Study and Development of a Battery Monitoring System (BMS) for a Formula Electric Vehicle

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***Abstract*—In recent decades, the world has witnessed a significant increase in population growth rates, bringing the number of people living on the planet to over 8 billion. This growing number of people, along with the development of large urban centers, has resulted in a gigantic vehicle fleet, most of them powered by internal combustion engines, which operate by burning fossil fuels and generate polluting greenhouse gases such as carbon dioxide (CO_2) and methane ($CH-4$). In this scenario, the generalized demand for more sustainable transportation alternatives has led vehicle manufacturers to seek to reduce the emission of pollutants by producing electric and hybrid vehicles. In this type of vehicle, the propulsion system is based on electric motors and batteries. A battery management system (BMS) is required to increase vehicle safety further. The BMS can measure parameters such as voltage, current, and temperature of the battery cells and calculate important information such as the State of Charge (SoC), State of Health (SoH), among others. Thus, this work sought to develop the hardware and software of a BMS, using as reference the BQ76PL455A-Q1 integrated circuit produced by Texas Instruments, implemented for monitoring the cells used in an accumulator of a standard competition electric vehicle SAE formula.**

***Index Terms*—BMS, electric vehicles, SAE, lithium cells.**

I. INTRODUCTION

Currently, with the growing concern about the environment, especially concerning the reduction of the emission of gases that cause the greenhouse effect, the automotive scenario is taking the first steps towards the transition from combustion to electric vehicles, reducing dependence on fossil fuels and adapting to new technologies of energy storage for the creation of vehicles with greater autonomy and reliability [12], [13], [14].

In this sense, to encourage and prepare future engineers and designers for the automotive market, several universities worldwide participate in the Formula SAE Electric competition, aiming to idealize and build a fully electric racing vehicle. As the power supply for electric vehicles (EVs) comes from a set of batteries called an accumulator, and among the technologies currently available in the market, the most widespread is the Lithium Ion battery, it is known that the operation with this type of cells can present several risks to the project, especially fire in case of overheating. Thus, to prevent accidents and optimize the vehicle's energy supply, the accumulator needs to be monitored and managed by a Battery Management System (BMS), a circuit capable of collecting and analyzing a series of data, such as temperature, voltage and current of the accumulator, besides estimating the state of charge (SOC) of each cell, entirely ceasing the energy supply in case of any abnormal reading of these parameters, thus increasing the vehicle's safety and preserving the pilot's life.

The first essential point to develop a battery management circuit is to understand the concepts regarding the operation and functioning of lithium-ion cells, such as the *Safe Operating Zones*, addressed in several works related to the subject, such as " [1], [2], [3], [5]. These zones refer to voltage and temperature ranges indicated by the manufacturer in which the cells can operate without risking their integrity and the safety of those who operate them since lithium-ion cells have the characteristic of being flammable when exposed to critical damage.

Another essential point to note in using Li-ion cells, whether in electric vehicles or any electronic device such as smartphones, is to perform a state-of-charge (SOC) determination of the cell set. By definition, the SOC represents the ratio between the current capacity and the nominal capacity of the cell and is given in percentage values.

By thoroughly analyzing several related bibliographies, it is possible to identify two main methods for determining the SOC, being the first, the simplest, called *Coulomb Counting* citeb3, [6], [7], which consists in the integration of the current that enters or leaves the battery in a specific time interval to estimate the SOC, which gives this method a low degree of complexity and an easy practical application. At the same time, it results in certain inaccuracies in the values. The second method, based on statistical methods, is the Kalman filter, which consists of a mathematically more complex method, but allows a more accurate estimation of the load.

Furthermore, for the development of a BMS circuit, the most diverse technologies can be implemented in order to provide a better fit to the project in which it will be used, taking into account factors such as available resources and ease of construction. Thus, this work was developed with the intention of presenting a hardware and software arrangement with a high degree of scalability in addition to meeting a series of requirements capable of ensuring the full operation and safety of the battery system of an electric vehicle while seeking to follow a financially viable model in the context of an academic project.

II. BMS SYSTEM OVERVIEW

A. Battery Model

Regarding energy storage systems for electric vehicles, the battery cells that employ lithium-ion technology have been gaining more and more space in the automotive market due mainly to their high energy density and speed in performing the charge and discharge cycles. Thus, to feed the traction system of the EV formula model SAE developed by the students of the Federal University of Paraíba, a set of 80 cells of the AMP-20 model from the manufacturer *A123 Systems* was used, each one presenting a nominal voltage of 3.3V.

In addition to the main features of lithium cells mentioned above, the AMP-20 model also stands out for its high safety due to its lithium-ion *nano-phosphat*technology, thus allowing the cell to be more tolerant to abuse during its charge and discharge cycles, reducing the risks of combustion and emission of harmful gases.

III. METHODOLOGY

The battery management system (BMS) proposed in this work was developed based on the operation patterns of commercial models following the methodology described by means of , seeking to conceive a software and hardware arrangement capable of allowing the real-time monitoring of the set of critical variables of a battery, such as voltage, state of charge (SOC) and temperature. In addition, from the collection of the aforementioned data, the BMS circuit implements the passive balancing processes and the charge and discharge control of the cells, like the equivalent models available in the market. To enable the monitoring of the individual voltages of the set of lithium-ion cells that make up the vehicle's accumulator, the BQ76PL455A-Q1 integrated circuit (IC) produced by *Texas Instruments* was used. The IC consists of a lithium battery cell monitor with passive cell balancing, which allows real-time monitoring of up to 16 cells simultaneously.

Some other functionalities, such as state-of-charge estimation (SOC) and control of the charging and discharging process, could be realized thanks to a Hall-effect current sensor connected to the microcontroller (MCU) that manages the system. The proposed hardware relies on the implementation of specific parts dedicated to performing the passive balancing process by discharging the cells in resistors, [1], [2], [3], [4], [5], [6], [7], [8], addition to specific pins for reading the temperature data collected by a set of thermistors and protection circuits.

In order to perform the data communication with the voltage monitoring IC, the TIVA EK-TM4C1294XL board from Texas Instruments was used as the central microcontroller or *host*. The software developed through the CodeComposer Studio interface describes the set of logical and configuration operations of the peripherals used during the BMS circuit operation process, allowing the system to monitor and intervene in the operation of the set of cells case they present fault conditions.

Finally, to enable the user to have access to the data collected by the central microcontroller (MCU), the proposed software establishes a communication protocol using a *Can BUS* interface, allowing, employing a simplified visual interface, the data to be transmitted in real-time to a computer and, later on, to the sensing system of the developed vehicle.

IV. HARDWARE DEVELOPMENT

The literature review found that for a BMS to monitor the cells efficiently, reducing the possibility of failures as much as possible, the hardware must implement several monitoring functions simultaneously. In this sense, after a comprehensive consultation in the market, it was chosen to use the

BQ76PL455A-Q1 [9] Integrated Circuit produced by *Texas Instruments*, mainly due to its vast monitoring capacity, allowing it, through its 14-bit analog-digital converter (ADC), to acquire and monitor voltage data from 6 to 16 cells simultaneously, sending these data to the MCU afterward.

Even being able to monitor a more significant number of cells compared to other IC's available in the market, for the application in the EV under development, it is necessary that the battery management system simultaneously monitors 80 lithium-ion cells. At this point, the choice of the BQ76PL455A-Q1 took into account its ability to compose a Daisy Chain network with up to 15 other circuits, allowing the formation of a decentralized BMS with a monitoring capacity of up to 256 cells simultaneously. To meet the project's requirements in question, five IC's were used, thus allowing the monitoring of the 80 cells that comprise the battery bank.

The process of forming the Daisy Chain network represented by Figure 1, is only possible since each of the IC's has two serial communication buses indicated by COMM (*high and low*) and FALT (*high and low*). The COMM bus transmits general communication data, such as read voltages and temperatures, over the network. The suffixes H and L refer respectively to the transmission of the data to the monitoring circuit located up or down the network. The FALT bus is responsible for transmitting, up to the host, indications of faults in any of the BQ circuits that make up the network.

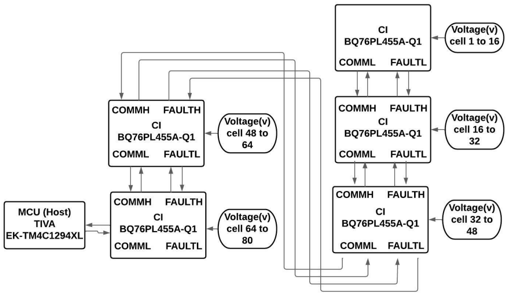

Fig. 1. Daisy Chain Network Operation Diagram.

The data collected by each IC will be sent to a single *host* located at the beginning of the network through serial communication. From this, the MCU will be able to make the decision based on the logical operations configured by the software, thus initiating the set of the main processes executed by a BMS, such as interrupting the charge or discharge process of the cells in under or over voltage conditions, initiating the balancing process, and sending the user the measured data and the occurrence of possible failures.

As highlighted, the cell balancing process stands out among the main functionalities of a BMS circuit. By definition, this process is necessary to ensure greater efficiency in feeding the EV since, in a battery, cells that present a greater degradation of their state of health (SOH) tend to charge or discharge faster than the others. Thus, to prevent the battery charging process from being interrupted after a single cell reaches its maximum voltage, the BMS must be able to balance this cell so that its voltage matches the others. Thus, by analyzing various works and literature related to the subject, it is possible to verify that the process of balancing cells is divided into two main types that differ according to their complexity of implementation, being these, the active balancing process that consists in discharging the excess energy of a cell that presents a voltage closer to the maximum in a cell that presents a lower voltage. The second model, implemented in this work, is called passive balancing. The excess energy of the cell with the highest voltage is dissipated in a discharge resistor until it presents a voltage equal to the others.

Although the IC allows the implementation of active balancing through additional IC's such as the EMB 1425-Q and EMB 1499-Q, the decision to use passive balancing is due to the ease of implementation of this method even though it wastes energy in the form of heat through the joule effect. Therefore, a MOSFET was used for the developed hardware to control the cell discharge into a 75 Ohms resistor from the signal sent by the *host*.

The hardware architecture of the BMS circuit in question was developed based on the application notes made available by the manufacturer to meet best the operating requirements of the BQ76PL455A-Q1, such as power supply, cell monitoring, sending and receiving data, among other important parameters.

The proposed hardware can be divided into five main working blocks, as shown in Figure 2.

1) Measurement of cell voltages;
2) Power supply of the BQ76PL455A-Q1;
3) Communication among multiple IC's;
4) Communication with the *host*;
5) Cell balancing;
6) Auxiliary pins.

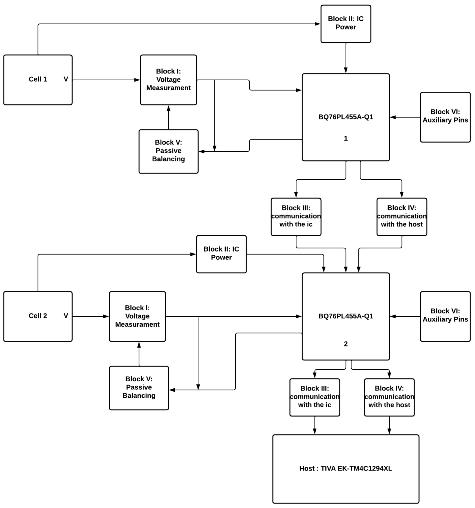

Fig. 2. Developed hardware block diagram.

By analyzing the schematic shown in Figure 2, it is possible to verify the general operation of the BMS hardware according to the specific functions performed in each of its seven blocks. Among the main functions of a lithium cell management circuit, the voltage monitoring block connects directly to the cell array via its VSENSE pin. Thus, to measure the voltage value of each cell, represented by the variable Vcx the IC uses the following relationship where Vsx represents the value read from the VsenseX pin:

$$Vc0 = Vs0 - Vgnd; \tag{1}$$

$$Vc1 = Vs1 - Vs0; \tag{2}$$

Thus, Equation1 represents the voltage cell 0 (Vc0) and Equation 2 represents the voltage cell 1 (Vc1).

The next block common to all BMS circuits is the balancing block. In this model, passive balancing will be performed depending on the voltage present on the VSENSE pins of Block I. Therefore, during the charging process, if any of the cells reaches a voltage much higher than the reference voltage of the rest of the cells, the IC will send a signal to the EQX pin, which in turn will be responsible for controlling a MOSFET transistor allowing the excess voltage to be dissipated in a discharge resistor as shown in Figure 3 presented below.

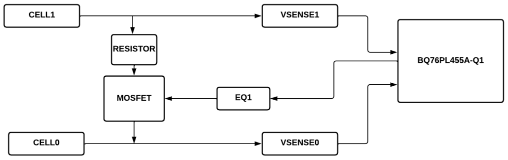

Fig. 3. Active balancing schematic.

V. SOFTWARE DEVELOPMENT

As discussed at the beginning of this work, for the integrated circuit to perform the set of functions to which it was designed, it must be controlled by an MCU or *Host*, responsible for sending data to the IC and transmitting the data collected by it to the user via serial communication. Thus, for the host to configure the integrated circuit according to the project's needs, it must follow a set of instructions established by the software.

The program developed through the IDE Codecomposer Studio was based on the TIVAWARE library made available by Texas Instruments, which is a tool to simplify the programming of the board peripherals without the need for direct operation with the registers. On the other hand, to develop the logical operations that govern the set of cells' management process, some of the main concepts of the C language such as repetition and conditioning structures were used.

A. Serial Communication Process

The proposed software's main functions include facilitating serial communication between the *host* and the integrated circuit, as well as between the *host* and the user. This involves using UART ports on the TIVA EK-TM4C1294XL board. Two UART ports were utilized, with one operating at a transmission rate of 250 kbps (from BQ to Host) and the other at 115.2 kbps (from Host to Desktop). Data transmission between the BQ and the host occurs through 8-bit transmission queues.

B. SOC Estimation

In addition to the serial communication process, the software was developed to perform the state-of-charge (SOC) estimation of the set of eighty cells from the Coulomb-counting method [3] [4] [6] [7], in which it consists of integrating the battery's charge or discharge current to determine its current capacity and then comparing it to its nominal capacity as presented in Eq.1.

To facilitate the development process of the SOC estimation algorithm and to have comparison parameters, the algorithm was developed for two different microcontrollers, being the first MCU, the Arduino with its C-based IDE, and the second, the TIVA EK-TM4C1294XL embedded board using the TIVAWARE library.

The design of the algorithm for determining the state of charge (SOC) consists of two main steps, the first is related to the acquisition of the current value measured through a DHAB S/24 Hall Effect sensor, and the second is related to the calculation of the battery state of charge at the current instant SOC(t). For this, it is first necessary to measure the current capacity of the battery Q(t) and then divide this value by the nominal capacity of the battery (Q_n), resulting in the value of the variation of SOC in that time interval Δ SOC(t).

Considering that the battery management system will be implemented in an EV, it must allow the user to access in real-time the data related to the estimation of the SOC of the set of cells, avoiding problems related to the vehicle's autonomy. This way, the SOC in a given instant of time (t), can be calculated through Equation 4, which relates the variation of the SOC in this same instant of time as described by Equation 1, with the value of the initial state of charge of the cell $SOC(t_0)$.

$$Q(t) = \int_{t0}^{t} I \, dt \tag{3}$$

Thus, the SOC at the instant of time (t) can be calculated through the Equation 4 defined by:

$$SOC(t) = SOC(t_0) + \left(\frac{\int_{t0}^{t} I \, dt}{Qn} \cdot 100\right) \tag{4}$$

To continue the constant charge estimation, the state of charge of the accumulator can be recalculated, now for the next time instant $(t + \tau)$ using the 4 again presenting a difference in the values that will be used since the $SOC(t_0)$ will now receive the value of the SOC(t) calculated for the previous time instant.

Thus, the SOC at time $(t + \tau)$ is defined in Equation 5 as :

$$SOC(t+\tau) = SOC(t) + (\frac{\int_t^{t+\tau} I\,dt}{Qn} \cdot 100) \qquad (5)$$

For the project in question:

- Initial state of charge $SOC(t_0) = 100\%$;
- Rated battery capacity Qn = 20 Ah.

C. Software Block Diagram

In order to simplify the comprehension process regarding its development, besides the set of logical operations based on the C language, the proposed software can be synthesized in two main blocks. The first block comprises the functions responsible for configuring and initializing the peripherals of the *host* needed in essential steps such as the serial communication process and the State of Charge (SOC) estimation. The second block, on the other hand, contains another set of functions used to configure the operation of the BQ76PL455A-Q1 integrated circuit according to the project's needs. The graphic representation of the block diagram is shown in Figure 4.

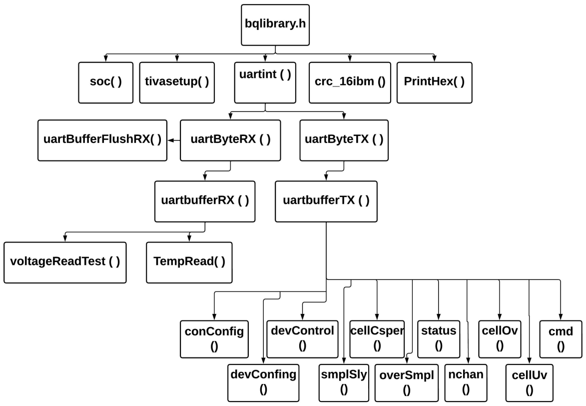

Fig. 4. Software block diagram.

As discussed previously, from the diagram analysis in Figure 4, it is possible to verify the set of functions in each of the two blocks. Thus, to facilitate the understanding of the proposed software, the main functions of each block are presented more succinctly below.

D. Definition of Functions

Among the many functions presented above, analyzing some of the main ones in each block is possible.

The first function to be analyzed is *tivasetup* which aims to configure and connect the peripherals of the*host* that will be used in the project, such as the two UART ports and the GPIO pins.

Given the importance of configuring the Uarts ports to establish serial communication, the function $uartInt()$ is implemented to configure the interrupts generated by the Uart port in receiving or sending data.

Finally, to set another crucial point in the serial communication process, the function $crc16ibm(*buf, len)$ returns the CRC16-IBM code of the len first bytes of the buffer vector.

From the second block, we highlight mainly the $conConfig()$ function responsible for configuring the BQ76PL455A-Q1's serial communication bus, setting parameters such as the *baudrate* of the Uart used to communicate with the BQ, enabling the COM(High and Low) and Fault(High and Low) buses. Besides this, the $cmd()$ function is used to request the IC to send the measured analog data to *host*.

For general purpose chip settings, the function $devConfig()$ sends a type command to the device with identifier id addressed to the DEVCONFIG register of the BQ76PL455A-Q1. Thus, this function is able to configure some of the main points related to the operation of the BQ chip, such as enabling the voltage regulator for the VP and VIDG power supply pin, among other points.

The $devControl()$ function controls some of the chip functionalities related to operation mode, such as ordering the chip to go into ShutDown mode in order to reduce power consumption, reset the memory, store the chip identifier, among other points.

Regarding the point of view of safety parameters related to voltage, temperature limits and more general faults linked to the process of stabilizing serial communication, either between multiple BQ's or between a chip and the host, the $faultSum()$ function is implemented to reset all the faults that the device may identify during its operation.

VI. RESULTS

In order to verify the functionality of the proposed hardware, a series of tests were performed using a set of eight cells integrated into a test bench, developed to ensure the and simulate the operation of the electrical system of the FSAE model vehicle.

A photograph of the developed test bench is shown in Figure 5.

Fig. 5. Validation Test bench.

As discussed earlier, the test bench was developed to simulate the shutdown circuitry with a primary focus on the circuits that directly interfere with the operation of the accumulator. In this sense, the test bench implements safety components such as normally open type relays, and protection fuses, thus ensuring that, in case of failure, the high voltage present in the set of eight cells, is contained within the bench.

Thus, using the software and hardware developed, it was possible to perform measurements of voltage, current, and temperature of the cells, comparing the results obtained with those expected to validate the system. Next are presented some results obtained for each type of magnitude.

A. Voltage Measurement

The first step in verifying the functionality of the voltage monitoring was to compare the values collected from the $V senses$ pins with the actual values. Thus, it can be seen in Figure 6 that, although the first three values show some discrepancy with the voltage data measured using a multimeter, the rest of the values fall within a range of expected values considering the cells charged with a nominal voltage of 3.3v.

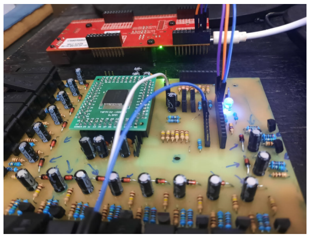

Fig. 6. Prototype board connected to the MCU.

TABLE I
MEASURED CELL VOLTAGE

Cell Number	Voltage (V)
Cell 1	0.572
Cell 2	2.923
Cell 3	3.736
Cell 4	3.340
Cell 5	3.338
Cell 6	3.338
Cell 7	3.414
Cell 8	3.216

B. SOC Estimation

To validate the SOC estimation tests, we used a cell with a voltage of 3.3 v discharging into a resistive load of approximately 0.3 Ohms generating an average discharge current of 7.48A, measured through the Hall effect sensor model DHABS/24, connected to the Tiva board during a time interval of 15 minutes. Although nominally the expected current was about 11 Amperes, due to the excessive temperature rise of the resistive load (100W resistor) suddenly during the start of the discharge tests, by Joule effect its internal resistance also gradually increased, causing the average discharge current to drop from 11 A to about 7.5 amperes while the cell was kept connected to the cell. It was evidenced that after disconnecting the cell, the temperature of the resistive load decreased, causing its internal resistance to return to the nominal value of 0.3 Ohms.

It is worth noting that, although the the test was performed in a simplified way without direct application of the main software, in its final version it was implemented the control In its final version, the control of the maximum and minimum load thresholds the main program that delimits the working range of the working range of the cells.

Using the Putty software, it is possible to send the current measured value in real time to the serial monitor, allowing the user to directly analyze the obtained data. Thus, over the 15 minutes allotted for the test, the load state of the cell can be compared with the theoretical value calculated from 4.

It is possible to check the behavior of the load state from Figure7.

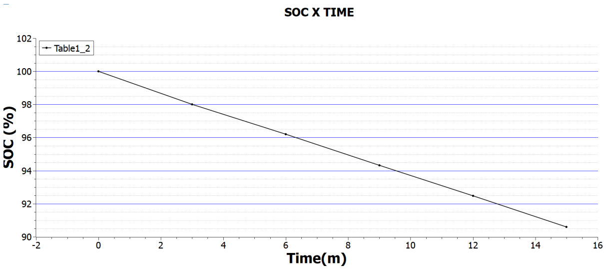

Fig. 7. SOC Variation Graph by Time.

The theoretical calculation of the load estimation can be performed by:

$$SOC(t) = 100 + \frac{(-7.48) \cdot (0.25)}{20} \cdot 100 \tag{6}$$

$$SOC(t) = 90.65\% \tag{7}$$

In order to verify the relationship between the SOC value and the voltage measured at the cell terminals, the data collected during the test was grouped together in the form of a spreadsheet. From this, it was possible to plot a graph adjusted to better detail the behavior of the voltage (V) and SOC(%) decay over the fifteen minutes established for the discharge test.

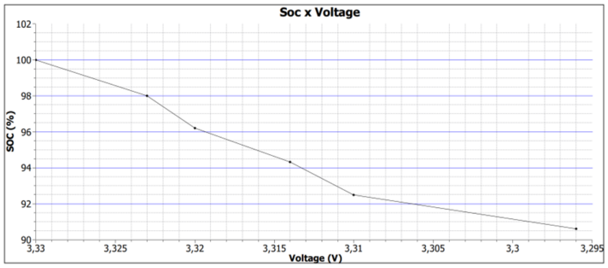

Fig. 8. SOC and voltage decay graph.

As cited in several related bibliographies, the accurate, current measurement is the main factor in ensuring more excellent reliability in a SOC estimation algorithm employing Coloumb Counting. Thus, to validate the reliability of the proposed algorithm, the value of the current measured from the Hall Effect current sensor can be compared to the value obtained by using a Minipa ET-3367C precision clamp meter capable of measuring DC currents.

C. Temperature Measurement

Last but not least, an efficient battery management system must be able to monitor the temperature of a significant portion of the batteries since, as these cells use lithium-ion chemistry, temperature variation directly affects their performance and lifetime, reducing their energy efficiency over charge cycles and charge-discharge cycles, directly affecting the battery's state of health (SOH). In addition, increasing the temperature to values outside the safety range recommended by the manufacturer can cause an increase in the internal pressure of the cells, causing an imminent risk of harmful gas leakage or even explosions if the battery is exposed to higher temperatures. In order to avoid operating the cell in critical temperature ranges, the MF52 103 NTC temperature sensor was implemented, validated in a temperature monitoring test performed in conjunction with the cell discharge test.

Using the thermistor during the discharge tests, an average value for the temperature of 24.40 ºC was obtained and validated using a reference infrared thermometer *VONDER TIV6500* to regress the actual value, thus ensuring that the values obtained through the sensor coincide with those indicated by the infrared thermometer.

VII. CONCLUSION AND FUTURE WORK

This work presented an alternative battery management system (BMS) based on the implementation of the BQ76PL455A-Q1 reference lithium cell management integrated circuit. As the BMS is an essential circuit for the safe operation of an electric vehicle model FSAE, developed by the Formula E-motion team from the Federal University of Paraíba, the use of a battery management system that allows a high degree of adaptability due to its ability to form a Daysi-Chain network with multiple circuits, in parallel the ease of maintenance and low production cost when compared to commercial models are some of the main positive points attributed to the proposed model. Moreover, unlike other models available in the market, the BMS circuit proposed in this work presents the differential of being more compact and consequently being more easily allocated inside the EV accumulator.

Moreover, for the set of initial tests performed in the laboratory environment, the prototype presented satisfactory results, since the measurement of essential data, such as the discharge current used in the SOC estimation process and the temperature of the Li-ion cell, presented results consistent with those obtained through the use of measurement devices such as an ammeter clamp and an infrared thermometer. Although some data obtained during the voltage measurement process present some discrepancy with the real values, it can be verified that the others are satisfactory, considering that the hardware is in the prototyping phase.

Finally, considering the future stages of the project, it is intended to continue with the development of the project, integrating the current and temperature measurement functions to the leading software of the *host*, as well as creating a visual interface for the data. From the hardware point of view, the project aims for a final version built with surface mount components (SMD), making it easier to install in the vehicle and reducing the possibility of errors during the data acquisition process. Additionally, the goal is to validate the passive balancing during the loading and unloading process of the cells, followed by the implementation of the model in the vehicle and the verification of its behavior in adverse conditions that may arise during the operation of the car.

VIII. ACKNOWLEDGMENTS

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