Project Report

2013

Propulsion Battery and Battery Management System

- for Shell Eco-marathon 2013

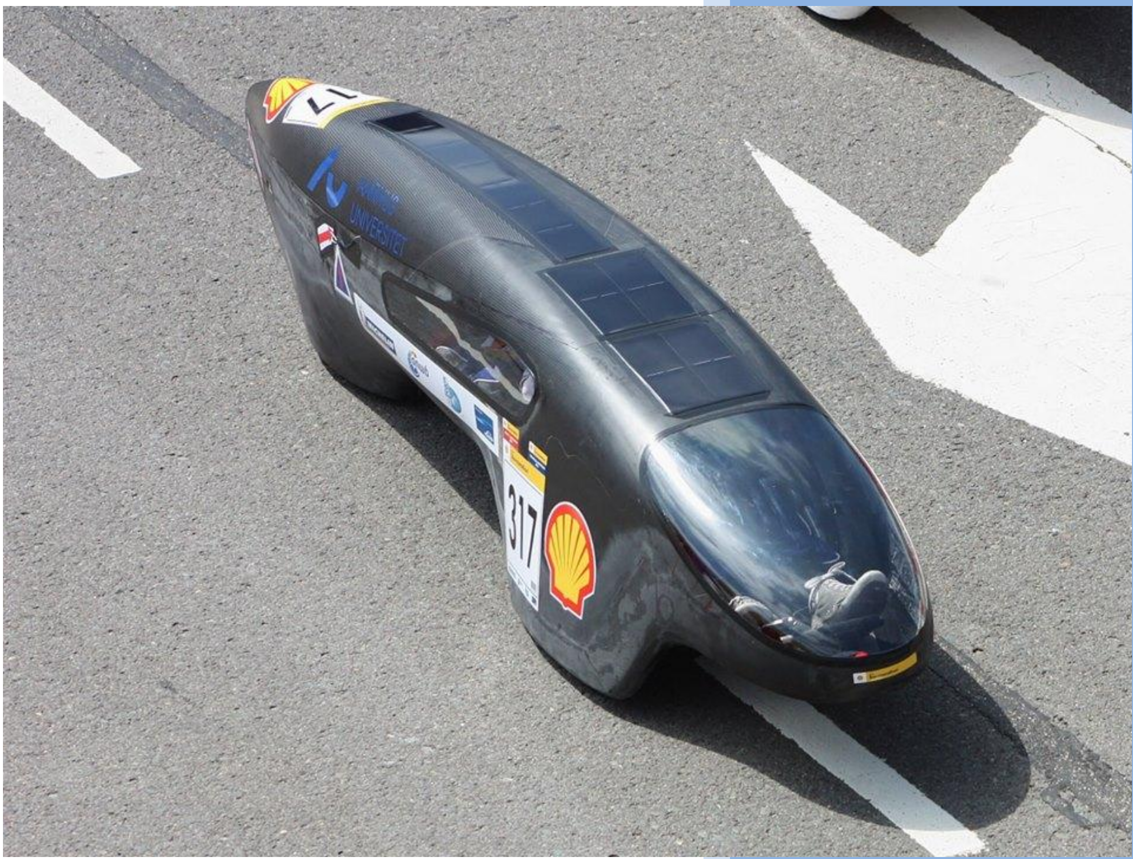

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Figure 1 - Battery and Battery Management System

ABSTRACT

The aim of this thesis has been to develop a propulsion battery and Battery Management System(BMS) specially designed for a vehicle participating in Shell Eco-marathon 2013.

The project took its starting point when Aarhus University decided to sign up for participation in the eco-friendly race Shell Eco-marathon 2013. A number of projects, needed in order to form a complete vehicle, were outlined, both within the mechanical design and within the design of the electrical system. The project which has been treated in this report was derived from the need of a complete electric drive train. Other project groups have been responsible for the execution of projects interfacing to the propulsion battery and BMS. These peripheral units include a motor and motor controller, solar panels with MPPT, vehicle main computer and a vehicle data logging device.

The goal of creating a customized battery/BMS solution has been to achieve a very light and energy efficient solution without compromising the functionality. A system with features contained in sophisticated commercial BMSs, such as, CAN and USB interface allowing the Eco-marathon team to survey the battery performance at cell level, has been designed. Through a combination of low power devices and techniques, the power consumption has been dramatically decreased when compared to commercial of-the-shelf systems. Furthermore, a high energy density battery with just enough capacity to propel the vehicle for one race has been implemented, as opposed to traditional applications where the battery is preferably over dimensioned to improve cycle life. Through this strategy, the weight has been dramatically reduced. As a result, the designed battery and BMS was part of the very successful entry to the recently conducted Eco-marathon where Aarhus University, despite an unsatisfying motor efficiency, managed to reach top five in its class.

The strategy used to achieve a reduced power consumption has been to lower the quiescent current of all system units and ensure that these units are only in an active stage while needed. As an example on the execution of this strategy, a current sensor with a quiescent current of 44.4uA has been designed without compromising measuring range, linearity or offset. Furthermore, an alternative switching scheme has been used for the designed DC/DC converter to allow a no-load current of 230uA, a fragmental part of the power consumed by preassembled commercial converters.

This project is untraditional in the sense that the designed system had to be refined to an extend allowing use in a harsh automotive environment. Therefore, the circuit designs have been verified by fabricating initial PCBs in-house to ensure the expected functionality. Afterwards, a more compact, durable and EMC optimized system has been achieved through the layout of a 4-layer PCB which was subsequently professionally manufactured.

CONTENTS

Preface

The project to be treated originates from Aarhus University's(AU) decision to participate in the Shell Eco-marathon 2013. Shell Eco-marathon is a competition on vehicle energy efficiency where AU attended the battery electric prototype class, which means a very light vehicle, carrying one person, equipped with battery and solar panels as energy sources.

All documentation has been written in English on request from AU Herning. This allows exchange students to use results achieved through this project, in projects to come, which is convenient as the participation in Eco-marathon is expected to be ongoing.

1. INTRODUCTION

A part of the solution on the human-induced climate changes, is to reduce traffic related emissions. This will not only help decrease greenhouse warming, but also defeat health threatening air pollution in areas with massive traffic density. Electrical Vehicles(EVs) generate no local emission and can be charged from sustainable sources. These vehicles must, however, be equipped with a high energy density battery to achieve a satisfying range. Such high energy density can be achieved with Lithium-Ion batteries, which, unfortunately, causes fire hazard and reduced lifespan if not monitored correctly. Therefore, a Battery Management System(BMS) tailored to the battery chemistry must be used.

While the overall goal of the participation in Shell Eco-marathon has been to contribute to the development of more sustainable transportation, the aim of the project described in this report has been to design and implement a battery and BMS customized for Shell Eco-marathon 2013. An aim that must be considered achieved as the system was successfully approved and used during the recently conducted Eco-marathon.

1.1. Reading Guide

The project documentation is divided into two reports:

- **Project Report**
  Contains the description of project execution, including aim of project, issues to be handled, and achieved results. Furthermore, methods and tools used to accomplish achieved results will be described.
  The entire project will be reflected on and suggestions on improvements will be given.

- **Technical Documentation**
  Contains documentation of the designed system, including Specification Requirements, System Architecture, and a description of the implementation including considerations behind the chosen solutions. In addition, system tests are included in this document.

Common for both reports; figures and tables will be sequentially numbered. However, each report has individual numbering. All appendices and both reports will be included on a CD-ROM.

1.2. Project Approach and Methods

To ensure the necessary overview, needed for a flawless integration between sub systems, and thereby achieve a functioning overall system, a structured documentation is of great importance. Methods used for structured documentation are as following:

- Project documentation will be based on the waterfall model[1]. However, with liberty of subsequent adjustment of documentation within the entire documentation chain.
- Time management will be ensured using Gantt charts.
- Overview of daily tasks will be ensured through the use of milestones.
- Weekly meetings with the supervisor will be held to ensure adaption of expectations.

1.3. Stakeholder Expectations

As this project involves a number of stakeholders, an ongoing adaption of expectations has been considered a necessity in order to successfully meet such expectations. To involve stakeholders and ensure a feedback loop, all information considered relevant to stakeholders has been distributed. Subsequent feedback has led to either adjustments of the topic or more thorough explanation to gain acceptance from stakeholders.

List of stakeholders: Project Supervisor, Danish Technological Institute(DTI), AU Herning and AU Aarhus (project teams involved in Shell Eco-marathon).

2. STATEMENT OF INTENT

BMSs for medium to large scale batteries are widely available and may offer many useful features such as State Of Charge(SOC) estimation, State Of Health(SOH) estimation, and communication interfaces allowing the user to monitor battery status at cell level. The before mentioned BMSs are, however, often too bulky and/or power consuming to be suitable for a small vehicle with a very small battery capacity. Therefore, the aim of this project has been to design a battery and BMS tailored for Shell Eco-marathon. This means that the battery must be as light as possible while the BMS must have the lowest possible power consumption, but still offer advanced features and communication interface, which enables the Eco-marathon team to survey battery and cell performance.

[1] See: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4107640 (date:16-03-2013)
[2] See: Battery Cell Type Test in appendices

3. SYSTEM DESCRIPTION

The system consists of a propulsion battery containing a number of series connected Lithium-Ion cells and a BMS.

Commercial BMSs are based on different topologies. Some consists of simple analog comparators, comparing cell parameters to predefined thresholds, while other (so called digital BMSs) includes processing power to allow more sophisticated cell analysis and user interfaces. Furthermore, the BMS may be either distributed with circuitry located at each cell, partly distributed as a master slave system, or centralized with all circuitry placed in one location.

As the propulsion battery required for the Eco-marathon is small in size and the cell count is low, a centralized BMS has been considered the only practical solution. The BMS consists of an Analog Front End, a Digital Unit, a Current Sensor and an Isolation Switch. The system outline can be seen in Figure 2, below the functionality of each block has been described.

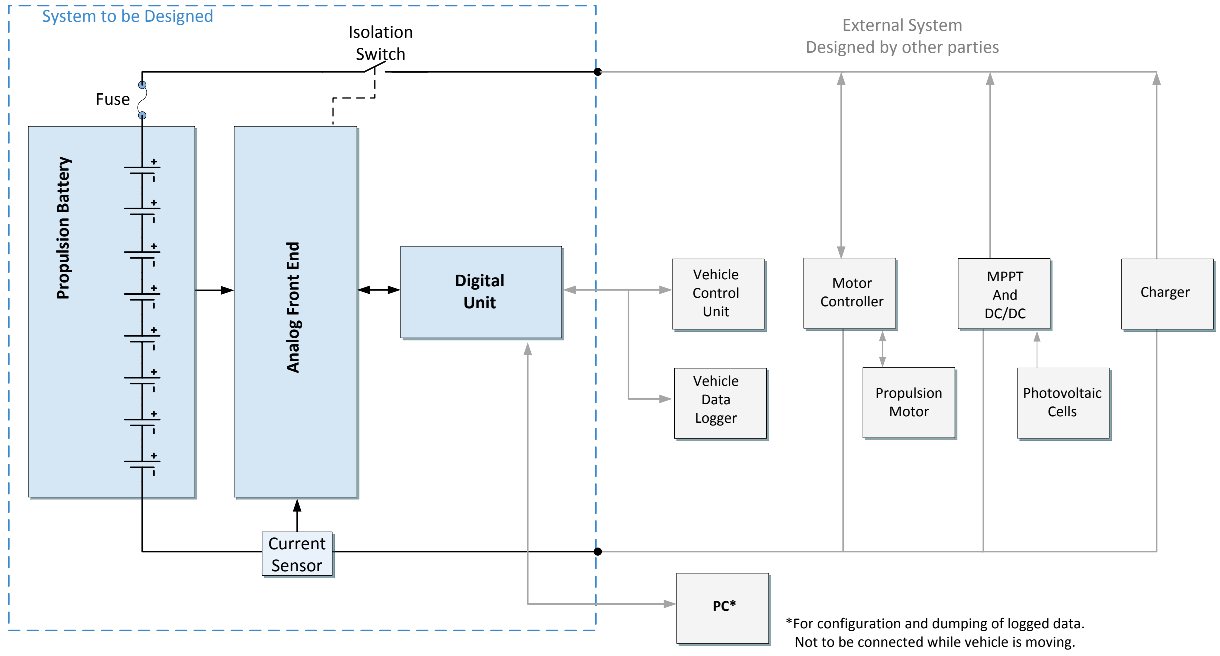

Figure 2 - System outline including peripheral units

Propulsion Battery: Performs storage of energy. It is being charged from an off-track charger as well as solar panels mounted on the vehicle.

Analog Front End: Acquires battery and cell measurements by performing ADC conversion of cell voltages, current and temperature on request from the Digital Unit. Furthermore, redundant protection is included in this unit to improve safety.

Current Sensor: Outputs a voltage proportional to the battery current. The output is converted to a digital value by the Analog Front End on request from the Digital Unit.

Isolation Switch: Enables the Analog Front End and the Digital Unit to interrupt the battery current.

Digital Unit: Requests data from the Analog Front End and analyses received data, to ensure that all parameters are within its Safe Operation Area(SOA). In addition, the Digital Unit performs SOC estimation, data logging and communication with peripheral units(CAN and USB).

4. SPECIFICATION REQUIREMENTS

The system must fulfill the minimum requirements given by the Shell Eco-marathon committee which means that the battery must be of Lithium-Ion type, and the BMS must be able to protect the battery from exceeding current, voltage, and temperature limits. If any of the stated limits are exceeded, the BMS must be able to isolate the battery from its load. Furthermore, requirements has been added to impose the possibility to survey cell performance and to detect poor cell/battery performance, these include; CAN communication interface, SOC and SOH calculations, estimation of internal resistance including CAN warnings if abnormalities are discovered. In addition, redundant protection has been added to the requirements to improve safety.

As the system is to be used at the Shell Eco-marathon 2013, all system components (PCBs, plugs, battery etc.) must be designed and assembled in a way that ensures proper operation in a harsh automotive environment. Technical documentation fulfilling Shells requirements must be prepared, and back-up replacement modules must be made to facilitate on-site repairs.

5. PROJECT DELIMITATION

As functioning propulsion battery and BMS are mandatory to ensure participation in Shell Eco-marathon 2013, effort must be put into designing low power durable hardware and functional error proof software rather than focus on comprehensive research on highly optimized SOC, SOH and balancing algorithms. The choice of algorithm for such functionalities are, however, of importance, and will be discussed to the extent allowed by the given timeframe.

The delimitations below have been introduced to allow optimum focus on the development of the BMS and selection of battery.

- Off track charger will not be implemented, as a CC-CV (Constant Current - Constant Voltage) charging profile can be accomplished using a laboratory power supply.
- Analog Front End will be based on a number of ASIC's in order to reduce power consumption and time to market. Achieving lower power consumption with a discrete design, within the given timeframe, is predicted to be unrealistic.
- PC software for analysis of BMS data will not be implemented.

6. PROJECT EXECUTION

In this paragraph, the project phases and their purposes will be explained. A diagram showing the sequential execution can be seen in Figure 3, and the purpose of each project phase can be found below.

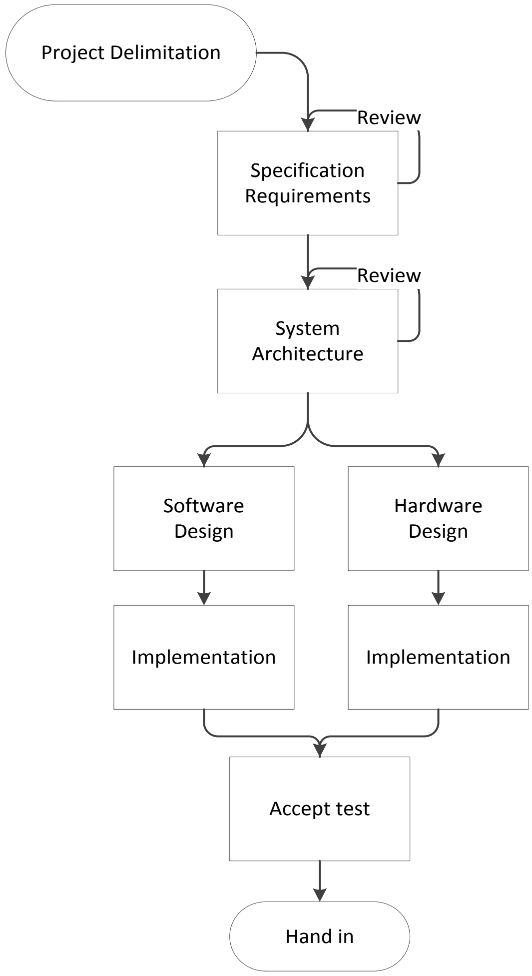

Figure 3 - Project execution flow

Specification Requirements: Documents all specification requirements composed with client. These requirements are specified as external interfaces and required functionalities.

System Architecture: Outlines all internal interfaces between system units and required functionality of these units.

Design: Technical solutions needed to meet functionalities outlined in the system architecture are found.

Implementation: The practical execution of solutions found in the design phase.

Accept test: Ensures that specification requirements are met.

6.1. System Architecture

In this paragraph, methods used to carry out the System Architecture will be described, and hardware and software chapters from the system architecture will be summed up to give an overview of the system and interaction between system units.

6.1.1. Methods

To achieve a flawless interaction between the hardware units to be designed, all internal interfaces have been graphically outlined using block diagrams and specified by signal type, voltage, current, input impedance etc. Furthermore, the Input Process Output model(IPO) has been used to present needed functionalities of each block contained in the block diagram. The software functionalities have been outlined using IPO and flow charts.

6.1.2. Hardware Architecture

A block diagram outlining internal and external interfaces can be seen in Figure 4 and below the functionalities of each block have been briefly described. For an elaborated description of functionalities and interfaces see the project documentation.

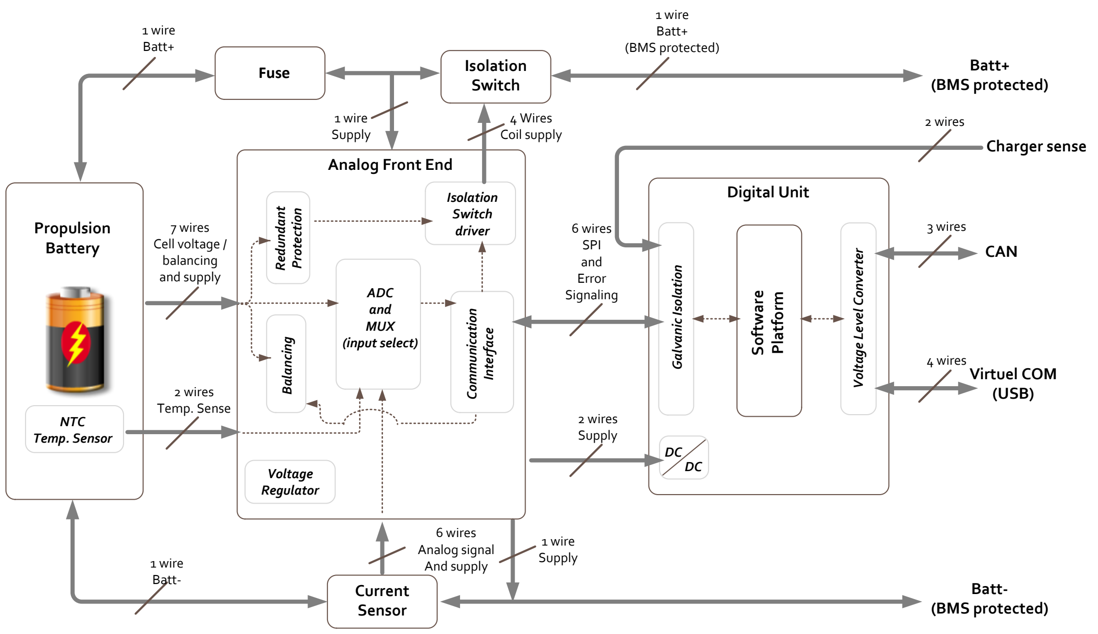

Figure 4 - System blocks and interfaces

Propulsion Battery: Consists of a number of battery cells and a thermistor for temperature monitoring. Wires are connected from cell terminals to Analog Front End to allow voltage surveillance and balancing.

Analog Front End: This unit performs measurements and analog to digital conversion of cell voltages, battery temperature and current sensor signal. Furthermore, it handles cell balancing on request from the digital unit, and redundant battery protection independent of the digital unit.

Current Sensor: Outputs voltages proportional to charge and discharge current. Individual amplifiers are used for charge and discharge monitoring to allow use of two ADCs covering a smaller measuring range, and thereby increase the resolution.

Isolation Switch: This unit enables the BMS to interrupt the battery current. When the switch is opened galvanic isolation between the battery and its load is obtained.

Digital Unit: Collects measured values from the analog Front End and perform calculations and estimations of cell and battery parameters. Furthermore, it handles communication with external units. Galvanic isolation is achieved through an isolated DC/DC converter and isolated data transfer.

6.1.3. Software Architecture

To give an impression of functionalities performed by software, IPO has been included below. For a full overview see the project documentation.

Digital Unit Software Platform IPO(Input, Process, Output)

<table>
<tr><th>Input</th><th>Process</th><th>Output</th></tr>
<tr><td rowspan="2">Battery data acquired by Analog Front End.
(bq76PL536A protocol)</td><td rowspan="4">Calculation and estimation of SOC, SOH, Internal resistance etc. from data acquired by Analog Front End.
Performing communication with Analog Front End and external units.
Log data as specified in Specification Requirements.</td><td>Data log (via virtual COM)
See protocol in Specification Requirements</td></tr>
<tr><td>Battery status information
(via CAN)
(See protocol in Specification Requirements)</td></tr>
<tr><td>Charger information
(connected or not)</td><td>Start Analog Frontend conversion request.
(bq76PL536A protocol)</td></tr>
<tr><td>Fault Interrupt
(Indicating errors)</td><td>Request data from Analog Front End.
(bq76PL536A protocol)</td></tr>
</table>

Table 1 – IPO for Digital Unit Software Platform

6.2. Hardware Design and Implementation

In this paragraph, the methods applied to convert system blocks, specified in the system architecture, into circuitry will be described. Furthermore, the design of each block will be presented.

6.2.1. Methods

System blocks with high complexity have been broken down to a number of sub circuits and visualized as block diagrams to enhance the overview, while simple ones have been directly converted to circuitry. The simulation tool TINA, provided by Texas Instruments, has been used during the design of the current sensor, while other blocks have been designed based on traditional calculations.

6.2.2. Propulsion Battery

To find a battery fulfilling the requirements, a battery test was conducted[2]. Li-PO and LiFePO4 batteries of similar capacity were tested, and the Li-PO battery was, despite its worse safety performance, an obvious choice, as it performed well under worst case Eco-marathon conditions, and has a high energy density. Furthermore, the battery was chosen based on its high charge current rating, as a charging of several C will occur during regenerative braking. The selected battery is originally intended for RC hobby use which means it is preassembled, packed in light weight plastic wrap and readily available. The rather troublesome assembly of loose cells is thereby avoided.

Figure 5 - Picture of battery[3]

Propulsion Battery Test and Measurements

The effective capacity available at the output of the BMS/Battery Unit. At a discharge current of 4A and a ambient temperature of 8°C is 75Wh (measured after 5 charge cycles, Start condition 4.2V per cell, End condition 3V per cell). See accept test for further test results.

6.2.3. Analog Front End

The core of the analog front end is the bq76PL536A battery monitor and secondary protection IC which interfaces to a number of circuitries. An overview of sub circuits contained in the Analog Front End can be seen in Figure 6. Each circuit is described below.

[2] See: Battery Cell Type Test in appendices
[3] http://www.hobbyking.com/hobbyking/store/uh_viewItem.asp?idProduct=27121 (Date: 22-05-2013)

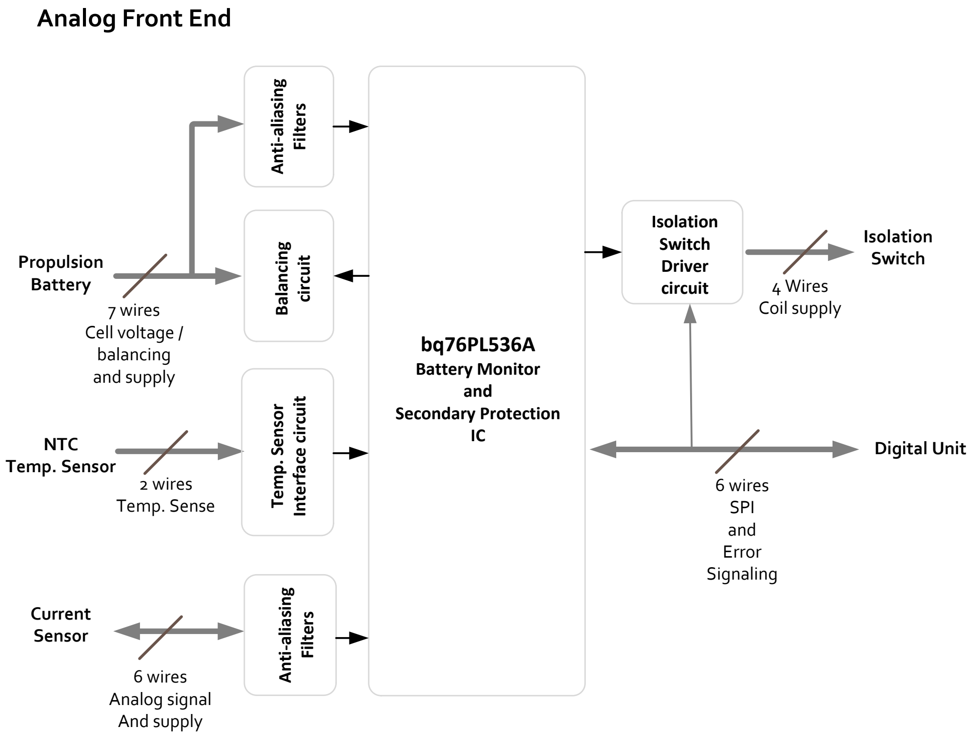

Figure 6 - Analog Front End block diagram

bq76PL536A

Performs ADC conversions on request from the Digital Unit, includes secondary protection, performs interfacing between Digital Unit and peripheral circuitry connected to this IC.

Anti-aliasing Filters

Low pass filters, reduces unwanted ac noise present at the dc signal of interest.

Balancing circuit

Dissipative balancing consisting of a MOSFET and a power resistor per cell. The MOSFET is driven into saturation mode by bq76PL536A on request from the Digital Unit. Thereby, the power resistor is connected across the cell, and energy is dissipated in this resistor resulting in a reduced charging of the cell.

Temp. Sensor Interface circuit

When connected with the thermistor(NTC) contained in the battery pack, this circuit creates a temperature dependent voltage divider. This temperature dependant voltage is led to a dedicated ADC input of the bq76PL536A.

Isolation Switch Driver circuit

Consists of a circuit driving a pre-charge relay and a driver controlling the Isolation Switch relay. AND logic has been added to the driver to ensure that the Isolation Switch is only closed when both the Analog Front End and the Digital Unit allow it, this has been done using stacked MOSFETS as this technique dramatically decreases the subthreshold leakage[4]. These kinds of techniques have been used to ensure that the BMS consumption is as low as possible when it is put to deep sleep after an undervoltage failure in order to avoid further discharge.

[4] http://ambienthardware.com/courses/tfe01/pdfs/Roy1.pdf (date: 11-06-2013)

Analog Front End Test and Measurements

Tested as part of the accept test. See accept test results. However, the Temp. sensor circuit was tested individually see Figure 7

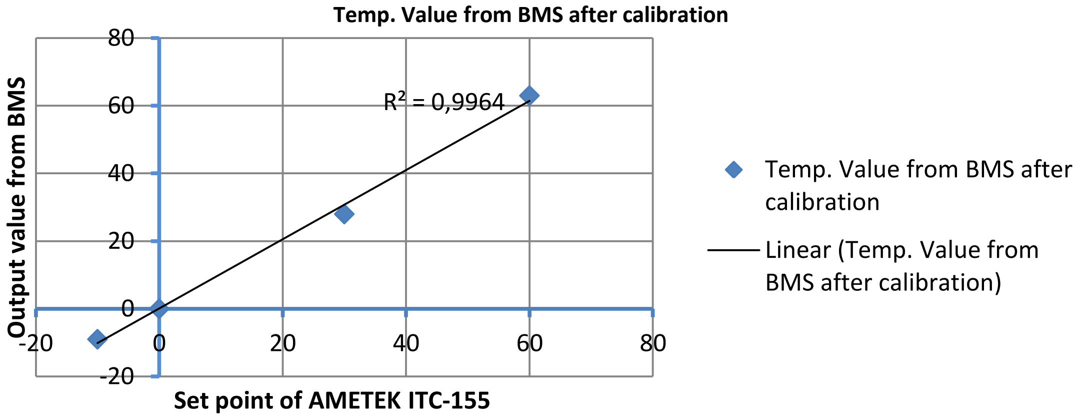

Figure 7 - Temperature measurement results compared with trend line

6.2.4. Analog Front End Extension Module

If more than 6 cells are to be connected, Analog Front End Extension Modules must be connected to the Analog Front End. This scalability feature means that up to 18 cells are supported, but the extra weight and power consumption introduced by the added circuitry is only applied when needed. The circuit of the Analog Front End Extension Module is similar to that of the Analog Front End but without Isolation Switch driver and the SPI interface for connection to the Digital Unit. Instead the Extension Module connects directly to the Analog Front End as shown in Figure 8.

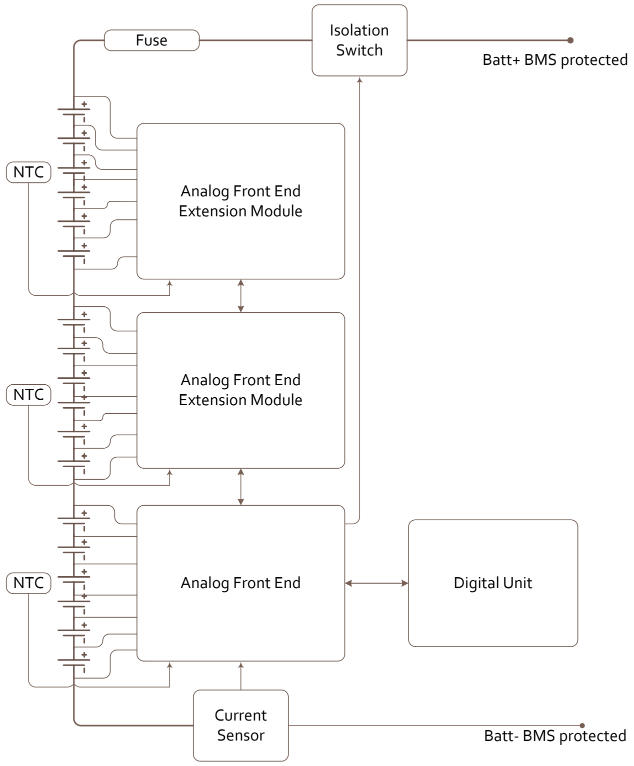

Figure 8 - System with 2 Extension Modules (Up to 18 cells)

6.2.5. Current Sensor

Two sensor topologies has been considered. Hall current sensors introduces almost no resistance in the conductor, but have a higher quiescent current, whereas, a shunt sensor introduces resistive loses but can be made with ultra low power Op Amps. A comparison can be seen below.

Sensor type power consumption comparison:

The current to be measured is estimated to be within a range of -10 to 10A at least 90% of the time. And the average current is estimated to be well below 4A, therefore a current of 4A has been used for comparison.

Parameter to be compared	Hall current sensor ACS756	Shunt current sensor based on OPA333
Supply voltage	5V	5V
Supply current	10mA(typ.)	< 100uA(estimated)
Resistive loses at 4A	2mW	16mW
Total power consumption at 4A	52mW	16.5mW

Table 2 - sensor comparison

The implemented shunt current sensor (see Figure 9) is based on ultra low power Op Amps with very low offset drift, configured as difference amplifiers, amplifying the voltage drop across the shunt resistor. Low offset drift has been prioritized above low initial offset as the initial offset can easily be compensated for. The shunt consists of two parallel resistors in order to divide power dissipation and thereby heat. Low side current sensing has been chosen as this allows changes in cell count without modifying the current sensor. Chosen components and the design have been optimized for low power consumption, which has resulted in a quiescent current of only 44.4uA, without compromising offset drift and linearity.

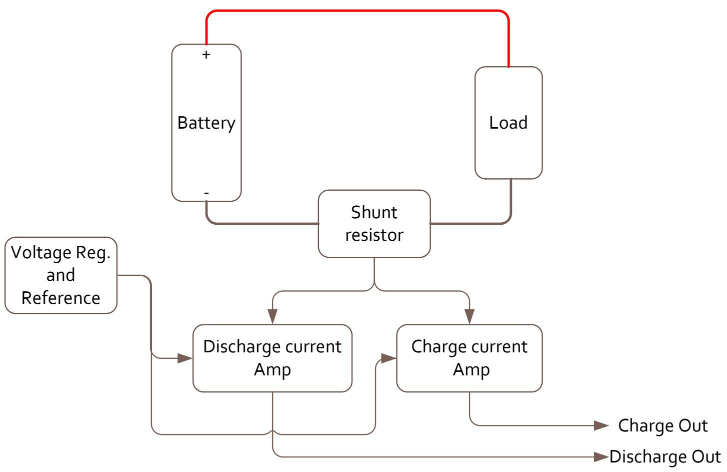

Figure 9 - Current Sensor block diagram

Current Sensor Test and Measurements

Supply current: 44.4uA (Vsupply = 5V, output unloaded)

In Figure 10: Linearity and gain measured after ADC to allow compensation for ADC linearity and gain errors. Only the discharge graph has been presented. A full measurement report can be seen in the project documentation.

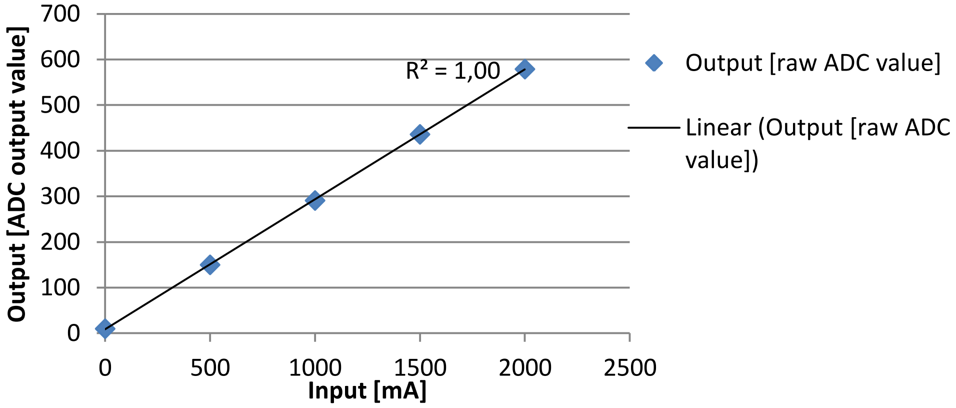

Figure 10 - Discharge measurements and trend line

6.2.6. Isolation Switch

The Isolation Switch is Implemented using a traditional relay, as true galvanic isolation (when the switch is open), is required by the Eco-marathon rules. Alternatively, a better solution had been N-channel MOSFETs with low RDS.

To reduce wearing on the relay contact set, caused by inrush current peaks, a pre-charge circuit consisting of a relay and a power resistor has been implemented. This also reduces the risk of relay welding.

Isolation Switch Test and Measurements

Tested as part of the accept test. See accept test results.

6.2.7. Digital Unit (HW)

This unit consists of a Microcontroller unit with USB and CAN interfacing, a galvanic isolation and a DC/DC converter. An overview can be found in Figure 11. Each circuit is described below.

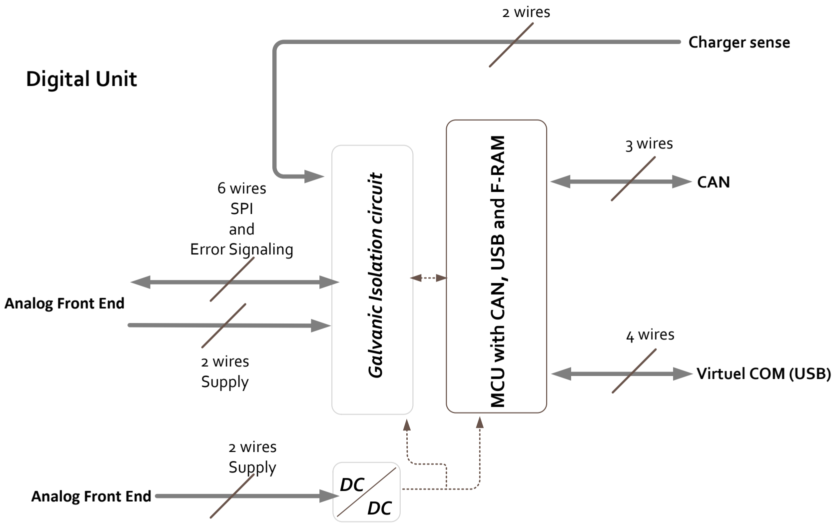

Figure 11 - Digital Unit circuit blocks

Galvanic Isolation circuit

This circuit performs isolation between the battery side and the digital side connected to external vehicle units. Different solutions have been considered. See comparison below.

The digital isolator ISO7141CC from Texas Instruments and The iCoupler ADuM1401 from Analog Devices has been used to compare technologies.

Digital Isolator(ISO7141CC) pros and cons: High speed can be achieved, however both the dynamic and static supply current at both sides of the isolator are unacceptably high[5].

iCoupler(ADuM1401) pros and cons: Very high speed, low dynamic supply current. Unacceptably high static supply current at both sides of the isolator when not in use[6].

As none of above solutions offers satisfying low power consumption, another approach based on optocouplers has been implemented. This allows a design which consumes very little power while in use and next to no power while quiescent.

Data is being transferred via optocouplers and reshaped by inverters. As optocouplers with a high Current Transfer Ratio (CTR) has been used, the LEDs of the optocouplers can be directly driven from the Analog Front End and the Microcontroller. A low power consumption has been achieved, the speed is, however, compromised.

Galvanic Isolation Test and Measurements

As seen in Figure 12, the propagation delay and pulse widening is noticeable, but a necessary tradeoff to achieve a low power consumption. Furthermore, it can be seen that the galvanic isolation conducts the necessary voltage level conversion.

[5] See " iso7141cc - digital isolator" in appendices
[6] See " ADuM1400_1401_1402 - iCoupler" in appendices

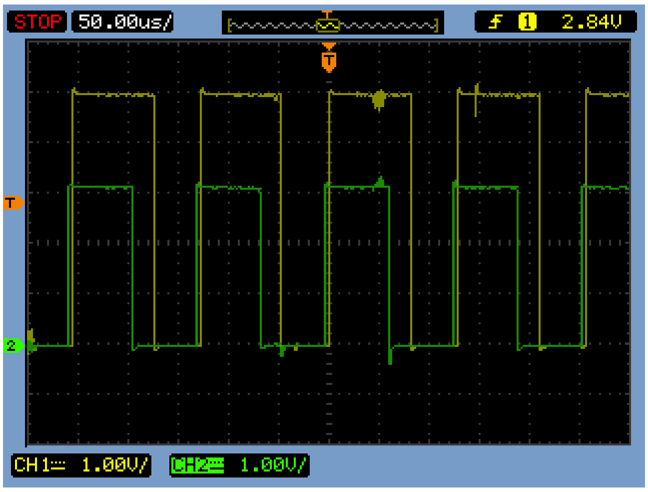

Figure 12 - Input(green) and output of galvanic isolation (SCLK signal)

DC/DC Converter

As this unit is on at all times, but driving a very light load most of the time(when Microcontroller is in sleep mode), the no-load power consumption must be very low to achieve a satisfying result. A search for a commercial isolated converter with satisfying performance was unsuccessful, which has been further consolidated by research results by Rodrigo et al. documented in, Ultra Low Quiescent Current Consumption Isolated PFM Power Supplies under No-Load Condition[7]. However, based on knowledge gained through this paper, it has been possible to design a DC/DC converter with very low quiescent current. As the power requirement is low, a very simple design based on the LT8300 flyback controller IC has been possible. The converter is designed to support a wide input range of 13.5 to 55V to allow scaling of cell count without modifying the converter.

DC/DC Converter Test and Measurements

Quiescent current at no-load: 230uA

Max. output current: 50mA

Min. output current: 0 (no-load required)

Input range: 13.4 to 55V

Based on measurements, output filtering has been implemented to achieve satisfying noise performance. See Figure 13.

[7] Rodrigo et al. date unknown. http://www.icrepq.com/icrepq-08/434-de-diego.pdf (date:14-04-13)

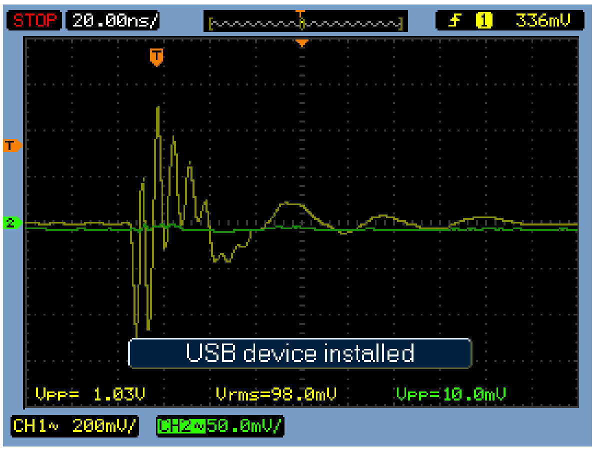

Figure 13 - Output ringing before and after ferrite bead filtering

MCU with CAN, USB and F-RAM

This block consists of a Microcontroller interfaced to external circuitry via a CAN transducer, UART to USB converter and a SPI bus. To allow later upgrade of CAN functionalities, a Microcontroller with integrated CAN controller has been selected as opposed to using emulated CAN. USB functionality is obtained using a USB to UART converter which creates a virtual COM port when connected to a PC. Furthermore, to ease firmware installation and tests, USB supply opportunity has been implemented. The physical layer of the CAN connection is handled by a CAN transceiver, which features a low power sleep mode, and thereby only consumes noticeable power while active.

As data logging is required, the memory included in the microcontroller is not sufficient, a number of solutions have been considered; SD cards which are cheap but too power consuming and not made for operation in a harsh environment, EEPROM which is non-volatile but have limited write cycles, battery backed-up RAM a reasonable solution but more consuming than the implemented solution which is based on F-RAM. Ferroelectric RAM(F-RAM) offers 10^{14} write cycles, very low power consumption between writes and is non-volatile[8]. It is therefore considered the obvious choice in an application where cost is of less concern.

MCU with CAN and USB Test and Measurements

Functionality tested during general system test.

[8] See "FM25V20 - F-RAM memory IC" in appendices

6.3. Software Design and Implementation

In this paragraph, methods used to design and implement software classes will be described. In addition, each class will be described.

6.3.1. Methods

The software has been implemented based on requirements and protocols stated in the specification requirements, as well as the elaborated description of functionalities described in the system architecture. Functionalities have been divided into classes depending on their type, for example all functions to setup and collect data from the Analog Front End are placed in Frontend.c, while functions for analysis of battery parameters are placed in CellAnalysis.c.

The final implementation of source code has been performed using Atmel Studio 6.

6.3.2. General Software Considerations

Besides fulfilling the functional requirements, a combination of efficient, fast executable code and excessive use of sleep modes is required if the goal of a very low power consumption is to be met. To achieve this goal, the Microcontroller is put to sleep whenever possible and woken by an interrupt generated, with fixed time intervals, by a Real Time Counter(RTC). This method will influence the safety and the precision of SOC calculations if the interval between data reception from the Analog Front End is too long. Therefore, a dynamic change in data request rate has been incorporated, so that new measurements and data analysis are performed more often if a rapid change in current is detected or if any parameter approaches its safety limit.

6.3.3. BMSmain1.1.c

This class includes the main function which calls all functions required to perform initialization and puts the Microcontroller to sleep. It also includes a interrupt routine, which wakes the Microcontroller and performs calls to functions which are to be executed with fixed time intervals. Furthermore, interrupt routines to sense charger connection and Fault signal from Analog Front End have been placed in this class.

6.3.4. Frontend.c

Contains all functions required to perform communication with, and initialization of, the Analog Front End. This includes functions to start a new ADC conversion, collect data, address and setup bq76PL536As and handle errors reported by the Analog Front End. Functions have been made in a manner which allows changes in number of connected cells.

6.3.5. CellAnalysis.c

Contains function to analyze cell and battery parameters, such as, SOC, lowest and highest cell voltage, balancing etc.

SOC estimation
Knowing the SOC is very convenient in an eco-marathon vehicle as it allows the team to monitor if the battery capacity was correctly dimensioned, or if the capacity can be further reduced to save weight. In more traditional vehicles, it can give the user a fuel gauge effect, and in hybrid vehicles, furthermore, ensure that SOC is kept around 50% at all times by using knowledge of SOC to intelligently control charging.

A number of methods can be used for SOC estimation, a common method is coulomb counting which rely on the integration of current. This method is easily implementable but may drift over time, and the precision depends on the precision of the current measurement. Another method is voltage based SOC calculation, this method gives a good result(provided that the internal resistance is taken into account) at high and low SOC where the voltage changes are significant. However, the voltage is rather steady while SOC is 20-70% which decreases the applicability of this method within this region. Therefore, a combination of these two techniques has been used. When the SOC is high, a piecewise linear relation[9] between calculated Open Circuit Voltage(OCV) and SOC is used to determine SOC, while coulomb counting is used for the flat region of the voltage curve. At SOC = 0, the voltage based method is applied to reset the coulomb counting. The applied technique has been illustrated in Figure 14 and Figure 15.

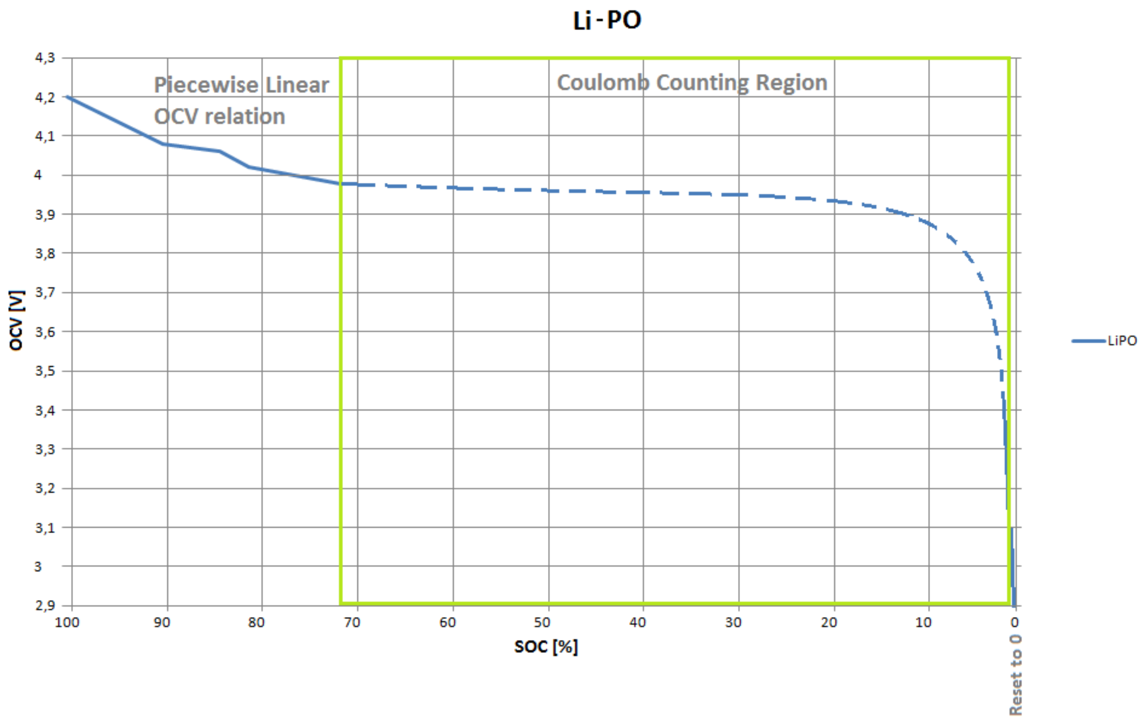

Figure 14 - Illustration of applied mixed SOC estimation methods

[9] Derived from: Valer Pop et al. " Battery Management Systems: Accurate State-Of-Charge Indication for Battery Powered Applications" Page29

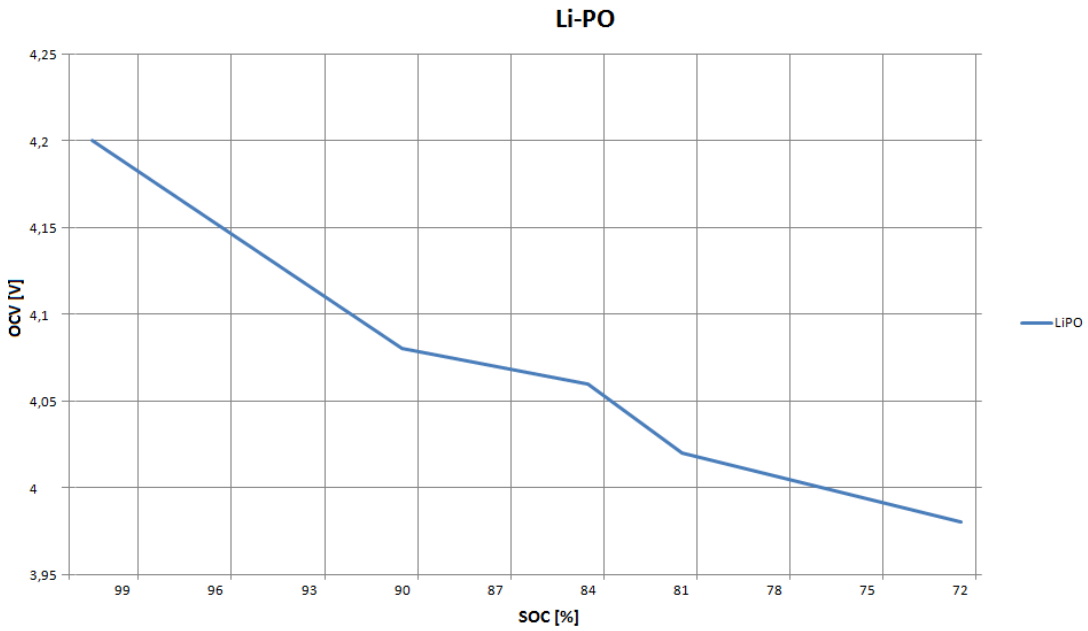

Figure 15 - Piecewise Linear OCV/SOC relation (zoomed)

Internal Resistance

Advanced measurement methods like Electrochemical Impedance Spectroscopy(EIS) can give a full overview of both the imaginary and real components of the impedance, and provide insight in equivalent circuit models for the Lithium Ion battery. However, EIS is preferably performed at OCV and would, furthermore, impose the need of extra circuitry to apply an ac signal of small amplitude and varying frequency, and other circuitry to detect and analyze real and imaginary components as well as phase angle[10]. Therefore, this method is too complex for the scope of this project.

As the real component of the impedance can be found by indirect measurement, without adding complexity, and as the real component is sufficient to determine cell to cell variations, and allow OCV calculation from the terminal voltage, it has been decided to implement a rather simple internal resistance(IR) measurement method. From the voltage change imposed by a change in current, the resistance can be found as $IR_{Cell} = \frac{|\Delta V_{Cell}|}{|\Delta I|}$, this calculation is performed when a significant change in current is detected. A threshold has been introduced, so that large changes at a small current draw are ignored. The performed operation can be seen in Figure 16 and Figure 17.

[10] http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/8090/1/02-0055.pdf (Date:08-06-2013)

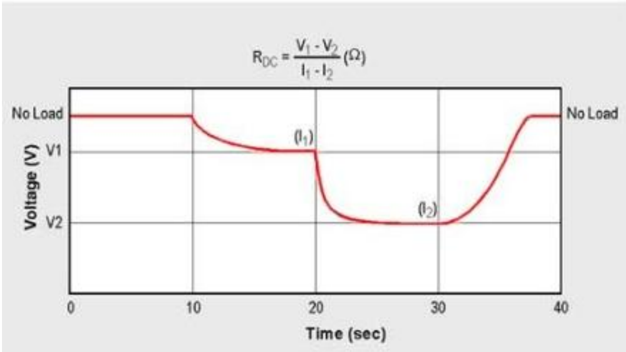

Figure 16 - Illustration of method[11]

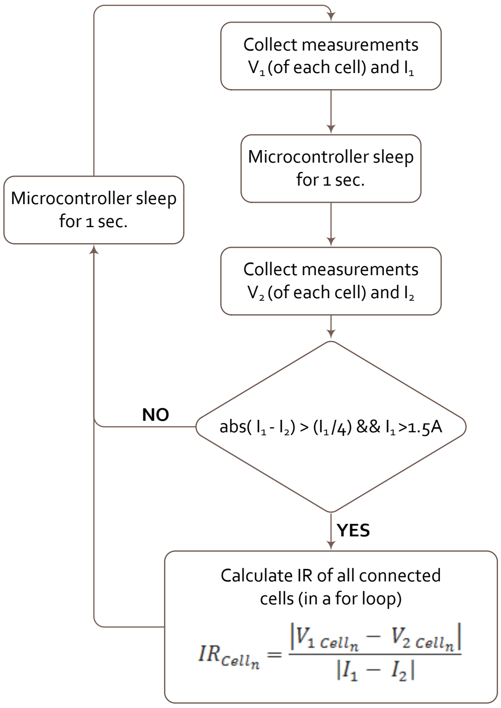

Figure 17 - implemented IR calculation

[11] http://largebattery2012.fotopages.com/?&page=15 (Date:08-06-2013)

Balancing

If cells are out of balance, the available capacity will be reduced as charging will be interrupted once the cell with highest SOC reaches the overvoltage limit, meaning that the cells with lower SOC are never being fully charged. Balancing can be performed in a number of ways; a distributed charger can be used for individual charging of cells to the same SOC level, this would, however, be impractical in a small system. Alternatively, balancing can be performed by the BMS and be either active or passive(dissipative). Dissipative balancing is used in this project, as it is simple and implemented to only dissipate energy while the battery is being charged by an off-track charger. While an active system might appear more appealing, the added complexity of the balancing circuit could potentially increase the quiescent current, and decrease the reliability[12].

A voltage based algorithm is used to control the balancing. To ensure that energy is dissipated from cells with the highest SOC, and not cells with highest IR, the OCV is calculated and used for the balancing analysis. The balancing analysis is applied when cell voltages exceed 3.8V, and compares all OCVs, cells with OCV above average are being partly bypassed by turning on the appurtenant balancing MOSFETs. When all cells are within a range of 10mV(SOC variation <1%), balancing is disabled[13].

6.3.6. RTC_internal.c

Contains function needed for RTC initialization. The RTC functionality is based on an internal timer counting pulses from an internal oscillator, which frequency is defined by an external 32.768kHz crystal.

6.3.7. F_RAM.c

Includes all functions to communicate with the external F-RAM memory. The SPI bus speed is increased when these functions are called to decrease the time consumption. A function to put the F-RAM to sleep is included to allow low quiescent power consumption.

6.3.8. power_save.c

In this class functions to scale the system clock speed is contained. The system clock speed is reduced while the Microcontroller waits for low speed SPI communication to execute.

6.3.9. SPI.c

The low level function for sending SPI data, contained in this class, is shared by Frontend.c and F-RAM.c

6.3.10. CAN_transmit.c

As the Microcontroller contains a CAN controller, the purpose of the function in this class is to prepare relevant data, place it in message object buffers and send it.

[12] http://liionbms.com/php/wp_passive_active_balancing.php (Date: 10-06-2013)
[13] Andrea, Davide, Battery Management Systems for Large Lithium Ion Battery Packs, paragraph 3.2.3

6.3.11. Standard drivers

To ease the source code implementation, standard libraries, provided by Atmel, has been used for CAN and UART communication.

6.4. Physical System Realization

As the system is to operate under automotive conditions, robustness has been considered during all project phases especially during the physical realization where PCBs, connectors and battery fixation have been made to withstand shocks and vibrations. Furthermore, EMC considerations has been necessary, as the BMS is located next to an electric motor with integrated motor controller and a DC/DC converter used for solar panels.

As a transparent cabinet is required, a shielded cabinet has not been an option, therefore, a four layer PCB with full ground plane layer has been designed, as this ensures the lowest possible impedance of the return path, and gives a shielding effect. Below the ground layer, a full power plane ensures a clean and low impedance supply shielded from high frequency traces at the top layer. In addition, decoupling capacitors has been located where considered beneficial. A ferrite bead has been used to filter the output of the DC/DC converter, as measurements revealed the need of filtering.

To allow field firmware updates, a boot loader[14] has been installed. This means that the firmware is updated simply by connecting a USB cable, open a PC GUI and resetting the BMS.

The solid PCB fixation can be seen in Figure 18. The cables have been fixated to avoid stressing the soldering points.

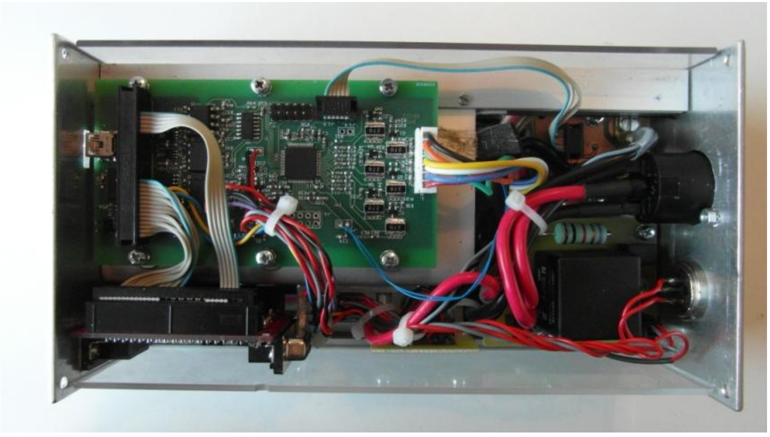

Figure 18 - Top view of BMS without lid

A Speakon connector is used as power connector(see Figure 19), as it is lockable and safe with no exposed poles. A XLR plug (placed at the other end of the cabinet) is used as charger connector, as it is durable and lockable. The emergency switch connector allows an external micro switch to open the isolation switch. The fuse holder is accessible from the outside to ease fuse replacement.

[14] http://www.chip45.com/avr_bootloader_atmega_xmega_chip45boot2.php (Date: 06-06-2013)

Figure 19 - Power connector, emergency switch connector and fuse holder

In Figure 20, the battery fixation inside the BMS cabinet can be seen. The battery is held in place by a rubber material to allow expansion, as the battery expands at high SOC.

Figure 20 - Side view showing battery inside BMS cabinet

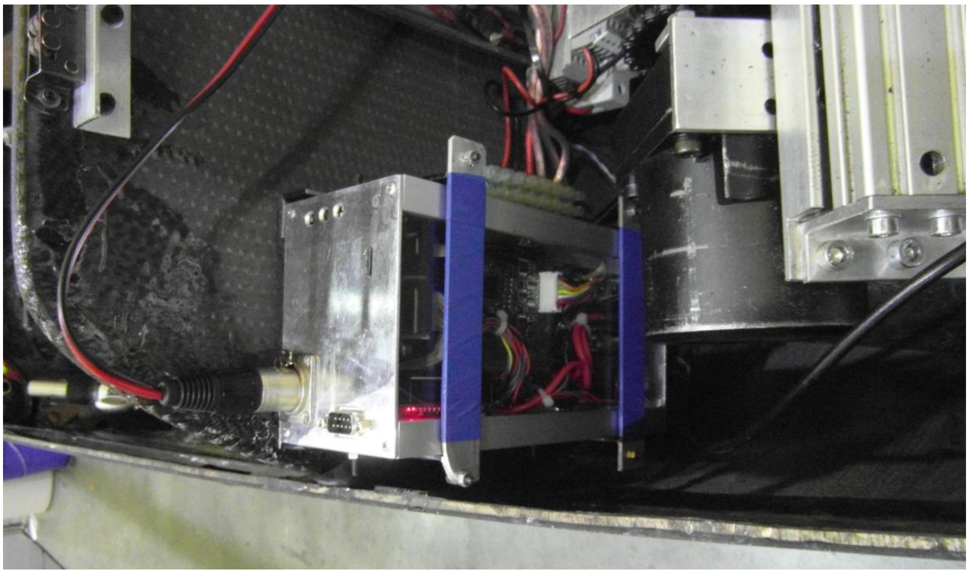

Figure 21 - Fixation in the vehicle

6.5. Accept Test

Besides Requirement BMS_F.5, which could not be met duo to only partially implemented logging functionality, requirements were met. The system power consumption measured during the test can be seen below, by adding the average supply currents of partial systems a total average power consumption below 70mW is achieved (Isolation Switch relay coil not included).

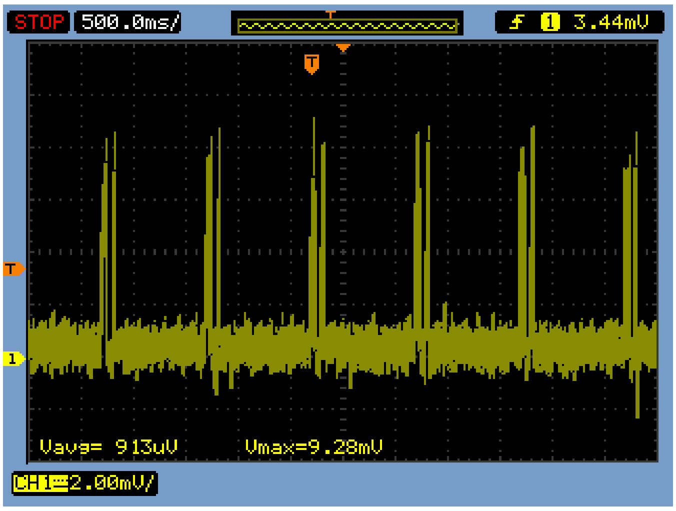

Figure 22 - Supply current for Analog Front End, current sensor and battery side of galvanic isolation (1mV = 1mA)

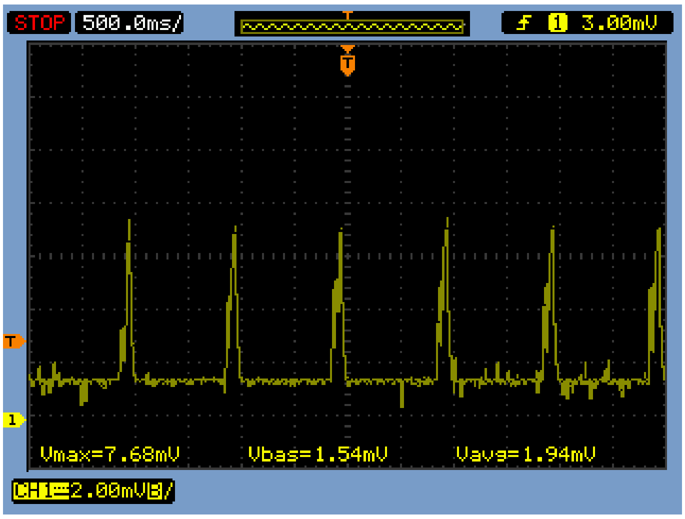

Figure 23 - Supply current of all remaining circuitry except Isolation Switch (1mV=1mA)

7. ECO-MARATHON PARTICIPATION

This paragraph describes the experiences and knowledge gain through the week spent at the Eco-marathon in Rotterdam.

As participants from AU Herning were detained from participating, I was put in charge of the electric system, a rather reduced system, as all electric vehicle units besides the BMS, the Battery and a motor were absent due to technical complications and failure to deliver. As I was informed about the absence of a MPPT/converter for the solar panels at a very late stage, I only managed to design and implement a very simple boost converter with manual power point adjustment. A wiring diagram for the electric system was prepared and can be seen in appendices to get an overview of the system which the BMS/battery is a part of.

After a tremendous effort from the mechanical crew, the vehicle was finished at the last minute, and was approved at the technical inspection after an extra bleeding of the brakes. The decision to design a digital BMS with user interface proved its worth when a bad cell prevented the completion of the first run. The defect was immediately discovered by connecting a PC to the USB interface, and all subsequent runs were successful.

Due to tremendous team work and a fearless driver, we managed to drive 661 km/Wh. The BMS, propulsion battery and solar boost converter performed well, and besides a battery delivered with a weak cell, no defects were experienced. However, the BMS/Battery cabinet can be improved to support faster battery replacement between the runs.

9. DISCUSSION OF RESULTS

A low power consumption has been achieved, and the BMS is able to perform voltage and current measurements of high precision. Furthermore, the system has proven the needed durability, reliability and safety throughout the Eco-marathon event. Especially the USB interface feature was found to be practical, as it allows the user to ensure a high and even SOC at all cells, and an ideal battery temperature right before the execution of each run.

10.IMPROVEMENT SUGGESTIONS

The possibility of lowering the measuring rate without compromising safety must be investigated if further reduction of supply current is required. An appropriate method for SOH analysis must be found and implemented. Data logging must be fully implemented. SOC functionality needs improvements, and the CAN protocol can be refined. The cabinet must be optimized for lower weight and improved battery access, and the battery capacity can be reduced once the overall efficiency of the vehicle has been improved. The software can generally be improved to increase execution speed, and the use of interrupts can be extended to include SPI, UART and CAN functions which all includes significant waiting time. The disabling of the temperature sensor must be improved, so that the sensor only consumes power while measurement is performed, where as now it is turned on when a new ADC conversion is requested, and turned off at next timer interrupt.

11. CONCLUSION

The goal of specifying, designing and implementing a tailored battery / BMS solution before the participation in Eco-marathon 2013 has been reach. Furthermore, it has been possible to embed the designed system in a vehicle and achieve reliable and safe operation throughout the Eco-marathon event. A power consumption low enough to allow use of the BMS in conjunction with a battery of low capacity has been achieved provided that the Isolation Switch is turned off while the vehicle is quiescent. The conducted battery test led to selection of a readily available, but very suitable battery which is light and easily replaceable(once the access is improved) as it comes in one unit with all cell terminals available at one connector.

The project process has been very instructive, not only has it been a foundation for a substantial gain in technical knowledge, it has also given an impression of the complexity involved in execution of projects involving a large number of stakeholders. Especially taking part in the junction of a number of sub projects to a functioning vehicle has been educational.

The cooperation with project supervisors at Aarhus University School of Engineering and Danish Technological Institute has been very giving, as the ongoing dialog has maintained focus on the overall targets of the project, and ensured adaption of expectations.

To sum up, the achieved results, cooperation with other parties involved, and finally the verification of system functionality at the recently conducted Eco-marathon, taken into account, the project must be considered successful.

12. LITERATURE

Articles/Papers

Rodrigo et al., date unknown, http://www.icrepq.com/icrepq-08/434-de-diego.pdf (date:14-04-13)

Kaushik Roy et al., 02/2003, http://ambienthardware.com/courses/tfe01/pdfs/Roy1.pdf (date: 11-06-2013)

Davide Andrea, 08/11/2009 http://liionbms.com/php/standards.php (date: 02-03-2013)

Davide Andrea, 13/03/2013 http://liionbms.com/php/wp_balance_current.php (date: 07-02-2013)

Davide Andrea,30/07/2010, http://liionbms.com/php/wp_passive_active_balancing.php (Date: 10-06-2013)

B. V. Ratnakumar et al. http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/8090/1/02-0055.pdf (Date:08-06-2013)

http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=4107640&url=http%3A%2F%2Fieeexplore.ieee.org%2Fstamp%2Fstamp.jsp%3Ftp%3D%26arnumber%3D4107640 (date:16-03-2013)

General Links

http://weatherspark.com/averages/28810/5/Rotterdam-Zuid-Holland-The-Netherlands (date: 02-02-2013)

http://batteryuniversity.com/learn/article/types_of_lithium_ion (date: 11-06-2013)

http://www.hobbyking.com/hobbyking/store/uh_viewItem.asp?idProduct=27121 (date: 22-05-2013)

http://largebattery2012.fotopages.com/?&page=15 (Date:08-06-2013)

Books

Valer Pop et al. 21/05/2008 "Battery Management Systems: Accurate State-Of-Charge Indication for Battery Powered Applications"

Davide Andrea, 30/09/2010 "Battery Management Systems for Large Lithium Ion Battery Packs"

Other

sem_rules_chapter01_2013, Official Shell Eco-marathon rules, see appendices

Referenced Datasheets are included in appendices