Battery Management System Design for Electric Vehicle

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***Abstract*— the aim of this paper is to design and build a custom battery management system suited for high voltage battery packs in Formula Electric Racecar. This is a simple battery management system which is able to monitor the voltages, temperatures and current of all the individual cells. As the design proceeded, numerous changes were made to reduce the noise effect while logging data from the high voltage batteries and also to make it compatible with the battery pack.**

***Keywords*— Battery Management System, lithium-ion battery, microcontroller, cell balancing, Controller Area Network, Serial Peripheral Interface, Graphical User Interface**

I. INTRODUCTION

The Battery Management System (BMS) is a fundamental component of electric vehicle, which represent a step towards sustainable mobility. From today's perspective, Li-ion chemistry is the best battery technology of choice due to its good energy density, good power rating and charge/discharge efficiency in pulsed energy flow systems like automobiles [1]. But Li-ion chemistry being very sensitive to overcharge and deep discharge, which may damage the battery, shortening its lifetime, and even causing hazardous situations, a proper battery management system which monitors the voltages and temperatures of the cells inside the high voltage battery is needed to ensure that they stay within their safe operating range. E-Propulsion Systems (EPS) cells of $LiCoO_4$ chemistry are used with the following Battery pack design, as shown in Fig. 1.

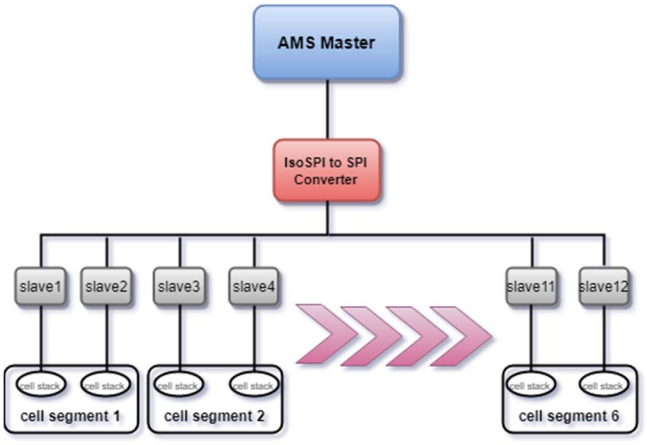

Fig. 1. Configuration of BMS on the cell segments of the Electric Battery Pack.

The whole model of the battery pack is designed with cell configuration of 84s1p giving a total pack voltage of 352.8V max and 310.8V nominal [2]. The battery pack is divided into 6 individual segments/compartments to restrict the segment voltage under 120V. So each segment (14 cells) is a combination of 2 stacks [3]. In order to accomplish this, the designed system required 12 BMS slaves where each slave is used to monitor 1 stack (7 cells), as shown in Fig. 1. Since we are dealing with high voltage batteries, safety was the first priority. So appropriate care has to be taken while making the custom made system like isolation from high voltage system, over current protection, etc.

II. METHODOLOGY

One of the primary reason for going with a custom made design is due to its low cost and lower weight compared to the commercial BMS available in the market. Other factors included the topology, cell balancing capability, and communication over CAN. It also depends on the number of cells it could monitor and whether it was isolated from its voltage taps. Some of the commercial BMS were taken into consideration before starting the design. Orion BMS which is available in the market has a centralized topology, which would increase problem in the wiring as all of them need to be connected to the common master. Elithion Lithiumate Pro was a good choice, due to its distributed architecture, but adding cell boards for each cell would have been a major assembly issue. Thus, a custom BMS based on Multi-cell battery stack monitor Integrated Circuits (IC) was finalized. This should be having a modular topology where a group of cells are monitored by individual ICs and all the IC's are connected to the master [4]. An IC which allows all the necessary measurement hardware to be incorporated into a single small package. These ICs should include all the required analogue multiplexers, Analogue to Digital Converters (ADC) and voltage references for measurement of individual cells.

A. Selection of the IC for the Custom BMS

As shown in Table I, Three IC's were chosen before finalizing with one. They are the MAX 11068 by Maxim, the ATA 6870 by Atmel and the LTC 6804-2 by Linear Technology Corporation (LTC) [5]-[7]. Due to certain regulations such as ability to transmit cell voltages and temperatures, the LTC 6804-2 was finalized [8]. The advantages over other ICs from the same family are: storage space for acquired analog signals, addressable multi-drop configuration, Isolated SPI (isoSPI) capability, on chip

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balancing MOSFETS. Each LTC 6804-2 IC has the ability to monitor up to 12 cells voltages and 5 General Purpose Input Output (GPIO) pins for the temperature.

TABLE I. SPECIFICATIONS OF DIFFERENT IC'S

Parameters	Type of BMS IC		
	MAX 11068	*ATA 6870*	*LTC 6804-2*
Application	Large size packs Stackable to 372 cells(1.4kV)	Medium size packs stackable to 96 cells(400V)	Medium size packs stackable to 100 cells(1kV)
Connection Topology	1 IC every 12 cells	1 IC every 6 cells	1 IC every 12 cells
Voltage Reading Range(V)	0-5	0-5	0-5
Voltage measurement ADC	Successive Approximation	Sigma Delta	Sigma Delta
Voltage measurement Speed for 12 cells(µs)	107	-	290
Internal Communication protocol	I2C	SPI	SPI & isoSPI
Operating Current(mA)	4.1	15	0.55
Cost per IC(₹)	-	700	1160

B. Proposed System Overview

The BMS comprises of a single master board and multiple slave boards. The whole system works on Serial Peripheral Interface (SPI) protocol with a simple master slave configuration. The master used here is a simple Arduino UNO, as shown in Fig. 2.

The slave boards are based on LTC6804 Multi-cell battery monitors, which can monitor and balance a maximum of 12 cells. On-chip balancing MOSFETs and an on-chip ADC for interfacing 5 thermistors are present eliminating the need for additional circuitry and chips on slave boards [7]. The number of slaves used is dependent on the battery pack configuration. For our design, we are monitoring 1 stack (7 cells) using 1 slave Printed Circuit Board (PCB). Thermistors are placed on any 5 of the 7 cells. Each slave is powered by the segment of the cells it monitors. This means that it doesn't need any external power supply to run the low voltage system.

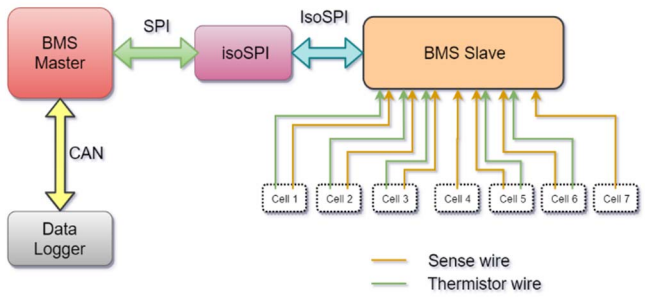

Fig. 2. System Architecture of the BMS Master, slave, isoSPI and Data logger.

Communication between the master and the slave boards is done using isoSPI. This is a two wire bus where all the slaves are connected to the bus nodes. This is preferred over the CAN protocol because of its less complexity and cost effectiveness [9]. This isoSPI bus connects to each of the slave PCB through a 1:1 HV rated isolation transformer, which provides an isolation of 1500VDC. At the end of the bus there is an extra LTC6820 isoSPI to SPI converter PCB placed to convert the 2 Wire isoSPI signal to a 4 Wire SPI signals. One side of the isoSPI PCB is connected to the two wired isoSPI bus with a transformer providing isolation for the 4 SPI lines on the Master side, as shown in Fig. 3. Since the slave PCB's are individually addressable, we can get data from them efficiently without any loss. The network layer for this protocol also provides for a Cyclic Redundancy Check (CRC) on all data transfers, which enables error detection in the transmission of data [10]. The master is responsible for gathering the data from all the cell boards and send commands for cell balancing and setting the threshold limits of the cells.

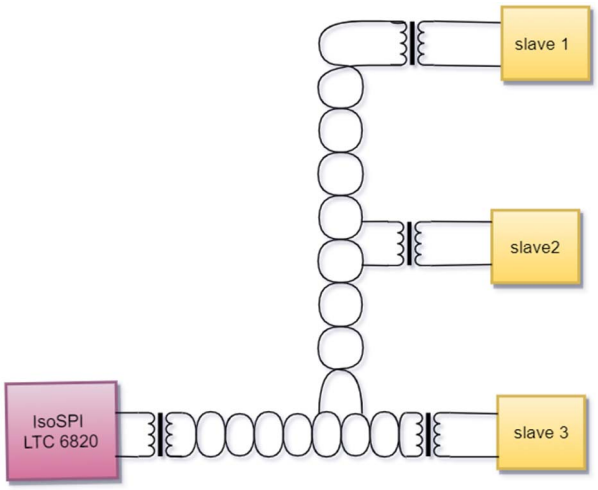

Fig. 3. The BMS slaves and Iso-SPI circuitry connections

III. Design and Implementation

PCB designs of BMS slaves using LTC 6804 -2 and isoSPI- SPI converter using LTC 6820 are made by the following procedures. All of them should have a transformer over the communication bus to provide galvanic isolation from High Voltage.

A. BMS Slave LTC 6804-2 PCB Design

The LTC6804-2 is a Multi-cell battery stack monitoring IC that measures up to 12 cells in series with a total measurement error of less than 1.2mV. The cell measurement range of 0V to 5V makes the LTC6804 suitable for most battery chemistries. Multiple LTC6804-2 devices can be connected in series with each device individually addressed, permitting simultaneous cell monitoring of long, high voltage battery strings. Each LTC6804 has an isoSPI interface for high speed, RF-immune, local area communications.

To support a distributed, modular topology with high electromagnetic interference (EMI), a robust communication system, is required. Most commonly, this is achieved with an isolated CAN interface, requiring a microprocessor, digital isolator and CAN transceiver. The LTC6804 eliminates the cost and software complexity of CAN by including a built-in isoSPI interface [9]. The isoSPI combined with a simple transformer allows for data up to 1 Mbps to be communicated

over long distances using only a twisted pair cable. It also passively balances the cells and can be powered directly from the battery pack. Fig. 4 shows the slave schematic with all the appropriately rated values of the resistors and capacitors used.

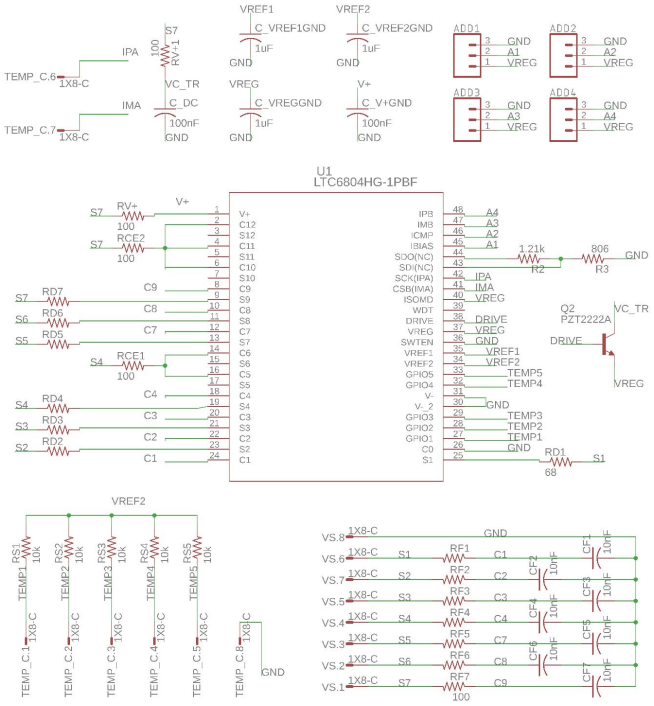

Fig. 4. BMS slave schematic using LTC 6804 -2

The internal part of the LTC is divided into 2 sections: the Core circuit and the isoSPI circuit. Both the internal circuits follow a sequence of state diagram to measure and transmit the cell data.

The core circuit is initially powered down. So a wakeup signal is used to wake up the ADCs and references from the sleep state. After which it enter into the standby state and depending if the ADC command is received, it enters the measure state. This goes back to the sleep mode if it doesn't receive any wakeup signal within a certain amount of time.

The isoSPI circuit has the three states: idle state, ready state and active state. The isoSPI bus is initially powered down. A wakeup signal is required to enter into the Ready state. When the serial interface is transmitting or receiving data it enters into the Active state. If there is no wakeup signal for greater than a certain time, then it enters back into the idle state and starts over.

The LTC 6804 has 2 ADCs built in. Both of them are used simultaneously to measure the 12 cells. The ADCs are of Delta- Sigma type with a maximum resolution of 16 bit. In the current design, the ADCs are used in the Normal Mode of operation (14 bit resolution) with a range varying from 0.5 to 4.5V. Only one ADC is used to measure the Thermistor values from the 5 GPIO ports [7]. All the data which is read from the ADC operation are stored in registers. This data is then send over the isoSPI bus to the master module.

Addressing of the individual LTC slaves is done by adjusting the shunts on the slave boards, as shown in Fig. 5. The 4 addresses A0, A1, A2 and A3 are adjustable and can be shorted to ground or power depending on which 4 bit address the user wants to set to communicate with the slave. Fuses of appropriate current rating have to be placed at the input side of the cell tab inputs to the slave.

B. *Temperature Monitoring*

For the Temperature monitoring, the Negative Temperature Coefficient (NTC) thermistors placed on any of the 5 cells tabs are taken as inputs through the GPIO pins of the slave. A voltage divider circuit is created by placing the thermistor of each cell and a resistance of 10KΩ in series, as shown in Fig. 4. The voltage dividing part is feed to the 5 GPIO pins. These are stored in the Auxiliary registers of the slave.

C. *Isolation*

The transformer is placed as close as possible to the isoSPI connector on the PCB to isolate the IC from the magnetic coupling fields. Layout of the isoSPI signal lines also plays a significant role in maximizing the immunity of a circuit. The following layout guidelines should be followed:

- The transformer should be placed as close as possible to the isoSPI cable connector to help isolate the IC from the magnetic coupling fields.
- On the top layer, no ground plane should be placed under the magnetic, the isoSPI connector, or in between the transformer and the connector.
- The Isolated Interface Plus Input/ Output (IP) and Isolated Interface Minus Input/ Output (IM) traces should be isolated from surrounding circuits. No traces should cross the IP and IM lines, unless separated by a ground plane within the printed circuit board.

D. *Cell Balancing*

The BMS is designed to provide passive balancing. This type of balancing is generally done by discharging the cell across a resistor. When there is any minimum deviation between the respective cell voltages in the stack, the slave discharges the cell with the highest voltages to balance them equally. A resistor of 68Ω is used as the discharge resistor R_{DIS}, as shown in Fig. 4.

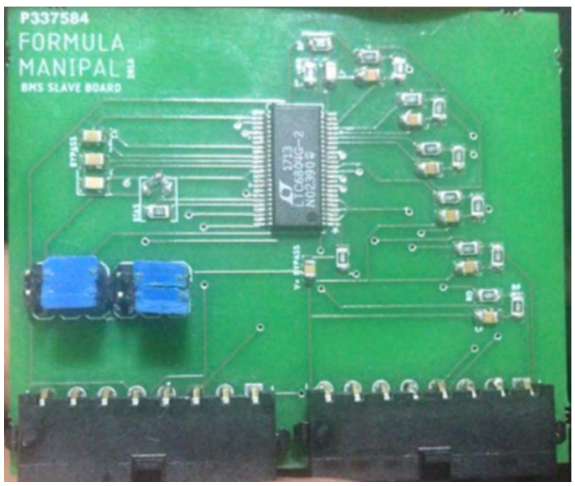

Fig. 5. BMS slave PCB.

The slave PCB was finalized after going through a certain number of iterations. The objective is to keep the circuit as small as possible so that it makes it easy to place and mount the slaves on the stacks with ease and it also keeps it safe from

the live contacts of the cell stacks. Since the design was to use two slaves per stack, the PCB was made to house two LTC6804 ICs so only one PCB was to be used per stack. This did not seem very safe as the slave turned out to be very big to mount on the stack so a more compact design had to be looked into.

The changes from the previous design being to reduce the size of the PCB were added and tested to get the best and compact design possible for the second iteration of the BMS slave design. Problems were faced with the ADC conversions of the LTC6804 and the addressable pins of the LTC6804, so a new design had to be looked into.

For the third iteration, the changes from the previous design were made with a change in the ADC calculations method and a more compact layout. Still problems were faced with the Isolated Interface Current Bias pin (I_{BIAS}) and Isolated Interface Comparator Voltage Threshold Set pin (I_{CMP}), current between slave and isoSPI PCB, Thermistor interfacing and also overcurrent protection and galvanic isolation between the slave and master was not included.

A final PCB design was made to house one LTC6804 slave with appropriate resistor and capacitor values for ADC calculations and appropriate capacitors to reduce noise and also proper resistors for I_{BIAS} and I_{CPM} in both isoSPI and BMS slave PCBs for the isoSPI communication, inline fuses were added to all the voltage sense paths and transformer was included for galvanic isolation, as shown in Fig. 5. The PCB was designed to measure voltage of 7 cells and also to interface with 5 thermistors, so two such slaves will be used per stack and a total of 12 such slaves will be used and will communicate to the BMS master through the isoSPI bus.

E. isoSPI LTC 6820 PCB Design

The LTC6820 creates a bidirectional isolated serial port interface (isoSPI) over a single twisted pair of wires, with increased safety and noise immunity over a non-isolated interface [11]. Using transformers, the LTC6820 translates standard SPI signals (CS, SCK, MOSI and MISO) into pulses that can be sent back and forth on twisted-pair cables, as shown in Fig. 6.

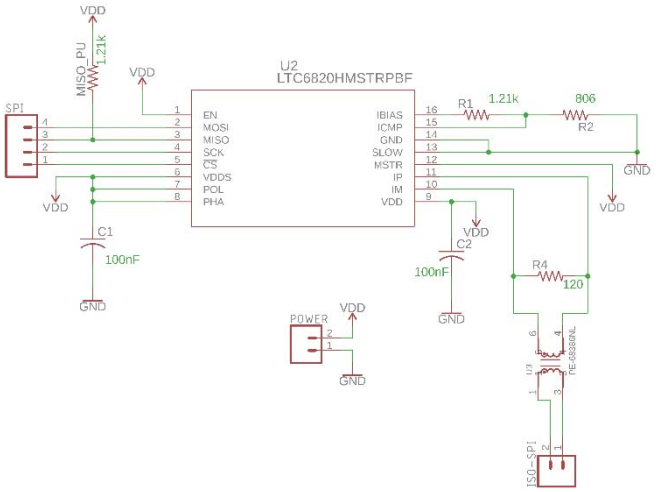

Fig. 6. LTC 6820 - isoSPI PCB Schematic

The SPI part of the IC is paired with a microcontroller or other SPI master like Arduino Uno. It's IP and IM transmitter/receiver pins are connected across an isolation barrier (transformer) to the IP and IM pins of all the slaves which also have a transformer on their side for protection. This ensures that the whole system is protected from High voltage failure by achieving hundreds of volts of isolation. The biasing resistors of the LTC 6820 should be the same as that of the biasing resistors of the LTC 6804 slaves for better channel communication. All the layout issues followed in designing the LTC 6804 slave board should also be followed in making the isoSPI PCB.

IV. Experimental Results

A. BMS Master

Arduino Uno/Due controller is used as BMS Master. The master module shows the live readings of the cell voltages, temperatures and current over the serial monitor window in the Arduino IDE, as shown in Fig. 8.

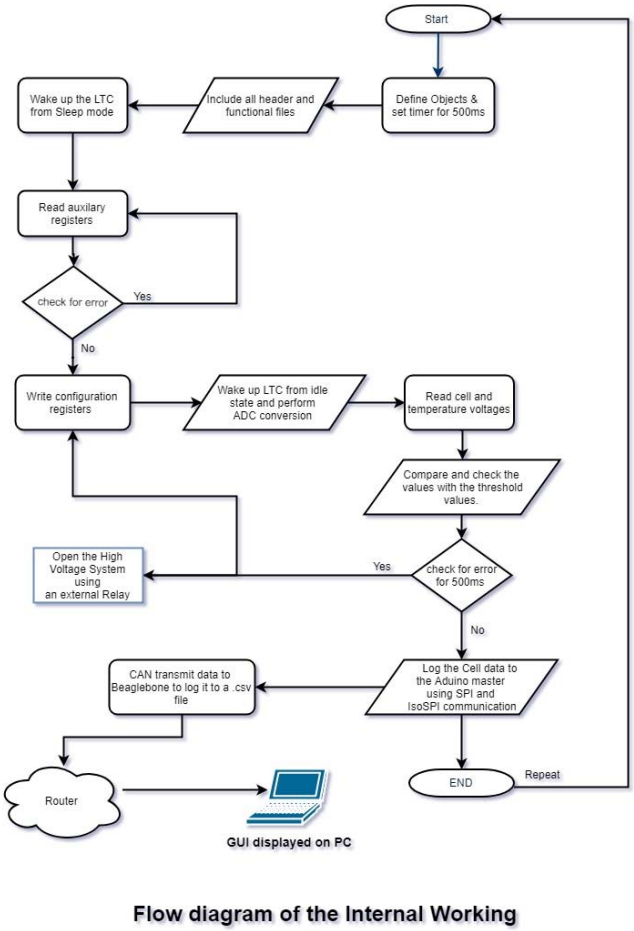

Fig. 7. Workflow of BMS Master.

Then again, a simple Arduino is not able to log the data and show them in a structured way. So a high end processor which has onboard Real-time Operating System for easy file handling capabilities. So Beagle Bone Black was chosen as the logger because of the availability of all the required packages over the Linux platform to create a Graphical User Interface (GUI) to monitor the cell data real-time [12]. It also has a built in CAN interface which made the whole system easier to interface.

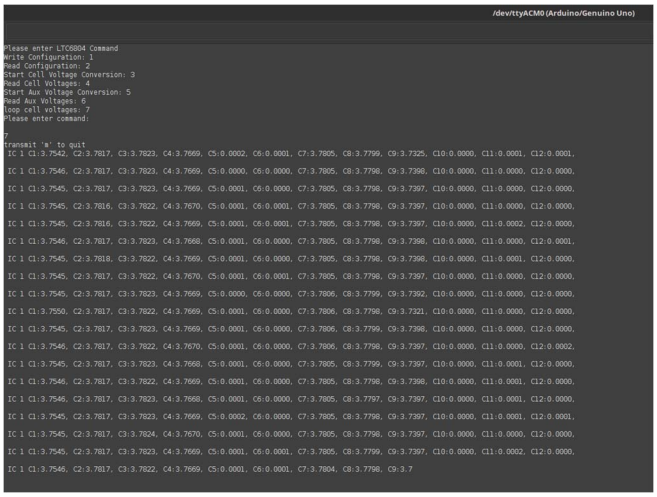

Fig. 8. 7 Cells Voltage Data over the Serial Monitor in the Arduino IDE

B. Data Logging and Telemetry

The Beagle Bone Black here is used for two specific purposes. One of them is to log the Real time CAN data of cell voltage and temperature of individual cells into a Comma-Separated Values (csv) file using the SD card slot provided on it [13]. This data is later used for further analysis. The other purpose is to live stream the data over a Linux based GUI application on the PC terminal to indicate the status of each cell. This was created using the GTK+ libraries available over the Linux platform and interfaced with the CAN data logging code [14]. The CAN data from the Beagle bone is sent to the router via an Ethernet cable and transmitted wireless over a PC terminal located in the pit stop with the help of an antenna.

Fig. 9 shows all the cells are numbered accordingly in the GUI. A Red box indicates a fault in the cell voltage or temperature while a Green box indicates no fault in the cell. A fault is occurred if the cell parameters falls below a minimum threshold voltage or due to over voltage or due to under voltage, etc. The GUI has 3 tabs of voltage, temperature and current where the faulty cells are indicated in red for each tab.

Fig. 9. Cell status indication over a Linux based GUI application on BBB for Telemetry.

The cell data which is logged in the SD card into a .csv file is used later for analysis. The following is a bar plot of a BMS slave voltage readings of 7 cells which is plotted using RStudio, as shown in Fig. 10.

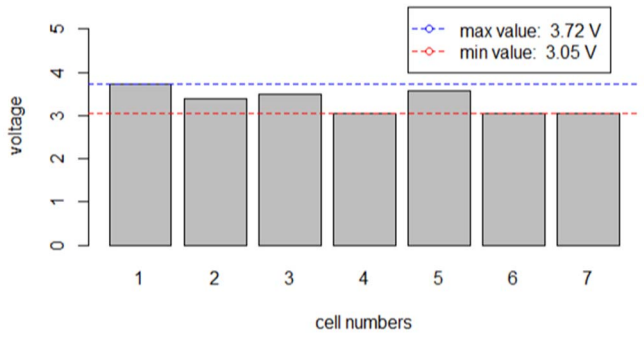

Fig. 10. Logged file cell voltage data plotted in RStudio

V. CONCLUSSION

To promote the growth towards sustainable development, many strategies in the energy domain were proposed. Within these new energy management scenarios, electric vehicles and decentralized stationary energy storage are considered to be growing application areas for advanced batteries, mainly those based on Li-ion multi-cell packs, as electrical energy storage devices. For these systems, either for mobility or stationary applications, a flexible and powerful embedded processing systems with electronic interfaces are required, offering proper functionalities, accuracy and communication capabilities at a reasonable cost, requested by smart environments.

In order to evaluate the improvements of BMS performance and cost with LTC6804 are compared with other available. In many high-voltage battery systems, including electric vehicles and industrial applications, the battery is a significant portion of the system cost, and needs to be carefully managed by a BMS to maximize battery life and to optimize charging and discharging performance.

This custom based BMS design of the LTC6804-2 devices provide architectural flexibility, scalability, customization, performance improvements, and system cost savings in BMS applications. Without comprising any of the commercial BMS features like CAN Interference, cell balancing, Data logging, Temperature monitoring, Safety actuation, galvanic isolation etc. used in the market, this simple custom designed BMS provides the same with less cost, weight and complexity. This is perfect for a system where the battery pack design is variable depending on any number of cells used and the type of topology.

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