



Development of a Battery Management System for Electric Vehicle's Batteries Reuse

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Abstract. Electric Vehicles (EV) or Plug-in Electric Vehicles (PHEV) batteries can have a second life in other vehicles, in stationary electrical energy storage systems, or in academic or research projects. For this purpose, it is necessary to control and access the battery data through a Battery Management System (BMS), which is often not available in open source, therefore, it is necessary to install and/or develop a new BMS. This article discusses BMS and its features that aim to improve the performance of electric vehicles, optimizing battery capacity during charging and discharging, ensuring the safety and lifetime of a traction battery, promoting sustainable mobility. The process of developing, building, and testing a BMS is presented in this work. It should also be noted that the developed BMS is software configurable, so it can be used with other batteries of the same technology. The battery model under study and the reason to produce a new BMS are briefly reported, as well as the choice of MAX17852, as the data-acquisition Integrated Circuit (IC) used to monitor the battery cells. This work describes the steps taken during the design of all BMS components, including the Printed Circuit Boards (PCBs) design and assembly process, as well as functional tests. It is also addressed the used communication protocols between the BMS elements/components.

Keywords: BMS · Battery Management System Development · Electric Vehicles · PHEV · Traction Battery · Battery Second Life

1 Introduction

Electric energy plays a fundamental role in industrial development, urbanization, and economic advancement, as well as in the quality of life of every human being. Across Europe, countries have been affected by the Covid-19 crisis and the economic recovery plan for these countries emphasizes sustainable mobility, energy efficiency, decarbonization, and the bioeconomy. The transition to clean energy should be highlighted, especially in the integration of electricity from renewable sources [1]. EVs are at the core of the sustainable mobility strategy. Sustainability can be achieved when the energy consumed for the production and operation of EVs is generated by renewable energy sources.

EVs will reduce the environmental impact by being built with long-lasting rechargeable batteries [1] and are much more energy efficient than ICE (internal combustion engine) vehicles. In fact, electric motors benefit from a very high energy efficiency, between 90–95%, when compared to combustion engines, between 20–35%. Electric vehicles do not burn fossil fuels, therefore, EVs motors do not produce direct emissions of pollutant particles or gaseous during their operation [2, 3].

However, with the emergence of electric vehicles, the demand for electricity increases, which can cause imbalances between the energy produced and the energy consumed. Energy must be managed to ensure maximum efficiency from the point of generation to the wheel. Consequently, electric vehicles and all constituent technologies are constantly evolving. Special care must be taken in relation to batteries. Monitoring and proper control of the traction battery is essential in EVs. BMS systems are developed with the aim of protecting and manage batteries parameters' state, as well as their performance. This is responsible for ensuring normal operating conditions, to prolong their useful life and enhance their charge and discharge. These systems are developed with a series of functions, supervising batteries charging and discharging (voltage operation limits, maximum current, and operation temperature), performing cell equalization, analyzing the State of Health (SoH) and the State of Charge (SoC), among other parameters.

There are several battery technologies on the market. However, lithium-ion batteries are currently by far the most used in electric vehicles, due to their notable advantages and significant performance improvements, namely, relatively high energy density and long-life cycles with 80% deep discharge [4].

The development of a BMS presented in this work was motivated by the possibility of reusing HEV (Hybrid Electric Vehicle) and PHEV batteries in second life, and could also be applied in larger capacity batteries, in EVs. In fact, in ISEC electromechanical drives laboratory there are several HEV and PHEV batteries, supplied by PRIO.e company (owner of fuel and EV charging stations), under a collaboration protocol. In particular, the presented case uses a lithium Iron Phosphate battery, LiFePO_4 , composed of 40 cells, obtained from a Mercedes-Benz PHEV. This battery model was applied to the 350e and 500e ranges. The goal is to use this battery in academic or research applied projects, for the VEIL platform. VEIL is a small EV developed at ISEC targeted for research and teaching. It consisted of a conversion of a small diesel ICE vehicle to EV. It is a LIGIER 162 GL, that weighs about 350 kg, currently equipped with a 400V, 50 Hz, 4 kW, 2860 rpm electric induction motor [5, 6].

With this objective, it was necessary to develop a BMS, starting with the study of which type of BMS to use. Initially, the components and layout of the BMS PCB were addressed, with the objective of creating small size boards, which is a very meticulous process. These PCBs are composed of two layers, and care was taken to separate the power components from the command and communication components to avoid noise or interference.

After this introductory section, this article is organized as follows: Sect. 2 addresses batteries for EVs, namely the battery that is being used in this project and for which the BMS was developed. Section 3 presents battery management systems, what they are for, and what their functions are, highlighting the type of structure used and the

reason why it was chosen. In Sect. 4, the processes that the project went through are discussed, describing each stage and the essential elements for the functioning of the BMS, the communication protocols that are used in the project are identified, where they intervene and what is the purpose of each protocol. Section 5 presents the results of some of the tests developed and, finally, Sect. 6 ends this work with conclusions.

2 Batteries for EVs

In EVs, rechargeable batteries (also called secondary) are used exclusively. A traction battery normally is made of several modules, each consisting of cell sets, which can be combined in series and/or parallel, in order to obtain the desired voltage, current and capacity [7].

For the project described in this work, a LiFePO_4 battery was used due to its availability and state of conservation. Lithium-ion batteries have established themselves as the reference technology in the world market for electric vehicles. These batteries are designed as a set of individual cells, which linked together form a battery, being monitored by a dedicated electronic circuit. The number of cells, the size of each cell and the way they are arranged determine the voltage supplied by the battery and its capacity, that is, the amount of electric energy that can be stored [8].

The main reason for the large-scale success of lithium-ion batteries is essentially the storage density that the technology allows. This concept of density refers to the relationship between storage capacity and volume or weight. These values can be compared, with a lithium-ion battery offering a density about ten times more than a lead-acid battery.

In Fig. 1 it is possible to visualize the battery used in this project, composed of 40 prismatic cells (2 strings of 20 cells in series). Usually, in this type of cells, aluminum or steel is used as casing material of the lithium-ion cells, guaranteeing structural stability, mechanical strength, and protection against moisture. Prismatic cells allow the space packed to be more efficiently packed than with cylindrical cells due to their shape. The use of prismatic cells allows constraining and retaining cells within their structure, with potentially higher energy density, but requires a complex module structure. The large surface area becomes beneficial due to thermal management. It is currently the most used cell format in electric vehicles [9, 10].

The thermal stability that lithium-ion batteries offer (depending on the used chemistry) must be considered to guaranty the needed safety. They enable fast charging, as well as reducing the use of raw materials, synthetic processes, and the use of low toxicity materials. These batteries also have functional issues, for example, they cannot be fully discharged because the battery can be irreversibly damaged, in case of cells' unbalance; therefore, it is common to have a protection circuit connected to the battery to keep the voltage and current within the limits established by the manufacturer. The charge of these batteries must be monitored, as they are not very tolerant to overloads or over-discharges. LiFePO_4 batteries, as mentioned in Table 1, are an interesting option within the lithium-ion batteries. They offer good electrochemical performance with low resistance, high rated current, good thermal stability, long life cycles and increased safety [3, 7]. These batteries present some self-discharge rate, which can cause imbalances with



Fig. 1. LiFePO4 battery, used in the project

aging, requiring more attention and the use of more effective monitoring systems. This battery is not tolerant to humidity, drastically reducing its longevity [8, 10].

Table 1. Main characteristics of the used battery

Specifications	Lithium-Iron Phosphate Battery (LiFePO ₄)
Energy (kWh)	2.9 kWh
Min/Max Cell voltage (V)	2 V/3.65 V
Nominal module voltage (V)	2x66 V
Current (Ah)	22,8 Ah
Number Cells in Series	2x20S
Anode / Cathode	Graphite / LiFePO ₄

3 Battery Management System

The EV's battery operating voltage is variable, and the battery capacity depends on the system power and autonomy. To obtain the voltage and power required for the vehicle, it is necessary to apply cells interconnected in series and/or parallel, and there may be a voltage imbalance between them, causing a decrease in the capacity and in the useful life of the vehicle. Battery [3, 11].

The battery operation management is carried out by the BMS, which monitor and control the cells status of the battery or a batteries bank. Its main objectives are to protect the cells and the battery against damage, extend the life of the batteries, keep the battery in a working state in order to supply the requested requirements and communicate with

a higher-level system, usually the Vehicle Control Unit (VCU). For that, the BMS is an electronic system that controls the performance of individual cells, with the aim of avoiding: overcharges, excessively deep discharges, exceeding the maximum and minimum limits of cell voltages, high temperatures, and short circuits. When one of these previously discussed limits falls within outside the programmed parameters range, the battery must be removed from operation, preventing the occurrence of accidents or even failures with greater damage.

In terms of the physical structure of the BMS, these depend on the number of cells used and the requirements of the system. BMS architectures can be classified as Centralized (each cell is connected to one unique central system), Modular (BMS is divided into multiple modules), Master-Slave (similar to modular architecture but the data processing is done in additional master module) and Distributed (each cell has its own data acquisition board). The main differences of this architectures can be verified at [12].

4 BMS Development Case Study

The battery being used for this study already contained a proprietary BMS but there was no access to its operation protocol, so it was necessary to install a new BMS. Initially, the market was researched for which BMS could satisfy the case study. Commercial BMS were not chosen because many of them do not offer an open-source solution neither allow access to all the intended parameters. Thus, it was decided to use a dedicated data acquisition system integrated circuit and create the entire BMS structure from scratch.

During this search, the integrated circuits that stood out for the proposed needs are listed in Table 2, presenting their main characteristics.

Table 2. Data acquisition ICs analyzed for the BMS project

Integrated	BQ76952	Max17852	LTC6813
N° Cells	16	14	18
HV Tolerance	85 V	80 V	75 V
Balancing up to	100 mA	650 mA	200 mA
cell accuracy worst case	± 5 mV	± 4.5 mV	± 4.2 mV

The Max17852 was chosen, mainly for its greater balancing capacity and for verifying that Maxim Integrated has a development Kit, the Max17852 EV Kit, which allows to demonstrate the resources and capabilities of the Max17852. This EV kit, through jumpers and switches, makes possible to carry out some configurations according to the user's needs. In this way, the Max17852 EV Kit served as a starting point for the PCB board design around the analog front end IC.

The Master-Slave model was chosen, due to its characteristics. As shown below in Fig. 2 it is possible to verify how this typology is structured.

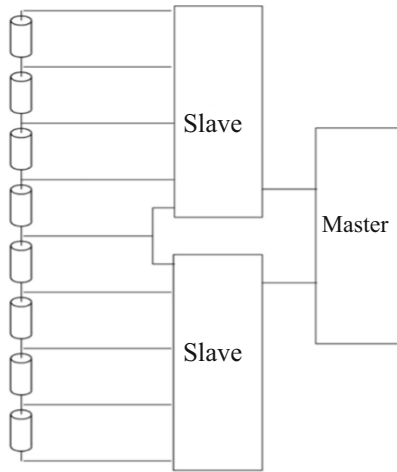


Fig. 2. Example of BMS typology with Master-Slave structure [13].

In the Master-Slave structure, there are two different types of BMS modules, Master and Slave. The Master-Slave structure is similar to a modular system; it uses several identical modules (slaves), in the developed system each module measures the voltage of 10 cells. However, the master is different from the modules and does not measure voltages, it only handles computing and communications. This structure is recommended for applications with a high number of cells; in the case of the Max17852, up to 32 devices can be daisy-chained to manage 448 cells and monitor 128 temperatures. This structure is ideal for situations where it is predictable or desired to increase the number of cells (or modules). Although it is the model that has the highest implementation cost, it is the one that makes it easier to expand the number of cells [11].

In a first analysis, the crucial aspects for the functioning of the BMS were verified, such as the Universal Asynchronous Receiver Transmitter (UART) communication mode. For robust communications, the system uses Maxim's battery-management UART protocol, is optimized to support a reduced feature set of internal diagnostics and rapid-alert communication through both embedded communication and hardware-alert interfaces to support ASIL-D and FMEA requirements.

These can be the Battery-Management UART Protocol or SPI, Fig. 3, depending on the hardware configurations, but they cannot be dynamically changed: the UARTSEL pin allows the configuration of this interface.

In order to maximize the integrity of communications, the battery-management UART protocol uses several features: all transmitted data bytes are Manchester-encoded, (G.E. Thomas convention), every transmitted character contains 12 bits, which include a start bit, a parity bit, and two stop bits, read/write packets contain a CRC-8 Packet-Error Checking (PEC) byte, each packet is framed by a preamble character and stop character and read packets contains a data-check byte for verifying the integrity of the transmission [14].

In this project the Single UART Interface with External Loopback is used and it is possible to check all the settings for the UART interface at [14] pp. 58. This UART protocol allows capacitive communication-port isolation, up to 2 Mbps baud rate (auto-detect) and Packet-Error Checking (PEC).

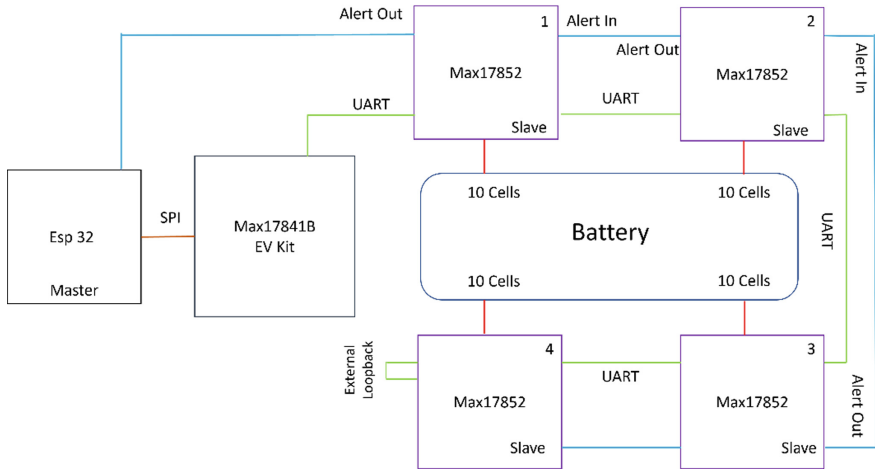


Fig. 3. Developed BMS block diagram.

The UART receiver has a wide common-mode input range to tolerate harsh EMC (Electromagnetic compatibility) ([14] pp. 132). MAX17852 is a high voltage data acquisition system, Automotive Safety Integrity Level D (ASIL D), with 14 voltage measuring channels and integrated current sensing amplifier.

Having defined the BMS structure, the schematic was developed, as can be seen in Fig. 4. To develop the PCB boards schematic and layout, based on the Max17852 EV Kit, the Autodesk Eagle software [15] was used.

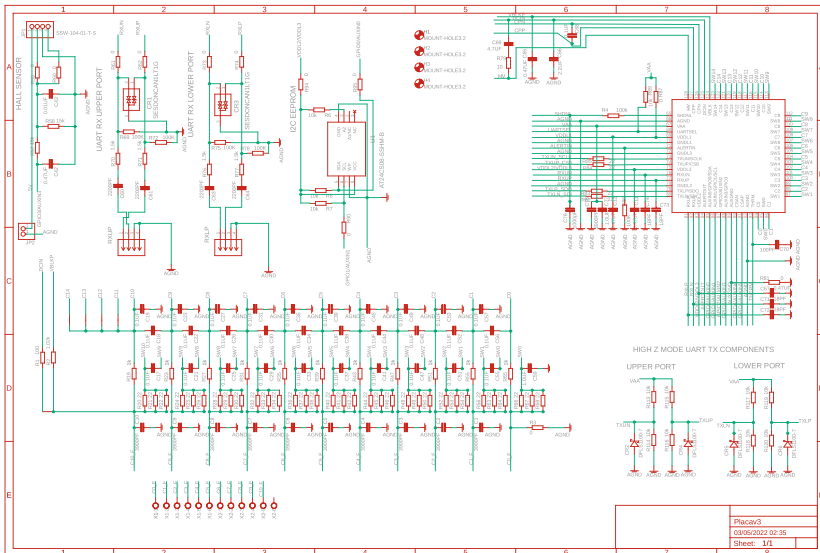


Fig. 4. PCB schematic.

During the construction of the board layout, several aspects must be considered. For example, the proper component packages footprint, and the current intensity that flows through the components, adjusting tracks width accordingly [15]. It is necessary to consider the components position, as the distance can affect the system accuracy.

The next step in the process was to place the components in the PCB desired location. As stated above, the power interface section was separated from the communication section. The Max17852 was placed in the bottom layer together with the battery pack interface, as shown in Fig. 5.

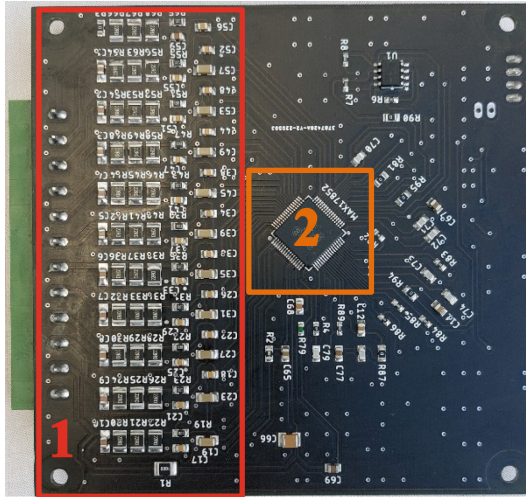


Fig. 5. Bottom Layer PCB: 1-Battery Pack Interface, 2-Max17852IC.

The Bottom layer contains the battery pack interface that includes as main components the battery connection plug and the balancing resistors mounted in sets of three 22 Ω (1210 package) resistors assembled in parallel. When balancing a cell, two of these sets are used, performing passive balancing. The hardware structure used for balancing is detailed at ([14] pp. 202).

In the top layer, the UART Upper Port (UP), UART Lower Port (LP), auxiliary ports and the in and out alarms are placed as identified in Fig. 6.

The top layer contains the components for the following functionalities:

- The auxiliary pins (Aux Input and Aux Output) provide direct interfaces for the temperature NTC probes. This is accomplished by 10 k Ω NTC sensors connected to the THRM pin, each PCB board allows connection of 3 probes.
- The CSAP and CSAN [14] MAX17852 inputs are connected to the Auxin 4 and Auxin 5 pins that allow to accurately measure the differential voltage of a shunt resistor, enabling to measure the battery current.
- Alert Out and Alert In perform alerts through fault condition. It communicates critical safety failures, whether these are: voltage measurements, temperature measurements, interface communication failures, calibration, and other hardware diagnostics [14].

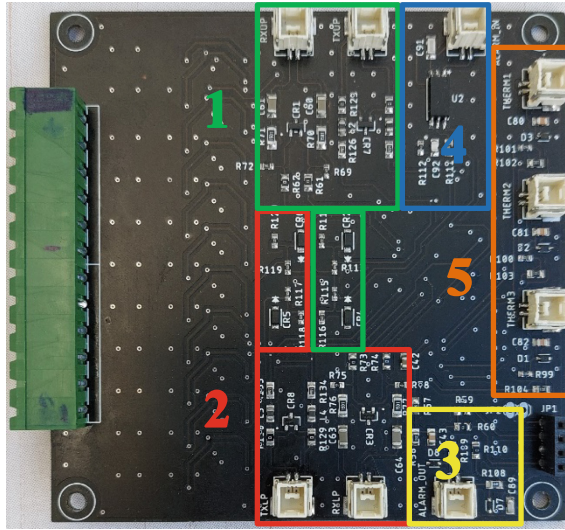


Fig. 6. Top Layer PCB: 1-UART UP, 2-UART LP, 3-Alert Out LP, 4-Alert In UP, 5-Aux Input, Aux Output, Current Sensor Amplifier interface (CSA, at JPI- right bottom).

- The UART LP and UART UP communication ports are identified as the upper port (RXUP/TXUP) and the lower port (RXLP/TXLP), referring to the MAX17852 device on the PCB. Each UART port includes a differential transmitter and a differential receiver. Communication data received at the lower receiver (RXL) is relayed via the upper transmitter (TXU) to the next PCB board, daisy-chained. Communication received at the upper receiver (RXU) is relayed through the lower transmitter (TXL) and down the chain.

Once the layout of the PCB boards was finished, their external production was requested. While the boards were being produced, the necessary components were requested to carry out the assembly. Each board is composed of 202 components.

The association of the PCB boards aimed to manage the 40 cells of the LiFePO₄ battery. For this purpose, 4 PCB boards were developed, therefore each board allows monitoring 10 cells. In the future, a PCB will be developed to support the ESP32 microcontroller, which will include the Max17841B, to remove the Max17841 EV-KIT used only for development. In Fig. 7, it is possible to visualize the assembly of the 4 boards, after components soldering, through hot air, at ISEC laboratory.

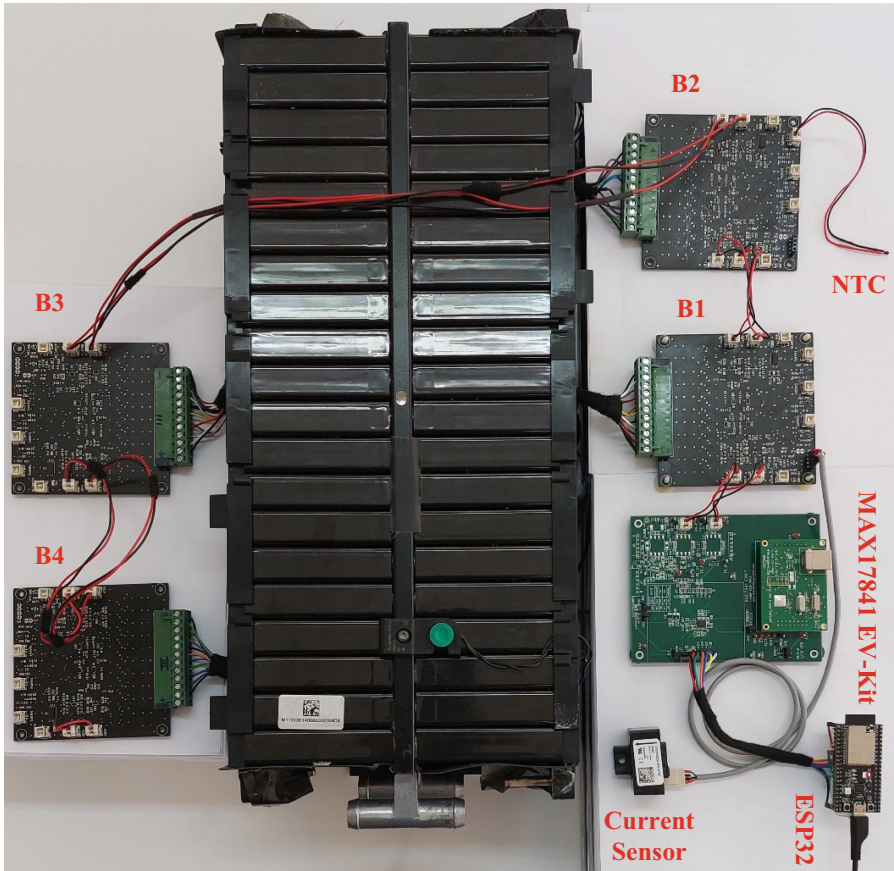


Fig. 7. - Four BMS PCBs mounted on a first battery test.

In Fig. 8 the fundamental process phases for carrying out the project are described, and it is currently in the experimental testing phase.

As mentioned above, there are many aspects to consider when designing a printed circuit board. The length and width of the tracks are important when the layout is made, considering the applied voltage and current. Tracks can be on inner or outer layers, but in this case, there are only tracks on the outer layers. The fact that there are only tracks in the outer layers allows them to have smaller widths than in the inner layers, due to heat dissipation. In Battery pack interface area (Fig. 5), a current of approximately 1A was considered (balancing currents will be less than 350 mA), hence for balancing was selected a track width of 0.508 mm, and in the remaining board, for control/communications it was considered 0.254 mm. All calculations were performed to have a track temperature raise below 5°C at a room temperature of 25 °C. The PCB board size is 99x97x1.6 (mm). An online tool can be of great importance to quickly evaluate the proper track width to use regarding the temperature rise and layer thickness [16].

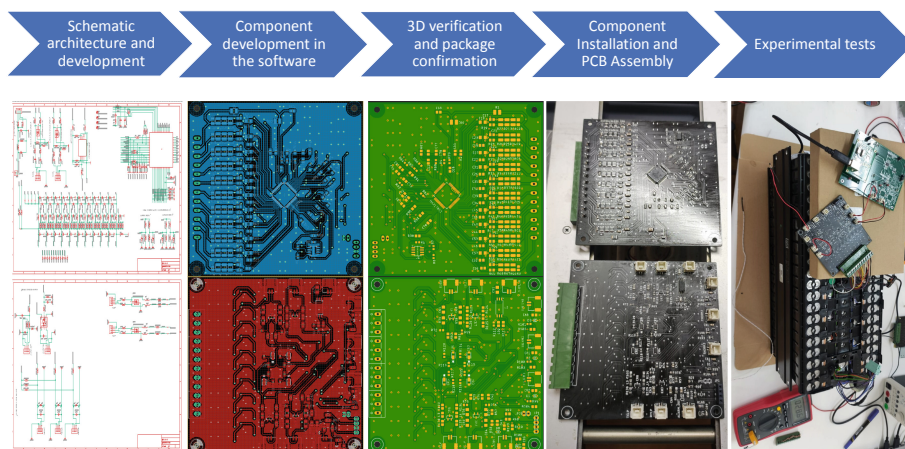


Fig. 8. Processes developed during the project.

After all the PCBs were connected in series, they must be connected to the EV VCU. To manage the BMS connection to the EV, an ESP32 microcontroller can be used to implement an open-source interface protocol. One advantage of this microcontroller is that it offers Bluetooth and Wi-Fi connectivity. This enables, for example, to create an Android BMS management APP.

Max17852 IC boards use the battery-management UART Protocol to interconnect, so the ESP32 must use Max17841B through SPI as a transceiver to the UART interface. It is also possible for the daisy-chained BMS boards to be connected through a MAX17841B EV KIT [18] with a Windows PC application, for example, using the Max17853 Evaluation Kit Software [17].

For greater security, the MAX17852 UART has Manchester encryption, and it was decided to purchase the MAX17841B EV KIT [18] for the decoding interface to the ESP microcontroller [14]. The chosen Max17852 allows two types of communication protocols to control the data acquisition. These can be the UART protocol or SPI, depending on the hardware configurations, but they cannot be dynamically changed: the UARTSEL pin ([14] pp. 176) allows the configuration of this interface.

5 Trials and Tests

Initially, to be able to carry out all the tests safely, mainly to confirm the normal functioning of the BMS boards after assembly, the tests were carried out without a battery. In this case, ten 2 k Ω resistors were installed in series, creating a voltage divider, to replace a battery, with the use of a power supply. To apply the equivalent voltages, resistors were installed between cells C0 to C10 inputs terminals, which in turn allow the voltage measurement reading of Max17852 [14]. Communications and cell reading essays were performed. Initially, the readings obtained were made using the Max17853 Evolution Kit software [17]–[19]. Figure 9 shows tests being carried out in real-time, obtaining

the voltage values of the 40 cells. Aux In 2 (AIN2 Fig. 9) shows the temperature value of four NTC sensors (one for each board). The temperature is scaled in volts. It is also possible to verify the group total voltage value of each board.

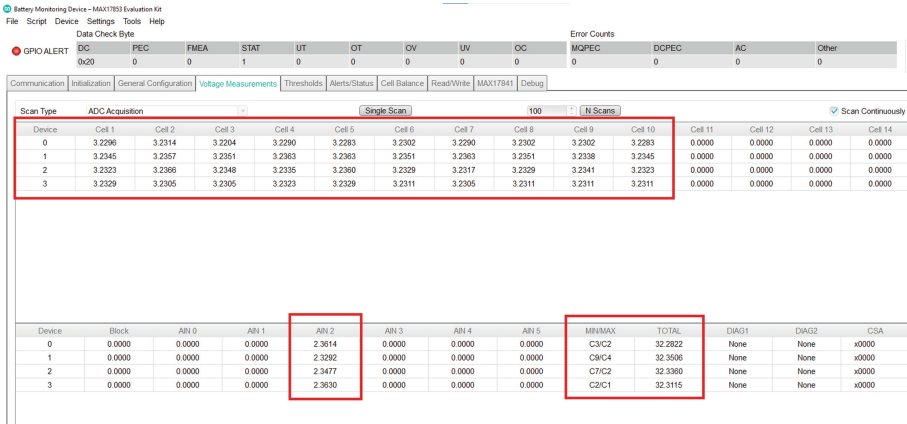




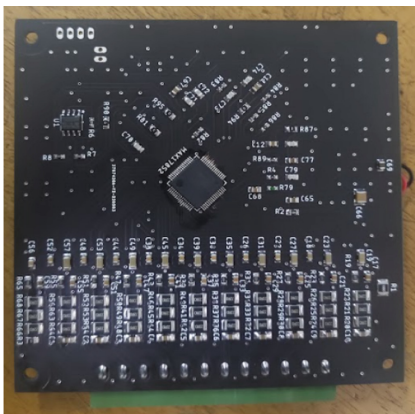
Fig. 9. Real-time reading of 10 battery cells through the Max17853 EV Kit software [14].

With tests evolution, the acquisition of cell values, temperature values and low and high voltage alarms were tested. Next, ESP-32 was used with C programming, also reading the parameters discussed above, and the balancing strategy techniques are being evaluated. Table 3 shows voltage and temperature values obtained after reading the 40 cells, using the setup presented in Fig. 7, being possible to verify through the photos at the bottom of the table the confirmation of the values using a high accuracy voltage meter from BK Precision (around 1 mV difference).

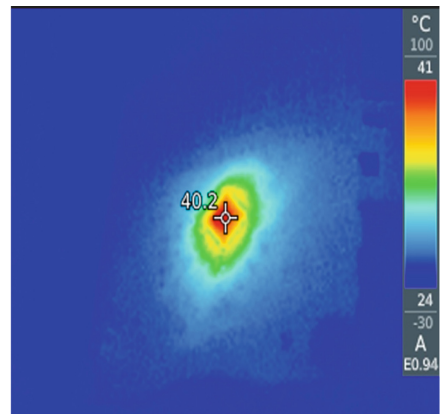
During the tests carried out, it was possible to analyze the behavior of the IC board in relation to possible hot spots. This test makes it possible to analyze if any component is overheating as hot spots may occur, for example, due to a bad soldering or a damaged component. After several hours of operation, the device temperature remained within the same values. In Fig. 10 it is possible to verify, through a photograph taken by a thermographic camera, the place where the temperature is highest, which in this case is where the Max17852 is placed, but well within the values recommended by the manufacturer [14].

Table 3. Data acquisition test on a serial monitor application.

DEVICE: 1 Cell 1: 3.224V Cell 2: 3.224V Cell 3: 3.226V Cell 4: 3.225V Cell 5: 3.228V Cell 6: 3.225V Cell 7: 3.227V Cell 8: 3.225V Cell 9: 3.226V Cell 10: 3.221V Min / Max Cell Voltages: C10 / C5 Block Voltage: 32.282V Temperature Cell: 24.772°C	DEVICE: 2 Cell 1: 3.227V Cell 2: 3.231V Cell 3: 3.230V Cell 4: 3.229V Cell 5: 3.231V Cell 6: 3.230V Cell 7: 3.229V Cell 8: 3.229V Cell 9: 3.229V Cell 10: 3.226V Min / Max Cell Voltages: C10 / C2 Block Voltage: 32.314V Temperature Cell: 24.534°C	DEVICE: 3 Cell 1: 3.228V Cell 2: 3.230V Cell 3: 3.229V Cell 4: 3.229V Cell 5: 3.230V Cell 6: 3.228V Cell 7: 3.228V Cell 8: 3.230V Cell 9: 3.229V Cell 10: 3.226V Min / Max Cell Voltages: C10 / C5 Block Voltage: 32.321V Temperature Cell: 24.813°C	DEVICE: 4 Cell 1: 3.224V Cell 2: 3.226V Cell 3: 3.213V Cell 4: 3.224V Cell 5: 3.225V Cell 6: 3.225V Cell 7: 3.225V Cell 8: 3.225V Cell 9: 3.226V Cell 10: 3.223V Min / Max Cell Voltages: C3 / C2 Block Voltage: 32.258V Temperature Cell: 24.402°C		
		Device 1 Cell 1			Device 1 Cell 2



a)



b)

Fig. 10. a) Board assembly, b) Thermography performed on the IC board.

6 Conclusion

In this article the development of a BMS for a LiFePO₄ battery was presented. The Data Acquisition System IC, MAX17852, is showing to be a good option for the battery reuse requirement. The developed PCB board includes all the control and monitoring configurations necessary for this battery technology.

This developed BMS is intended to be part of an Open-Source system and to allow working with other batteries of the same typology. The balancing system is currently being studied and carried out to integrate with the remaining experimental tests. The system can also be used to develop algorithms for SoC, SoH and other academic and research projects.

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