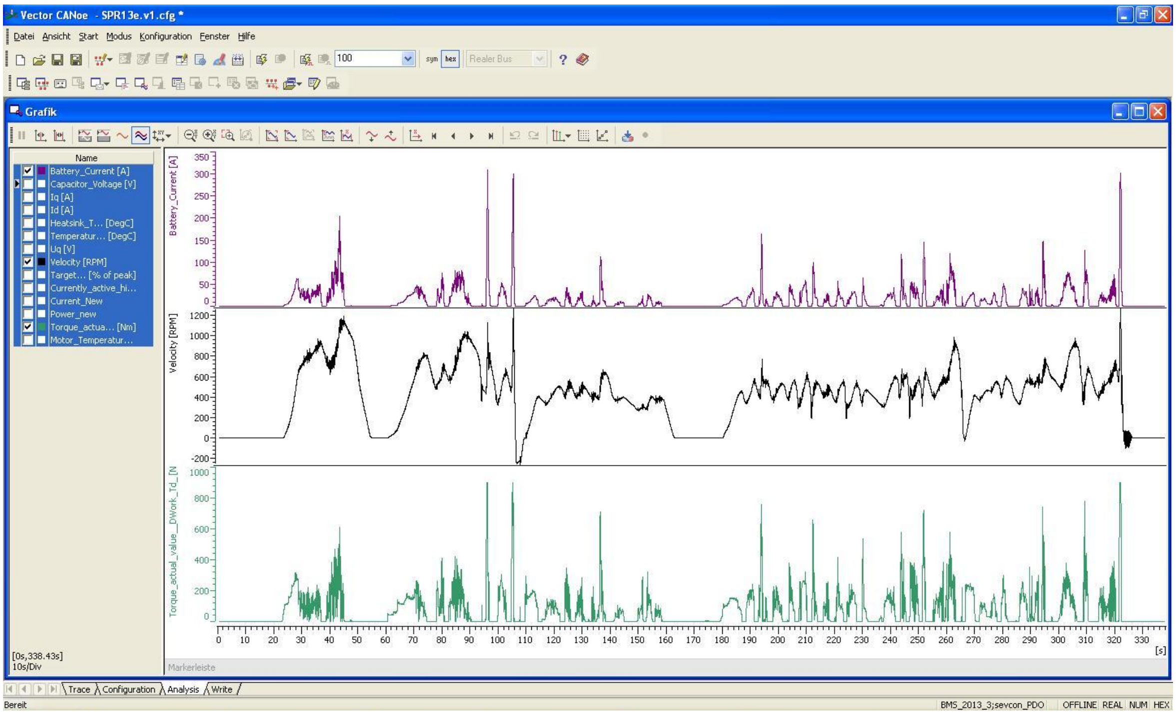

Figure 42 – Data analysis (graphic study) 2

6. EPILOGUE

6.1. CONCLUSIONS

It's important in this section to remember the research objectives within the context of the BMS:

1. Identify the main features and functions that a BMS should have in order to run a racing car.

2. Evaluate critically the options available to implement each function of the BMS.

3. Formulate the studied solutions and implement the function and thus built the BMS.

4. Analyze the behavior and performance of the system and implement adjustments if necessary.

This section will revisit the research objectives above, summarize the findings of this research work and offer conclusions based on the finding. The previous chapter – findings – was large and requires to be summarized, hence the summary in this chapter. Recommendations for future research will be discussed, in terms of how to progress this research study.

6.1.1. RESEARCH OBJECTIVE 1

The first objective of this research was to get familiar with a BMS, why is that an important part of an electric car and its influence in the performance of the vehicle.

It was concluded that besides the safety the BMS brings to the vehicle, it has a huge influence on the performance if it is not properly dimensioned it can give wrong information regarding the SOC or on the other hand let the battery die while still informs that there is energy left. This objective was import to know exactly what should have been implemented.

6.1.2. RESEARCH OBJECTIVE 2

This second objective was to check the difference between a BMS for an everyday vehicle in comparison to a racing car and learn how to implement the required fuctions.

It was concluded that a BMS for a racing car purpose is simpler than one for a conventional vehicle, an example is that in a racing car the Stage of Health which is the loss of capacity in the cells that happen as time goes by and with the charging and discharging cycles, and other feature that make it simpler is the fact if the battery energy is over during the run, that is no big deal because the car only runs under certain circumstances for example, in a racing track.

6.1.3. RESEARCH OBJECTIVE 3

This third objective was to understand the functions a BMS should have and compare the different ways of implement them.

The rules that the car has to respect regarding the competitions have an important function regarding this objective, since it establishes how the IMD, HV-interlock, contactor control and the pre-charge should be. This was a little help but still there was a lot to develop, with special attention to the SOC, power control and safety limits.

6.1.4. RESEARCH OBJECTIVE 4

The forth objective was, once the car is ready, we should have tested and make the proper setup in order to get the desired performance.

This year we had a short period of testing which was enough to make the car run in Hockenheim, respecting all the tight rules of the biggest formula student competition, but the testing period was not big enough to solve the general problems of the car, for example one problem we faced was that in the testing period we never tested the car completed, e. i. with the whole skin on it, wings, etc, only when in Hockenheim we had our first test with the car completed, then the mechanical problems show up and that problem compromised the whole performance during the event.

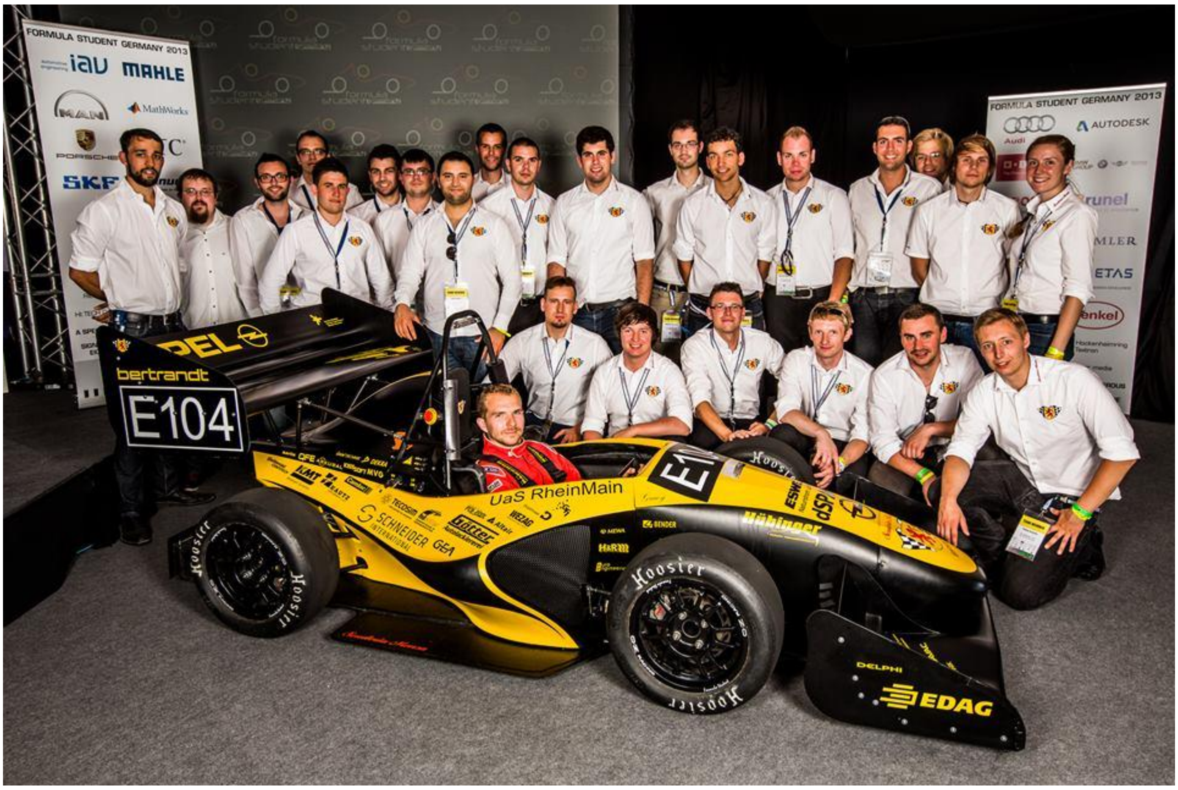

Figure 43 – Team picture in Hockenheim FSG 2013

6.2. Discussion

In this work it was developed a BMS for an electric racing car. The BMS consists in 2 parts, the slaves that were developed by David Brandt, last year he developed the BMS as well and therefore got experience, so that this year the slaves works very well with no major problems. The master was developed by me, sometimes during the semester I had the support of one Opel Engineer, Jochen Lenz, that gave very useful help, and he pointed the direction I should go and the priorities during the development.

The developed work is not a new solution for the industry, but regarding the intellectual propriety I believe dSpace can handle that task well, since is a very well developed device and very expensive as well, has many applications from air and land mobility until medical application. The way it works is, the program is made using Simulink and the code is generated during the compilation process when a file is created, that file is loaded to the dSpace through the Control Desk software. I believe all that steps are difficult to be done backwards, it’s easier to study the behavior of the system and make a similar programming.

One of the main discussions issue in the team is the weight of the car, this year we had a heavy car, weighing approx. 270 Kg while the other electric teams had cars with approx. 200 Kg. The problem is that the members of the team doesn’t have a plan to reduce the weight, instead of being projected a simple, working and reliable car and then add features to it, looks like what happens is from the beginning a very complex solution is built and in the end not all the features are implemented due to the lack of people and time. My suggestion regarding the weight is to get the current car and make a ABC classification, to check where the actual car could be lighter, I hardly believe the electrics has much weight to save but probably has some, the battery weight about 50 Kg, then we have the dSpace, Sevcon, HV box and wiring, so I believe the whole electrics weight around 70 Kg, it’s very hard to say where we could have saved weight, the ideal could be to have an ABC classification done to analyze the data and have a document to base the opinion on.

The LV battery was issue of discursions, the car is actually running with a normal motorcycle battery to supply the electric systems, a simple battery that operation normally is rare to fail, no special care handling it, just discharge and plug the charger and charge. But it was projected the LV battery to be a small version of the HV battery e. i. with cells a slave to get the data and a BMS for monitoring the discharge and an algorithm and specific power supply for charging. I couldn’t understand why to complicate so much when we could simply have a regular battery that barely will fail, the more components the system have, the bigger is the chance to fail and lower is the general reliability of the whole car.

Regarding the project management, all depends on the complexity of the car, since we have a small team, we should keep things simple, the project is very complete there is the technical project that consists in actually built the car, but there is also a lot of paper work to be done, e. g. cost report, business plan, presentation of the car, finance, marketing. It’s very difficult to handle all those tasks when there are not enough people. This year even if the milestones looked so early we had a successful roll out with the car running even if only the basic functions were implemented by that time. Later on we finished the car and had one week to test the car before Hockenheim, which was not enough but, we had no other choice.

The electric part of the car this year was relatively simple, even if all the PCBs were developed by David. The integration dSpace, Sevcon and motor saved us a lot of time and work and for this reason we were able to make the car run. It was a pleasure for me to have the opportunity to work with a device like dSpace, it is really incredible, the capabilities it has the processing power, for prototyping is really great, everything can be simulated and we can see in real-time the reaction of the system in every situation we find convenient to test.

6.3. FUTURE WORK

Scuderia Mensa develops one car every year since 2008 and in the last 3 year built electric cars. There was a meeting close to the end of the development of the current car to study the next year car. I had the opportunity to be part of that meeting and one of the discussions was about the motor, once the motor we are using this year has 100 KW of power which is “too much” since the rules doesn’t allow more than 85 KW of power being drained, but we are more close to the limit than we imagine, in our test we could see that the voltage drops to 280 V and the current can reach 300 A that give us already 84 KW, so that I defended the use of the same motor again for the following reasons, that motor is integrated with the motor controller, so, if the motor is changed probably a new controller has to be found and if the new motor doesn’t have a controller that can be integrated, then a controller has to be developed and that is the problem because the Scuderia Mensa has a problem of man power in the electric sector, another reason to defend the actual system is that there is still room for improvements, the controller has plenty of options which were not explored because our main objective was to have a running car for after think about improvements, an example of an improvement that can be implemented next year is the regenerative break. It was suggested the use of two motors just like the TU Darmstadt implemented in the car of this year, the withdraw of this solution is that the Yasa smaller engine (400 nM) requires 600 V to have the expected performance, that requires a bread new battery pack which requires a new BMS slaves and depending on the chemical construction of the cells may require a new master for the BMS as well. The problem is not the changes that have to be done, the problem is the lack of man power, this year we me working on the master of the BMS, David developing the PCBs, Simon working on the motor control, Mario working on the boards in the HV box, TSAL, battery light indicator, emergency chain, and so on, we had also, Florian and Max that gave us some support with some calculations and wiring harness respectively. Next session I will have my academic duties completed, David wants to disconnect from Scuderia, Mario is also leaving because he works, so the electric team will be Simon and hopefully Florian and Max, but not sure. The lesson learned of that meeting was that to make a proper development of a racing car from scratch would be necessary 10 people only in the electronic department.

I hope in the next session Scuderia Mensa make improvements in the actual car instead of creating a bread new project full of innovations, of course, the big problems of the current car should be solved even if a new project on that issue need to be done, like for example the total weight of the car and the size, the car is big in comparison with other formula students car. The actual car is very beautiful even the judges in the competition said that but in the general classification we were just 34th of 40 teams, that means that is not enough to be beautiful and works, all the decisions have to be explained and have to make sense. We had a car that run 2 of the 4 dynamic events, as shown in Figure 44, and there were cars that were not able to run any dynamic event and were in the middle of the twentieth places.

Figure 44 – Car running in Hockenheim

I had an opportunity to talk with some members of other teams during Formula Student Germany, and one team was very euphoric because their car was able to run the whole endurance which has 22 km. We were talking and I asked how they developed the car he explained and I could see that the system was simple, and commented that with him, and he told me a very true phrase that our team should keep in mind, it was, sometimes less is more.

Regarding the BMS there is always room for improvements, e.g. if the power supply is repaired the charging process can became totally automatic, with no need to set the set points manually. The SOH can also be implemented in order to get information regarding the health of the battery pack using for that inputs like, cycles and lifetime. The SOC can became more accurate if the NN method is used, that way the dynamic and unpredictable actions of the driver could be taken into consideration as well as factors of the cells itself like discharging efficiency, self-discharge and capacity loss, together with the already available data could be used to implement a very accurate SOC.

6.4. SELF-REFLECTION

I'm really glad to have the opportunity to join the project, it's highly recommended to all students to be part of it, the contact with a project like that while still studying add a lot of value and know-how to the students that take that opportunity.

When I started I had just basic knowledge about CAN communication, Simulink and no knowledge at all about BMS. Another important lesson learned is due to the learner circle, which is the fact of learning by the contact with the members that developed others tasks on the project.

The advice I would give to the members and new member would be to try to keep things simple always, there is always place for improvement, and it's easier to improve when you have something simple than to make something complex work.

I'm very glad with the opportunity to write my Master Thesis in Germany, and moreover in such a big project involving a lot of big companies and real world application.

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Appendix 1– Battery limits

Operation Sheet for Scuderia Pack SPR 13e

Content

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1 Document History 1
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1 Document History

Version	Comment
1.0	First draft PAN 12.06.13
1.1	2nd draft PAN 13.06.2013
1.2	Final PAN 04.07.2013

2 References

Index	Document Type	Document Name and Link
(1)	Cell Supplier Limits Sheet	Hier fehlt der Link
(2)	Material Safety Data Sheet (MSDS)	SDS High Power Lithium Ion Cell _SF000003_17.pdf [illegible]
(3)	Test Results Cell HPPC Test	MUK_HPPC_Res-Spread_16-Jun-2011.xlsx [illegible]
(4)	Main Contactor Datasheet (BDU)	Filename: tbd Link:
(5)	Test Asset Doku	Filename: tbd Title in PN:
(6)	DBC-File	n/a
(7)	SSTS	Filename: n/a
(8)	Electronic	Filename: tbd Link:
(9)		
(10)	DRE if available	Primary Contact: Peter Andes Second Contact: Alexander Dudek

3 DUT Information and Operation Parameters

DUT Information	Description	Comment
Cell Supplier	A123	[1]
Cell Type	Gen 1.5	[1]
Cell Chemistry	LFP - $LiFePO_4$	
DUT Name	Scuderia Akku SPR 13 e	[5]
Electronics	Scuderia build	
Module Design	BBC build	

Parameters	Value	Reference	Description / Comment
Interface	Studs		
Cell Configuration	96s1p		
Nominal Capacity	20 Ah	Number of parallel cells * nominal capacity of one cell [1]	
Nominal Cell Voltage	3,3 V	Nominal cell voltage [1]	
Nominal Pack Voltage	317	Number of cells in series * nominal cell voltage	
Nominal Energy	6,3 kWh	Nominal pack voltage * nominal pack capacity	
Power Size Factor (PSF)	n/a		
Cell Configuration Resistance	2,4 mΩ	[3] 10sDisChaRes / (Number of parallel cells	10sDisChaRes = 10 Sec Discharge Resistance for one cell at approx.. 50% SOC and 20 °C
Main Contactor Drive Voltage	12 V Const. (100% PWM)	[4]	

4 Voltage, Temperature, Coolant and Humidity Limits

Limit	Value	Reference	Description / Comment
Cell Voltage			
$U_{MaxCellSafety}$	4,0 V	$U_{MaxCellPeak}$ + 0,2 V	
$U_{MaxCellPeak}$	3,8 V	[1] max. 10s	
$U_{MaxCellContinuous}$	3,6 V	[1]	
$U_{MaxCellCharger}$	3,6 V	$U_{MaxCellContinuous}$ = Default	
$U_{MinCellCharger}$	2,0 V	$U_{MinCellContinuous}$ = Default	
$U_{MinCellContinuous}$	2,0 V	[1]	
$U_{MinCellPeak}$	1,6 V	[1] max. 30s@load	
$U_{MinCellSafety}$	1,4 V	Maximum of: 1. Lowest minimum cell voltage [per [I]] – 0,2V 2. Minimum cell voltage [per [I]] (currently LG VTSM selections for GEN I with 1.8 V 8-cells-controller)	
Pack Voltage and SOC			
$U_{MaxPackSafety}$	394 V	$U_{MaxPackPeak}$ + Margin (10 V)	
$U_{MaxPackPeak}$	365 V	$U_{MaxCellPeak}$ * Number of cells in series	Max. 10s
$U_{MinPackPeak}$	153 V	$U_{MinCellPeak}$ * Number of cells in series	Max. 10s
$U_{MaxPackCont}$	346 V	$U_{MaxCellCont}$ * Number of cells in series	
$U_{MinPackCont}$	192 V	$U_{MinCellCont}$ * Number of cells in series	
$U_{MinPackSafety}$	143 V	$U_{MinPackPeak}$ - Margin (10 V)	
$SOC_{Storage}$	50 %		
Temperature			
$T_{MaxOperationAmbient}$	+ 40 °C	$T_{MaxOperationAmbient}$ = $T_{MaxCellSafety}$	
$T_{MaxCellSafety}$	+55 °C		
$T_{MaxCellOperation}$	+50 °C	[1]	
$T_{MaxStorage}$	25 °C		
$T_{MinStorage}$	0 °C		
$T_{MinCellOperation}$	-20 °C	[1]	
$T_{MinCellSafety}$	-23 °C	$T_{MinCellOperation}$ – 3°C	
$T_{MinOperationAmbient}$	-23 °C	$T_{MinOperationAmbient}$ = $T_{MinCellSafety}$	
Coolant Pressure and Flow			
$P_{MaxPressureSafety}$	n/a		
$dP_{MaxPressureSafety}$	n/a		
$V_{MaxFlowSafety}$	n/a		
$V_{FlowDefault}$	n/a		
Humidity for Climate Chamber			
$H_{MaxSafety}$	< 100 % $T_{Sample} > T_{Dew}$		Temperature of test sample must be greater than dew-point temperature with in test chamber to avoid condensation. By MUNTRMA.
$H_{MinSafety}$	0 %	Tbd	

- Stress above these ratings may cause permanent damage. Exposures to absolute maximum condition, even for short periods of time, may degrade device reliability severely
- Command load to 0 and after 1s open contactors
- Averaging for debouncing acceptable

5 Current Limits

5.1 Absolut values for Control and Safety

Limit [A]	Time	Temperature					
	[sec.]	-30 °C	-20 °C	-10 °C	0 °C	25 °C	45 °C
$I_{ChargeSafety}$ *	<1	80					
$I_{ChargePeakT1}$	2	0	0	0			
$I_{ChargePeakT2}$	10	0	0	0	70	70	70
$I_{ChargePeakT3}$	20	0	0	0			
$I_{ChargePeakT4}$	30	0	0	0			
$I_{ChargeContinuousT0}$	>3600	0	0	0	10	25	25
$I_{DischargeContinuousT0}$	>3600	0	-60	-80	-80	-80	-80
$I_{DischargePeakT4}$	30	0	-80	-150	-200	-200	-200
$I_{DischargePeakT3}$	20	0	-80	-150	-200	-250	-200
$I_{DischargePeakT2}$	10	0	-80	-150	-250	-300	-200
$I_{DischargePeakT1}$	2	0	-80	-150	-250	-300	-200
$I_{DischargeSafety}$ *	<1	-300					

- *Operation within these limits may cause accelerated degradation. For low temperatures limitation is not effective, current only limited by peak-limits.
- Depending on SOC, voltage limit may be reached before current limit is reached.
- Calculation of actual limit from table values between the given temperatures shall be interpolated linearly.
- Margin for Current limits should be approx. 10 % of related safety limit from supplier.

Parameter	Reference	Description
$I_{ChargeSafety}$	Minimum of [1] 2 sec. Charge Current, Amps at 50% SOC and at 25 °C * Number of parallel cells * 1,1 [4] MaxContactorCurrent at specified time * 1,1	Shutdown if 1 sec. average exceeds the limit
$I_{ChargePeakTX}$	Minimum of [1] specified Discharge time Current, Amps at 50% SOC and at each Temperature * Number of parallel cells * 0,9 (if parallel cell config, to reflect uneven current distribution between parallels) [4] MaxContactorCurrent at specified time	Control limit (muss noch genauer definiert werden und TSTSW eingefügt)
$I_{ChargeContinuousT0}$	Minimum of [1] Continuous Charge Current, Amps at 50% SOC and at 25°C * Number of parallel cells * 0,9 (if parallel cell config, to reflect uneven current distribution between parallels) [4] MaxContactorCurrent at Continuous	Control limit (muss noch genauer definiert werden und TSTSW eingefügt)
$I_{DischargeContinuousT0}$	Minimum of [1] Continuous Discharge Current, Amps at 50% SOC and at 25°C * Number of parallel cells * 0,9 (if parallel cell config., to reflect uneven current distribution between parallels) [4] MaxContactorCurrent at Continuous	Control limit (muss noch genauer definiert werden und TSTSW eingefügt)
$I_{DischargePeakTX}$	Minimum of [1] specified Charge time Current, Amps at 50% SOC and at each Temperature * Number of parallel cells * 0,9 (if parallel cell config, to reflect uneven current distribution between parallels) [4] MaxContactorCurrent at specified time	Control limit (muss noch genauer definiert werden und TSTSW eingefügt)
$I_{DischargeSafety}$	Minimum of [1] 2 sec. Discharge Current, Amps at 50% SOC and at 25 °C * Number of parallel cells * 1,1 [4] MaxContactorCurrent at specified time * 1,1	Shutdown if 1 sec. average exceeds the limit

Appendix 2 – Cells datasheet

Nanophosphate® Lithium Ion Prismatic Pouch Cell

AMP20m1HD-A

KEY FEATURES AND BENEFITS

- High usable energy over a wide state of charge (SOC) range and very low cost per Watt-hour
- Excellent abuse tolerance and superior cycle life from A123's patented Nanophosphate® lithium ion chemistry
- High power with over 2,400 W/kg and 4,500 W/L

AMP20 Cell Specifications	
Cell Dimensions (mm)	7.25 x 160 x 227
Cell Weight (g)	496
Cell Capacity (minimum, Ah)	19.6
Energy Content (nominal, Wh)	65
Discharge Power (nominal, W)	1200
Voltage (nominal, V)	3.3
Specific Power (nominal, W/kg)	2400
Specific Energy (nominal, Wh/kg)	131
Energy Density (nominal, Wh/L)	247
Operating Temperature	-30°C to 55°C
Storage Temperature	-40°C to 60°C

Abuse Test	Test Result
Nail Penetration	Pass – EUCAR 3
Overcharge	Pass – EUCAR 3
Over-discharge	Pass – EUCAR 3
Thermal Stability	Pass – EUCAR 4
External Short	Pass – EUCAR 3
Crush	Pass – EUCAR 3

APPLICATIONS

PHEV and EV Passenger Vehicles

PHEV and EV Commercial Vehicles

Utility-scale Storage

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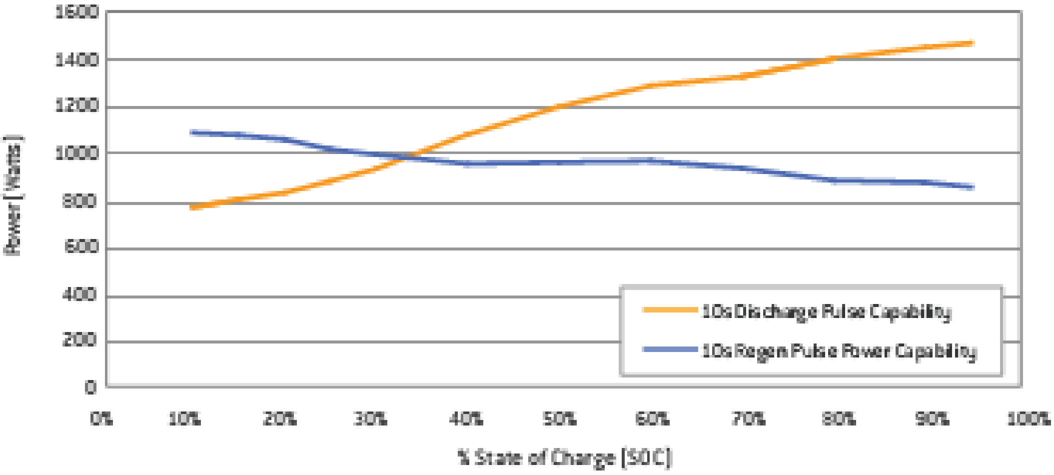
www.a123systems.com

Nanophosphate® Lithium Ion Prismatic Pouch Cell

AMP20M1HD-A

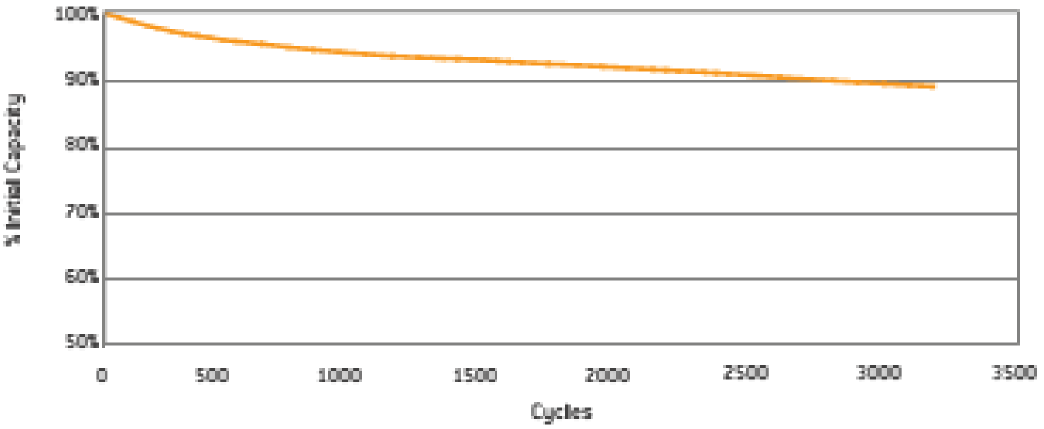
POWER

10s Pulse Power Capability vs State of Charge at 23°C, Using FreedomCAR HPPC
Vmax = 3.8 V, Vmin = 1.6 V



CYCLE LIFE

Capacity vs Cycles
100% Depth of Discharge (DOD), +1C/-2C, 23°C



Preliminary specifications, performance may vary depending on use conditions and application.
A123 Systems makes no warranty expressed or implied with this datasheet. Contents subject to change without notice.

CORPORATE HEADQUARTERS
A123 Systems, Inc.
200 West Street
Waltham, MA 02451
(617) 778-5700

www.a123systems.com

A123 SYSTEMS

Appendix 3 – Cable datasheet

DATA SHEET	0080000
ÖLFLEX® HEAT 205 SC	valid from : 14.01.2008

Application

ÖLFLEX® HEAT 205 SC are heat resistant insulated strands. Besides having excellent mechanical and physical properties, ÖLFLEX® HEAT 205 SC strands are characterized by very good electrical values, outstanding resistance against oil, weather and UV-radiation, as well as having high elasticity and tensile strength of the insulation material. ÖLFLEX® HEAT 205 SC strands are resistant against the action of water, acids, alkalis, solvents, synthetic liquids and oils. The cores are flame retardant.

Design

Conductor	fine strands of tinned copper wires acc. to IEC 60228 resp. VDE 0295, class 5 up to 0,5 mm² in support to IEC 60228 resp. VDE 0295, class 5
Core insulation	FEP compound 6YI1 in acc. to VDE 0207 part 6

Electrical properties at 20 °C

Nominal voltage	300 / 500 V
Test voltage	2500 V AC

Mechanical and thermal properties

Temperature range:	-100 °C up to +205 °C max. conductor temperature
Min. bending radius	4 x cable diameter for fixed installation 10 x cable diameter for flex. applications
EC directive	this cable confirms to ECD 2006/95/EC (low voltage directive).

elaborated by: TE-K: M. Herb / R. Krämer	Document: DB0080000 EN	page 1 of 1

Nr.: 0019/0894

Appendix 4 – Cells safety datasheet

A123 SYSTEMS

SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006

Section 1: Identification of the Substance/Preparation and of the Company/Undertaking

Product Name: High Power Lithium Ion Cell, Phosphate-Based

Product Codes:

ANR26650M1A	AHP68150202-M1-A
APR18650M1A	AHP68150202-M1-B
APR18650M1HDA	AHP70161227-M1-A
AHR32113-Ultra-A	AHP70165227-M1-A
AHR32113-Ultra-B	AHR18700-M1-ULTRA-F1
AHR32157-M1-A	AHR26700-M1-ULTRA-F1
AHR32157-M1-B	

Product Use: Cell and cell packs

Synonyms: High Power Lithium Ion Battery, Phosphate-Based

Manufacturer: A123 Systems Inc.
Arsenal on the Charles
321 Arsenal St.
Watertown MA 02472

Phone Number: (617) 778-5700
Fax: (617) 778-5749
24-hour Emergency: Chemtrec: (800) 424-9300

Section 2: Hazards Identification

Protective Clothing	NFPA Rating (USA)	EC Classification	WHMIS (Canada)	Transportation
Not required with normal use		Not Classified as Hazardous		See Section 14

Preparation Hazards and Classification: Not classified as dangerous or hazardous with normal use. The cell should not be opened or burned. Exposure to the ingredients contained within or their combustion products could be harmful.

European Communities (EC): This product is not classified as hazardous according to Regulation (EC) No. 1272/2008. This product contains dangerous ingredients however, there is no expected release during use of the product and there is a barrier preventing exposure of the user and the environment.

Appearance, Color and Odor: Solid object with no odor.

Primary Route(s) of Exposure: These chemicals are contained in a sealed enclosure. Risk of exposure occurs only if the cell is mechanically, thermally or electrically abused to the point of compromising the enclosure. If this occurs, exposure to the electrolyte solution contained within can occur by inhalation, ingestion, Eye contact and Skin contact.

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SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006

Section 2: Hazards Identification, continued

Potential Health Effects:	**ACUTE (short term): see Section 8 for exposure controls**
	In the event that this cell has been ruptured, the electrolyte solution contained within the cell would be corrosive and can cause burns to skin and eyes.
Inhalation:	Inhalation of materials from a sealed cell is not an expected route of exposure. Vapors or mists from a ruptured cell may cause respiratory irritation.
Ingestion:	Swallowing of materials from a sealed cell is not an expected route of exposure. Swallowing the contents of an open cell can cause serious chemical burns of mouth, esophagus, and gastrointestinal tract.
Skin:	Contact between the cell and skin will not cause any harm. Skin contact with contents of an open cell can cause severe irritation or burns to the skin.
Eye:	Contact between the cell and the eye will not cause any harm. Eye contact with contents of an open cell can cause severe irritation or burns to the eye.
	CHRONIC (long term): see Section 11 for additional toxicological data
	Not applicable
Medical Conditions Aggravated by Exposure:	Not available
Interactions With Other Chemicals:	Immersion in high conductivity liquids may cause corrosion and breaching of the cell enclosure.
Potential Environmental Effects:	Not available

Section 3: Composition/Information on Ingredients

As a solid, manufactured article, exposure to hazardous ingredients is not expected with normal use.

USA: This cell is an article pursuant to 29 CFR 1910.1200 and, as such, is not subject to the OSHA Hazard Communication Standard requirement. The information contained in this Material Safety Data Sheet contains valuable information critical to the safe handling and proper use of the product. This SDS should be retained and available for employees and other users of this product.

Canada: This is not a controlled product under WHMIS. This product meets the definition of a "manufactured article" and is not subject to the regulations of the Hazardous Products Act.

SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006

Section 4: First Aid Measures

Inhalation: If contents of an opened cell are inhaled, remove source of contamination or move victim to fresh air. Obtain medical advice.

Eye Contact: Contact with the contents of an opened cell can cause burns. If eye contact with contents of an open cell occurs, immediately flush the contaminated eye(s) with lukewarm, gently flowing water for at least 30 minutes while holding the eyelids open. Neutral saline solution may be used as soon as it is available. If necessary, continue flushing during transport to emergency care facility. Take care not to rinse contaminated water into the unaffected eye or onto face. Quickly transport victim to an emergency care facility.

Skin Contact: Contact with the contents of an opened cell can cause burns. If skin contact with contents of an open cell occurs, as quickly as possible remove contaminated clothing, shoes and leather goods. Immediately flush with lukewarm, gently flowing water for at least 30 minutes. If irritation or pain persists, seek medical attention. Completely decontaminate clothing, shoes and leather goods before reuse or discard.

Ingestion: Contact with the contents of an opened cell can cause burns. If ingestion of contents of an open cell occurs, NEVER give anything by mouth if victim is rapidly losing consciousness, or is unconscious or convulsing. Have victim rinse mouth thoroughly with water. DO NOT INDUCE VOMITING. If vomiting occurs naturally, have victim lean forward to reduce risk of aspiration. Have victim rinse mouth with water again. Quickly transport victim to an emergency care facility.

Section 5: Fire Fighting Measures

Flammable Properties: Lithium ion batteries contain flammable liquid electrolyte that may vent, ignite and produce sparks when subjected to high temperatures (> 150 °C (302 °F)), when damaged or abused (e.g., mechanical damage or electrical overcharge). Burning cells can ignite other batteries in close proximity.

Suitable extinguishing Media: Small Fires - Dry chemical, CO2, water spray or regular foam.
Large Fires - Water spray, fog or regular foam. Move containers from fire area if you can do it without risk.

Unsuitable extinguishing Media: Not Applicable

Explosion Data:

Sensitivity to Mechanical Impact: Extreme mechanical abuse will result in rupture of the individual battery cells.

Sensitivity to Static Discharge: Electrostatic discharges imposed directly on the spilled electrolyte may start combustion.

SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006

Section 5: Fire Fighting Measures, continued

Specific Hazards arising from the Chemical:	The interaction of water or water vapor and exposed lithium hexafluorophosphate (Li PF6) may result in the generation of hydrogen and hydrogen fluoride (HF) gas. Contact with battery electrolyte may be irritating to skin, eyes and mucous membranes. Fire will produce irritating, corrosive and/or toxic gases. Fumes may cause dizziness or suffocation.
Protective Equipment and precautions for firefighters:	Wear positive pressure self-contained breathing apparatus (SCBA). Structural firefighters' protective clothing will only provide limited protection. Fight fire from a safe distance.

NFPA

Health:	0
Flammability:	0
Instability:	0

Section 6: Accidental Release Measures

Personal Precautions:	As an immediate precautionary measure, isolate spill or leak area for at least 25 meters (75 feet) in all directions. Keep unauthorized personnel away. Stay upwind. Keep out of low areas. Ventilate closed areas before entering. Wear adequate personal protective equipment as indicated in Section 8.
Environmental Precautions:	Prevent material from contaminating soil and from entering sewers or waterways.
Methods for Containment:	Stop the leak if safe to do so. Contain the spilled liquid with dry sand or earth. Clean up spills immediately.
Methods for Clean-up:	Absorb spilled material with an inert absorbent (dry sand or earth). Scoop contaminated absorbent into an acceptable waste container. Collect all contaminated absorbent and dispose of according to directions in Section 13. Scrub the area with detergent and water; collect all contaminated wash water for proper disposal.

Section 7: Handling and Storage

Handling	Do not open, dissemble, crush or burn cell. Do not expose cell to temperatures above 80°C.
Storage:	Store cell in a dry location. Keep at room temperature (25°C +/- 5°C). Elevated temperatures can result in shortened cell life. Keep out of reach of children.

A123 SYSTEMS

SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006

Section 8: Exposure Controls/Personal Protection

Exposure Limit Values: Airborne exposures to hazardous substances are not expected when product is used for its intended purpose.

Engineering Controls: Use local exhaust ventilation or other engineering controls to control sources of dust, mist, fume and vapor.

Personal Protection:

Respiratory Protection: Not necessary under normal conditions.

Skin Protection: Not necessary under normal conditions. Wear neoprene or natural rubber gloves if handling an open or leaking cell.

Eye Protection: Not necessary under normal conditions. Wear safety glasses if handling an open or leaking cell.

Other Protective Equipment: Have a safety shower and eye-wash fountain readily available in the immediate work area.

Hygiene Measures: Do not eat, drink or smoke in work areas. Maintain good housekeeping.

Section 9: Physical and Chemical Properties

Physical State:	Solid	**Vapor Pressure: (mm Hg @ 20°C)**	Not applicable
Appearance:	Cell	**Vapor Density:**	Not applicable
pH:	Not applicable	**Solubility in Water:**	Insoluble
Relative Density:	Not available	**Water / Oil distribution coefficient:**	Not applicable
Boiling Point:	Not applicable	**Odor Type:**	Odorless
Melting Point:	Not applicable	**Odor Threshold:**	Not applicable
Viscosity:	Not applicable	**Evaporation Rate:**	Not applicable
Oxidizing Properties:	Not applicable	**Auto Ignition Temperature (°C):**	Not applicable
Flash Point and Method (°C):	Not applicable	**Flammability Limits (%):**	Not applicable

Section 10: Stability and Reactivity

Stability: Stable

Conditions to Avoid: Avoid exposing the cell to fire or temperatures above 80°C. Do not disassemble, crush, short or install with incorrect polarity. Avoid mechanical or electrical abuse.

Incompatible Materials: Do not immerse in seawater or other high conductivity liquids.

Hazardous Decomposition Products: This material may release toxic fumes if burned or exposed to fire. Breaching of the cell enclosure may lead to generation of hazardous fumes which may include extremely hazardous HF (hydrofluoric acid).

Possibility of Hazardous Reactions: Not available

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according to Regulation (EC) No. 1907/2006

Section 11: Toxicological Information

Acute Toxicity Data	Acute oral, dermal and inhalation toxicity data are not available for this article.
Other Toxicity Data **Irritation:**	Risk of irritation occurs only if the cell is mechanically, thermally or electrically abused to the point of compromising the enclosure. If this occurs, irritation to the skin, eyes and respiratory tract may occur.
Corrosivity:	Not applicable
Sensitization:	Not available
Neurological Effects:	Not applicable
Genetic Effects:	Not applicable
Reproductive Effects:	Not applicable
Developmental Effects:	Not applicable
Target Organ Effects:	Not applicable
Carcinogenicity:	Normal safe handling of this product will not result in exposure to substances that are considered human carcinogens by IARC (International Agency for Research on Cancer), ACGIH (American Conference of Governmental Industrial Hygienists, OSHA or NTP (National Toxicology Program).

Section 12: Ecological Information

Ecotoxicity:	Not available
Mobility:	Not available
Persistence and degradability:	Not readily biodegradable
Bioaccumulative potential:	Not available
Other adverse effects:	Solid cells released into the natural environment will slowly degrade and may release harmful or toxic substances. Cells are not intended to be released into water or on land but should be disposed or recycled according to local regulations.

Section 13: Disposal Considerations

Waste Disposal Method:	Cell recycling is encouraged. Do NOT dump into any sewers, on the ground or into any body of water. Store material for disposal as indicated in Section 7 Handling and Storage.
USA:	Dispose of in accordance with local, state and federal laws and regulations.
Canada:	Dispose of in accordance with local, provincial and federal laws and regulations.
EC:	Waste must be disposed of in accordance with relevant EC Directives and national, regional and local environmental control regulations. For disposal within the EC, the appropriate code according to the European Waste Catalogue (EWC) should be used.

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according to Regulation (EC) No. 1907/2006

Section 14: Transport Information

A123Systems lithium-ion cells and batteries are designed to comply with all applicable shipping regulations as prescribed by industry and legal standards which includes compliance with the UN Recommendations on the Transport of Dangerous Goods; IATA Dangerous Goods Regulations and applicable U.S. DOT regulations for the safe transport of lithium-ion batteries and the International Maritime Dangerous Goods Code. Each of the listed cells in Section 1 have passed the UN Manual of Tests and Criteria Part III Subsection 38.3, which is required by all of the directives listed above.

In the US, shipments of lithium ion cells and batteries are classified as Class 9, UN3480, Packing Group II, by the U.S. Hazardous Materials Regulations (HMR). Packaging, markings and documentation requirements are defined in the 49 CFR Section 173.185 of the U.S. HMR. Exceptions are made for cells that are less than 5 AH in nominal capacity rating. This includes the following listed cells from Section 1.

- ANR26650M1A, APR18650M1A, APR18650M1HDA, AHR32113-Ultra-A, AHR32113-Ultra-B, AHR18700-M1-ULTRA-F1, AHR26700-M1-ULTRA-F1

Exceptions also are made for batteries that contain less than the interconnected number of cells which together amount to less than 26.7 AH. This includes any product that contains less than the following number of interconnected cells listed in Section 1:

- 24 of either APR18650M1A or APR18650M1HDA
- 11 of ANR26650M1A
- 6 of either AHR32113-Ultra-A or AHR32113-Ultra-B
- 38 of AHR18700-M1-ULTRA-F1
- 19 of AHR26700-M1-ULTRA-F1

Excepted cells and batteries are allowed to be transported within the US without Class 9 packaging and markings, but must conform to other requirements as stipulated in Special Provisions 188 and 189 in the 49 CFR Section 173.185 of the U.S. HMR.

International shipments of lithium ion cells and batteries are generally classified as Class 9, UN3480, Packing Group II, by the International Civil Aviation Organization (ICAO) and the International Maritime Dangerous Goods (IMDG) Code. Packaging, markings and documentation requirements are defined in the International Air Transport Association (IATA) Dangerous Goods Regulations (DGR) Packing Instructions 965 and Packing Instruction P903 of the IMDG Code. Partial exceptions are made for cells that are less than 20 WH in nominal energy rating. This includes the following listed cells from Section 1.

- ANR26650M1A, APR18650M1A, APR18650M1HDA, AHR32113-Ultra-A, AHR32113-Ultra-B, AHR18700-M1-ULTRA-F1, AHR26700-M1-ULTRA-F1

Partial exceptions also are made for batteries that contain less than the interconnected number of cells which together amount to less than 100 WH of nominal energy rating. This includes any product that contains less than the following number of interconnected cells listed in Section 1:

- 27 of either APR18650M1A or APR18650M1HDA
- 14 of ANR26650M1A
- 7 of either AHR32113-Ultra-A or AHR32113-Ultra-B
- 43 of AHR18700-M1-ULTRA-F1
- 21 of AHR26700-M1-ULTRA-F1

A123 SYSTEMS

SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006

Section 14: Transport Information, continued

Excepted cells and batteries are allowed to be transported internationally without Class 9 packaging and markings, but must conform to other requirements as stipulated in Packing Instructions 965 of the IATA DGR and Special Provision 188 under the IMDG Code.

Section 15: Regulatory Information

USA

	TSCA Status:	All ingredients in the product are listed on the TSCA inventory.
	SARA Title III:	None
	Sec. 302/304:	None
	Sec. 311/312:	None
	Sec. 313:	None
	CERCLA RQ	
	California Prop 65:	This product does not contain chemicals known to the State of California to cause cancer or reproductive toxicity.
Canada		This product has been classified in accordance with the hazard criteria of the *Controlled Products Regulations* and the SDS contains all the information required by the *Controlled Products Regulations*.
	WHMIS Classification:	Not Controlled
	New Substance Notification Regulations:	Lithium hexafluorophosphate is listed on the NDSL. All other ingredients in the product are listed, as required, on Canada's Domestic Substances List (DSL).
	NPRI Substances:	This product does not contain any NPRI chemicals.
EC Classification for the Substance/Preparation:		This product is not classified as hazardous according to Regulation (EC) No. 1272/2008. Keep out of the reach of children.

EINECS Status:

Cell component	Chemical Name	CAS No.	EINECS	Concentration range in electrolyte (w/w %)	Mass range in cell (g/g %)
Electrolyte salt	Lithium hexafluorophosphate	21324-40-3	244-334-7	10 - 20	1 - 5
Electrolyte solvents	Includes one or more of the following: Ethylene Carbonate, Propylene Carbonate, Diethyl Carbonate, Dimethyl Carbonate Ethyl Methyl Carbonate	 96-49-1 108-32-7 105-58-8 616-38-6 623-53-0	 202-510-0 203-572-1 203-311-1 210-478-4 Not Listed	80 - 90	10-20

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according to Regulation (EC) No. 1907/2006

Section 16: Other Information

Preparation Information: Revision Date: October 13, 2009

Revision Summary:

October 13, 2009:

- Revised Section 5 Protective Equipment sub part.
- Revised Section 6 Personal Precautions sub part.
- Reformatted parts of SDS.

March 4, 2010:

- Revised Section 14 and removed reference to IATA edition and packing instruction part

Manufacturer Disclaimer: The information and recommendations set forth are made in good faith and believed to be accurate at the date of preparation.

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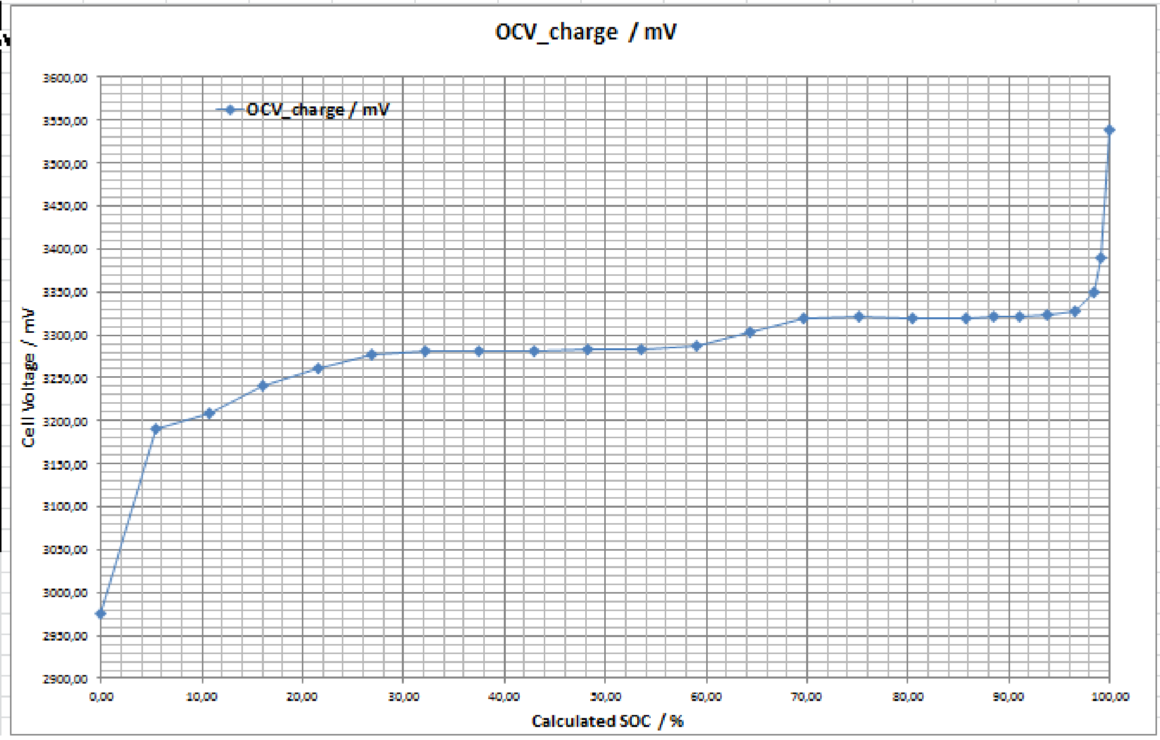
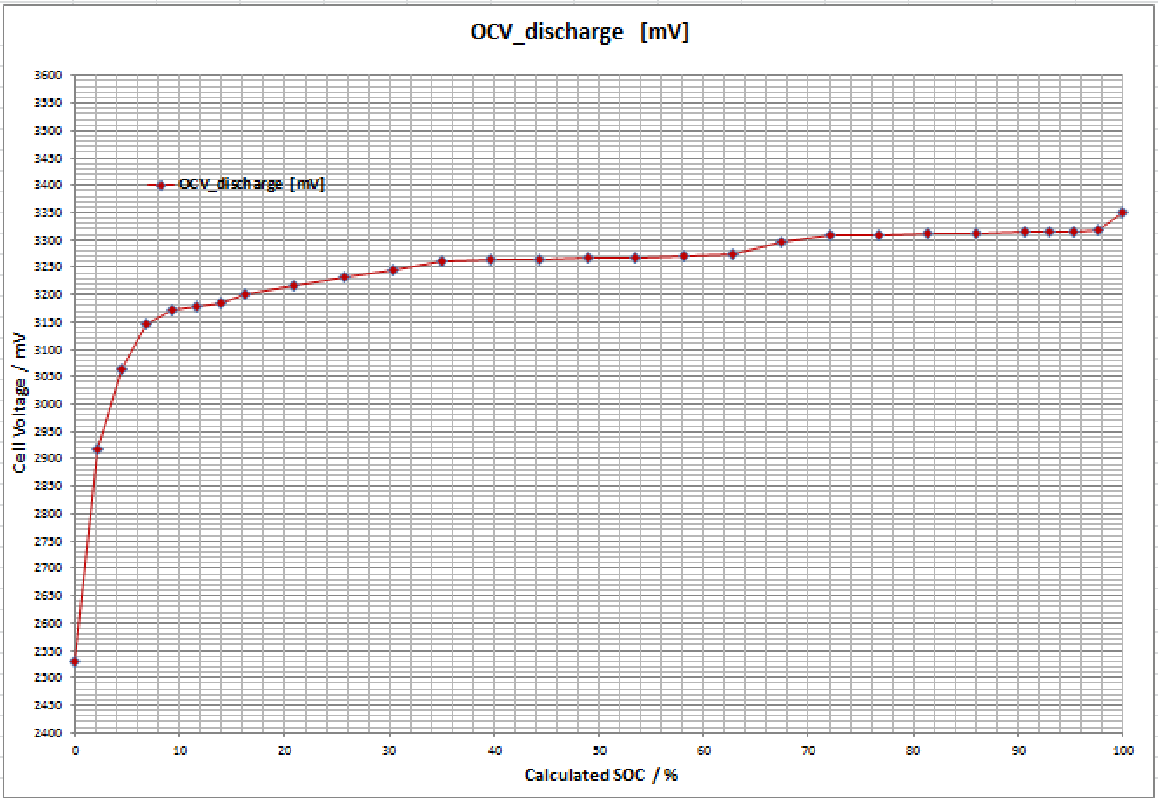
Appendix 5 – OCV/SOC Relation

Charge 2SOC		
calc SOC /	Capacity / A	OCV_charge / mV
0,00	0,00	2976,25
5,36	1,08	3189,89
10,73	2,15	3209,52
16,09	3,23	3240,05
21,46	4,31	3260,92
26,82	5,39	3276,40
32,19	6,46	3280,86
37,55	7,54	3281,54
42,91	8,62	3281,60
48,28	9,69	3282,47
53,64	10,77	3283,35
59,00	11,85	3286,94
64,36	12,92	3303,12
69,71	14,00	3320,20
75,07	15,07	3322,04
80,43	16,15	3320,21
85,78	17,22	3320,22
88,45	17,76	3321,15
91,13	18,30	3322,03
93,80	18,83	3322,29
96,47	19,37	3326,26
98,46	19,86	3348,76
99,14	19,90	3390,29
100,00	20,08	3539,01



calc SOC [%]	Capacity [Ah]	OCV_discharge [mV]
100	0	3351,15
97,6713	-0,4738	3319,35
95,3473	-0,9467	3315,02
93,0201	-1,4202	3314,18
90,6909	-1,8941	3313,36
86,0476	-2,8389	3312,28
81,4019	-3,7842	3310,89
76,7563	-4,7294	3309,98
72,1105	-5,6748	3309,12
67,4683	-6,6193	3296,44
62,8279	-7,5635	3272,24
58,1900	-8,5072	3269,61
53,5542	-9,4505	3266,91
48,9166	-10,3941	3266,02
44,2843	-11,3366	3265,23
39,6476	-12,2801	3264,38
35,0077	-13,2242	3261,69
30,3653	-14,1688	3245,77
25,6901	-15,1200	3231,905
20,9763	-16,0792	3216,29
16,2728	-17,0362	3199,09
13,9180	-17,5153	3185,62
11,5617	-17,9948	3177,98
9,2052	-18,4743	3173,11
6,8485	-18,9538	3145,85
4,4916	-19,4333	3062,11
2,1310	-19,9137	2918,14
0,0000	-20,3473	2528,92



Appendix 6 – Hysteresis curve