University of Padua

Department of Information engineering

Electronic Engineering

Master Thesis

48V battery testing and analysis for TLC applications

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Abstract

The purpose of this master thesis, in collaboration with Fiamm Energy Technology Spa, is to analyze and evaluate different 48V Lithium-ion batteries for telecom applications. Due to non-disclosure agreements between Fiamm and the different suppliers, the names of these producers cannot be shared so, in order to identify them, a number was assigned. In order to detect the best battery, the internal design and the electrical performances of each one were analyzed. For time constrains, only three batteries have been analyzed in details during the internship thesis.

In the first part of the document the purpose of the project from the company point of view and a description of the lithium-ion battery technology are explained. After that, there is a description of the instruments utilized and an explanation of the various tests performed.

The second part describes the teardown of three batteries and the results of the electrical tests.

After that, a comparison between the different batteries was performed from design, electrical performances and software point of view, in order to determine the best one. The design comparison is based on the main design features of the batteries like the components of the BMS, the cable management and the cells arrangement. Instead, the electrical performances comparison takes into account the most critical characteristics like the capacity discharged, the maximum charge/discharge rate and the safety functions of the BMS.

The comparisons mentioned above are based on the three batteries deeply analysed in this thesis and on others five analysed by Fiamm project team. Nowadays, supplier n.8 appears to be the best one.

Fiamm has planned to evaluate other two batteries within the next months so the partial result obtained in this thesis could be different from the final one.

Contents

Chapter 1

Introduction

1.1 Company Illustration

FIAMM Energy Technology is a multinational company that works in the production and distribution of accumulators and batteries for mobility and industrial application. It has more than 1000 employees and various production offices all over the world.

Figure 1.1: FIAMM headquarters

The company was founded in 1942, with the name of Fiamm that stands for *Fabbrica Italiana Motocarri Montecchio* and the first production focuses on electric traction and automotive starting batteries.
From the beginning, the company has played an important role in the battery industry, indeed a Fiamm battery was mounted in a Ferrari car for a famous race, the Mille Miglia. In the '80s the company began to expand outside Italy, starting to export their batteries to the USA and creating two plants, one in Germany and one in France. Subsequently, the company began to expand more and more by opening new foreign plants. The headquarters is located in *Montecchio Maggiore(VI)*, and it has numerous business and production sites.
The company started with Lead Acid batteries, and recently it has entered into the world of Lithium-ion batteries to meet different market needs. Fiamm works in two big fields: Reserve and Mobility. In the first field,it designs and manufactures backup batteries to guarantee the continuity of energy supply to critical applications when the main power is cut off. The applications are various, including telecom, data center, renewable energy and industry. Some key clients are ABB, Siemens, Telecom Italia. The main technologies for the battery are three:

- AGM Technology
- GEL Technology
- Flooded Technology

The first and the second type of technology do not need maintenance, instead the flooded one, with low maintenance they guarantee a high reliability.
The mobility area deals with batteries for cars, motorbike and commercial vehicles. They work with some big company in the automotive field like Toyota, Mercedes-Benz, Ferrari and others.
The technologies used for these types of batterie are the following:

- AGM VRLA

- AFB (Advanced Flooded Battery)
- Free lead acid (SLI/FB)

1.2 Project Illustration

The company Fiamm, to enlarge its products portfolio, has started a feasibility study regarding 48V Lithium-Ion batteries for telecom applications. The main goal of the project is to find a supplier that can cooperate with Fiamm to enter the Lithium batteries business.

At the beginning the team identified ten suitable suppliers, starting from more than one hundred possible suppliers, based on different parameters like: revenue, product portfolio, customers etc...

From the suppliers has been bought 100Ah and 50Ah 48V TLC batteries, in order to test them from an electrical point of view and to analyze the internal structure and the overall quality of the product. The main point of my master thesis project is to analyze in detail three 100Ah battery packs and after that, to find what of the ten batteries is the best in term of internal design, electrical performances and quality of the software provided by the producer.

Therefore, first, it has been analyzed the internal design, so the quality of the assembling, how the connections have been done and the quality of the electrical components. After that, various electrical tests are done:

- Open Circuit Voltage and Internal Resistance
- Capacity tests
- Self-discharge tests
- Stress tests
- Safety tests

Some of these tests were done at various temperature: 25°C, 0°C and 35°C but for the project of this thesis, only the 25°C tests have been done. A better description of these tests are done in the chapter 2. After that, a database of all the ten batteries is done, one for the design, one for the test and one for the battery software, in order to have a clear and better comparison to evaluate what is the best battery pack.

1.3 48V LFP for TLC applications

Telecom batteries provide instant and continued 48V to all the system to ensure the continuity of it. The 48V is the standard voltage for TLC applications. It is a comprised voltage to enable transmissions with low signal loss and to be a safe voltage since it is less than 50V.
There are also off-grid telecom towers combined with renewable energy sources or other hybrid systems, in emerging countries with a lack of power grids or in remote areas. In these cases, the batteries provide electricity when the energy from the renewable sources is insufficient or unavailable. The predominant Li-Ions technologies are LFP and NMC, but due to the cost and its characteristic LFP is taken more into consideration. LFP battery provides:

- high charging and discharging current;
- power density;
- high voltage;
- high energy density;
- long life cycle, low discharge rate;
- less heating;
- more safety.

that are the main features that a battery for TLC applications must have. Infact, the annual growth rate for lead batteries is expected to be 0.5% and for Li-ion batteries it is expected to be 8.5%.

Another important aspect is the recycling process that for the lithium battery is not yet mature and not efficient; due to the usage of different electrode chemistries, different recycling processes are required. The effective capacity of a LiFePO4 battery will decrease to about 70% after twelve years, unlike the lead acid that decreases to 70% after five years. Follows the graph.

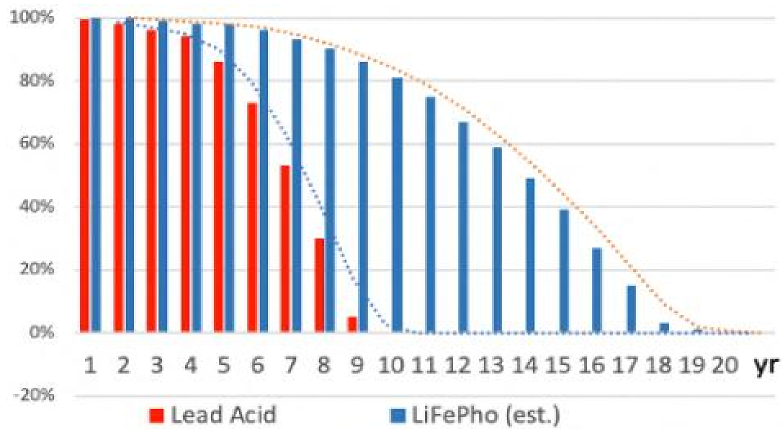


Figure 1.2: Storage Durability - LFP vs Lead Acid
www.fossilfreearoundtheworld.org

Then, due to the low resistance of LFP batteries, you will loses not much more than 2% of energy to bring it in and get it out. In contrary of a lead acid battery that lose about 30% of it. Instead the effective storage to not damage the battery is 90% for the LFP battery and 80% for the Lead Acid, this because it is not recommended to fully discharge them.

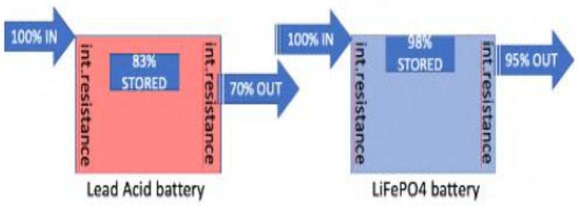


Figure 1.3: Efficiency - LFP vs Lead Acid
www.fossilfreearoundtheworld.org

Chapter 2

Lithium-Ion Batteries

2.1 Basic Battery Concepts

A battery is a device that converts chemical energy directly into electric energy by means of REDOX. They are classified into two categories:

- Primary batteries
- Secondary batteries

The difference between them is that the first ones are not rechargeable, so they are disposable because their electrochemical reaction cannot be reversed, instead the second type are rechargeable applying a certain voltage to the battery.

Anyway, the term battery is too generic, infact the smallest battery is called cell, a group of cell is called module, and two or more module together make a pack battery. The redox reaction (REDuction-OXidation) describes the chemical reaction in which atoms change their oxidation number: the oxidation is the loss of electrons by an atom that becomes a positive ion, the reduction is the gain of electrons by an atom that becomes a negative ion. The materials that take part to this reaction are called reactants.

The components that are present in a battery are the following:

- Anode

- Cathode
- Separator
- Electrolyte

The anode of a battery is the electrode that oxidizes, so it loses electrons during redox. These electrons go out from the anode and instead, the current enters into it, if we consider the charge operation.
The cathode is the electrode that reduces, so it gains electrons that enter into it and the current goes out, if we consider now the discharge operation.
The separator is a membrane placed between the anode and the cathode in order to, first, prevent a short-circuit between the two electrodes.
The electrolyte, instead, is a chemical substance that provides the ion transport mechanism between the cathode and the anode. It can be liquid, solid or gelatinous. A property that an electrolyte must have is a low conductibility to avoid self-discharge of the battery.
The two most common types battery chemistry are lead-acid and lithium-ion.

2.2 Li-Ion Battery Overview

Now we are gonna explain in detail the main components of a Li-Ion cell.

Cathode It is the electrode where the reduction takes place, and it limits the energy density and predominate the cost of the battery. If we analyze the structure of a Li-Ion cathode, we will find a thin aluminum foil that holds the frame of the cathode coated with an active material, conductive additive and binder. The active material of a Li-Ion cell is the lithium oxide and it intervenes in the electrode reaction. The conductive additive is added to increase the conductivity of the cathode, and the binder acts as an adhesive to help maintain the structure of the electrode and to maintain a good contact with the aluminium foil.
The cathode is the electrode that determines the characteristics of the

battery, like the capacity and the voltage. More lithium there is, more capacity has the battery.

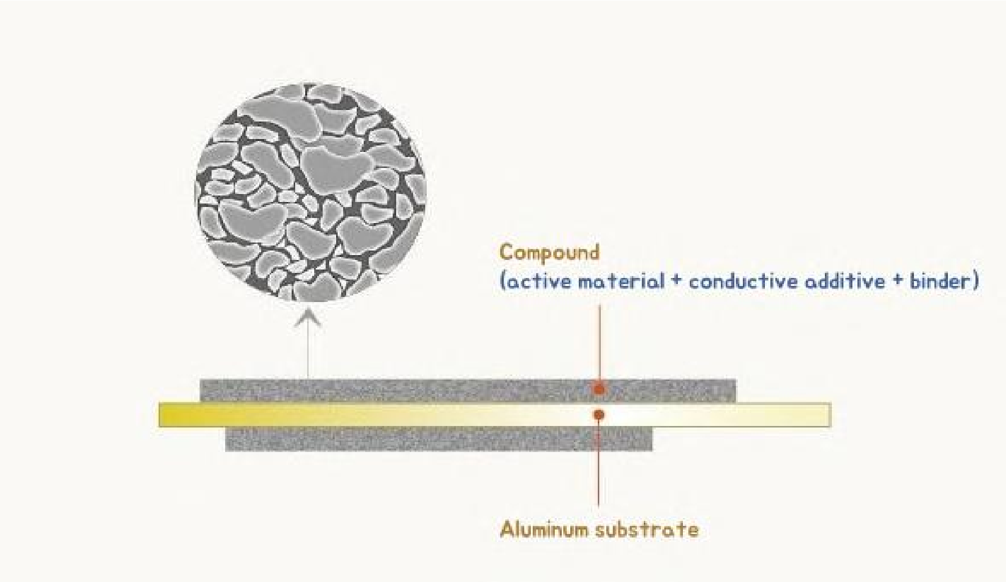


Figure 2.1: Cathode Structure
www.samsungsdi.com

Anode It is the electrode where the oxidation takes place and, as the cathode, it is coated with active material. Its role is to enable the flow of the current through an external circuit allowing the absorption or emission of Li-ions release from the cathode.
The anode in Lithium-Ion cell is typically made up of graphite. This material can meet various requirements like good conductivity and durability, light weight and low cost.

Separator It is the barrier between the cathode and the anode, in order to prevent the short-circuit. Nowadays, separator also helps to have a thermal stability. Separator has an important role regarding the performances of the battery, including cycle life, energy and power density. The separator increases internal cell resistance, and the separator takes up valuable space inside the Li-ion, so it is important to optimize it.

Separator has to be chemically stable because operates under strongly oxidizing and reducing conditions.

Electrolyte It provides an electrical path for the ions and it does not let electrons pass through. Depending on the design of the battery, it can be liquid or past-like. A material with high ionic conductivity is highly used so the ions can move easily. It is composed by salts, solvents and additives. The first one are the passage for lithium ions to move, the solvents is used to dissolve the salts.

2.2.1 Working Principle

Lithium ions $Li+$ are involved in the chemical reactions driving the battery. The ions are tied to an electron within the anode, that is made, as the cathode, of a material which can absorb them. When the battery is discharged, the intercalated lithium ions are released from the anode, and then they travel through the electrolyte solution to be absorbed in the cathode electrode. In detail, when there is a discharging process, the ions are released from the anode and travel, mean by the electrolyte solution to the cathode. This, also release the electrons that flows through an external wire, making the electric current. Current flows in the opposite direction from that of the electrons. When the battery needs to be charged, an oxidation reaction occurs at the cathode, so it loses some electrons. In order to maintain the charge balance in the cathode, some positively lithium ions are dissolved into the electrolyte solution and then, they travel over to the anode.

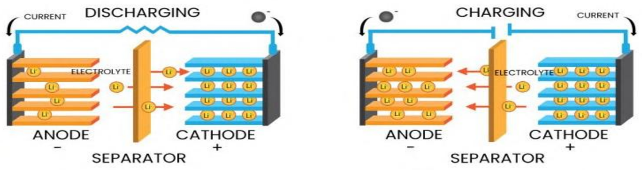


Figure 2.2: Working Principle

www.researchgate.net

2.2.2 Lithium-ion Chemistries

Li-ion batteries are classified according to the composition of their cathode. The most common are the following:

- Lithium iron phosphate, LFP
- Lithium manganese oxide, LMO
- Lithium cobalt oxide, LCO
- Lithium nickel cobalt aluminum, NCA
- Lithium nickel manganese cobalt, NMC

Lithium cobalt oxide was the first cathode material commercialized and it is still used. This type of batteries have high energy density but low cycle life and poor safety, indeed it is not good as off-grid battery type. NCA has similar properties as the LCO. LMO chemistry batteries have good thermal stability and safety but a lower cycle life.

NMC, instead, offers a good cycle life, safety and energy density. The LFP chemistry batteries make them suited for off-grid products or applications that require high load current and endurance, thanks to their properties like the low cost, good safety and stability, long life span, low energy density and a high current rating. This last type of batteries are analyzed in this project thesis.

Here a summary of the properties of the different chemistry.

	LFP	**LMO**	**LTO**	**LCO**	**NCA**	**NMC**
Specific energy [Wh/kg]	90 -160	105 - 120	50 - 80	150 - 200	80 - 220	150 - 220
Volt (per cell) [V]	3.2	3.8	2.2	3.8	3.6	3.7
Cycle life	2700 - 10000	>500	>4000	>700	>1000	3000 - 5000
Self-discharge per month [%]	<1%	5%	2 -10 %	1 - 5 %	2 - 10 %	2%
T [C]	-20 to +60	-20 to +60	-40 to +55	-20 to +60	-20 to +60	-20 to +55

Table 2.1: Comparison of Li-Ions Chemistry

2.2.3 Types of Cells

Lithium-Ions cells are available in three constructions:

- Prismatic
- Cylindrical
- Pouch

The cylindrical and the prismatic cells are similar in construction: the prismatic one uses a rectangular case to have a cell with a low thickness. The separator with the electrodes can be rolled together, or it can be a rectangular stack of electrodes. The terminals of the battery can be placed on the top, as usually happens, or on the side.

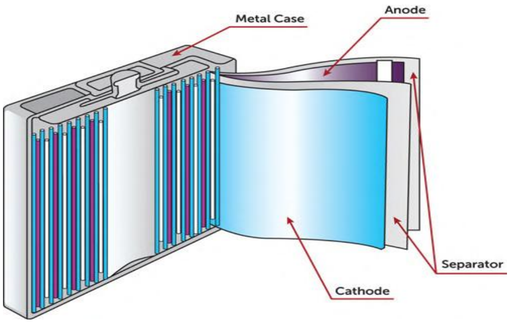


Figure 2.3: Prismatic Cell Structure
"https://www.lightingglobal.org/wp-content/uploads/2019/06/Lithium-Ion_TechNote-2019_update.pdf"

The cylindrical cells are made like the prismatic, so the cathode, separator and the anode are rolled together and then inserted into an aluminium case. Then it is filled with liquid electrolyte and the electrodes are welded to the battery terminals.

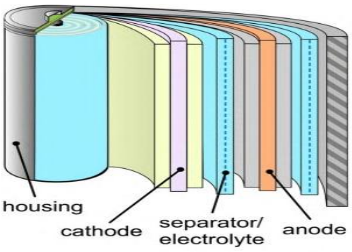


Figure 2.4: Cylindrical Cell Structure
"https://www.lightingglobal.org/wp-content/uploads/2019/06/Lithium-Ion_TechNote-2019_update.pdf"

Pouch cells have a similar shape to the prismatic one. They are composed of rectangular stacks of electrode and separator, but instead of a metal case they use a laminated aluminum film. The electrodes have tabs along one side that are welded with terminal tabs that goes out of the top of the case. The cell is saturated with a liquid electrolyte and the case is heat-sealed. Thanks to this type of construction pouch cells have low cost, low weight, and a low thickness. The flexible pouch is subject to swelling and this can lead to problems with lifetime, capacity loss and safety.

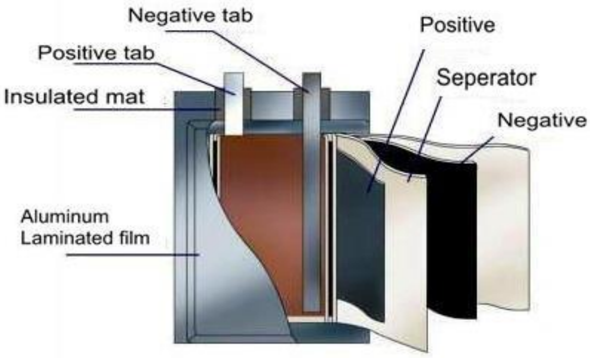


Figure 2.5: Pouch Cell Structure
"https://www.lightingglobal.org/wp-content/uploads/2019/06/Lithium-Ion_TechNote-2019_update.pdf"

2.2.4 Battery Parameters

To characterize a battery, some figures of merit are defined.

- Nominal Voltage [V]: is the voltage used as a reference to describe the battery.

- Cut-Off Voltage (charge or discharge) - $\mathrm{V_{CO}}$ [V]: this defines the maximum charge voltage or minimum discharge voltage of a battery.

$$\mathrm{V_{EOC}} = \text{End Of Charge Voltage}$$

$$\mathrm{V_{EOD}} = \text{End Of Discharge Voltage}$$

- Nominal Capacity [Ah]: The total Amp-hours available when the battery is discharge at a certain discharge current.

- C-rate: it is a measure of the rate at which a battery is charge or discharge relative to its maximum capacity.

$$C_{rate} = \frac{DischargeCurrent[A]}{NominalCapacity[Ah]}$$

- Energy Density: it represents the measure of how much energy the battery can contain in proportion to its weight [Wh/kg] or to its volume [Wh/l].

$$E_{density} = \frac{Ah * V_N}{Volume}$$

- Power Density: it represents the measure of how much power a battery can delivered in proportion to its weight [W/kg] or to its volume [W/l].

$$P_{density} = \frac{P}{Volume}$$

- State of Charge - SOC [%]: it is used to represent the percent of energy remaining in a given battery. Numerically, it is the capacity remaining divided by the total full charge capacity.

$$SOC = \frac{Ah_{remaining}}{Ah_{total}}$$

- State of Health - SOH [%]: it represents the condition of a battery compared to the one given by the manufacturer.
- End Of Life - EOF: it is a condition when a battery capacity is lower than 80 %.
- Cycle of Life: this term represents the total number of complete discharge cycles.
- Internal Resistance [mΩ]: it describes the electrical and thermal behavior of the battery and it has to be low as possible. A high resistance causes the battery to heat up and the voltage to drop. Two methods are used to read the internal resistance of a battery: DC method by measuring the voltage drop at a given current, and AC method, which takes reactance into account. The resistance values vary between the DC and AC methods. The DC reading looks at pure resistance instead the AC reading includes reactive components and provides impedance.
- Relaxation of a battery: The relaxation corresponds to the phase after a period of discharge, during which there is no current and the battery voltage tends to a steady state.
- Open Circuit Voltage [OCV]: The voltage measured at the end of the relaxation, with no load connected.

2.2.5 Battery Management System - BMS

The lithium-based batteries are equipped with an electronic management system, called Battery Management System or BMS, that is the central control unit of the battery pack. The BMS is a combination of sensors, a master board, a series of slave board and its software. Its purpose is to provides protection against overcharging, over discharging, high and low temperatures, short circuiting, it does acquisition of voltage cells, voltage pack, current and temperature, detection of faults. The BMS needs to be robust against electromagnetic interference and have redundancy for safety functionality. So, the main functions of the BMS can be divided in:

- Parameters Estimation: Determines cell and pack battery parameters like the voltages, current, the temperature, SOC and SOH; it communicates with controllers via CAN for cell balancing.
- Data Storage: Records pack and individual cell parameters data and stores them on a memory or cloud.
- Diagnosis: Monitors cell-to-cell variations over time and diagnoses errors or detects risks and send warning signals, or open the MOSFET.

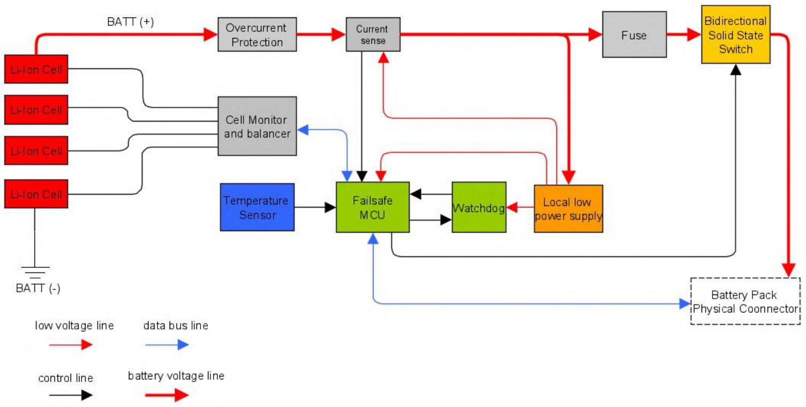
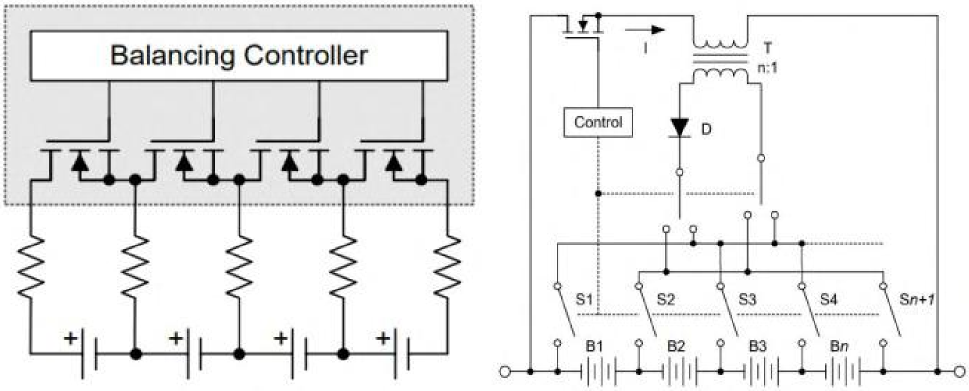


Figure 2.6: Block Diagram of a typical BMS

www.allaboutcircuits.com/technical-articles/introduction-to-battery-management-systems

One of the most important features is the balancing of the cell, that can be passive or active. The most common is the passive balancing that consists of a resistor placed in parallel to the battery cell, so a very simple system but not so efficient. A resistor, as we know, converts energy into heat, so the excess energy of the highest SOC cell is converted into heat and dissipated. The other balancing method is the active one, that is more complex, more expensive but with more efficiency than the passive balancing. It consists of moving the excess energy from the higher to the lower SOC until all the cells are at the same SOC. This can be done in different ways, one of them is to use capacitor.



(a) Passive Balancing (b) Active Balancing

Figure 2.7: Types of Balancing

Another relevant feature that the BMS contains is the monitoring of temperature. A battery needs to operate within an optimal range because if it is too hot, it will degrade or can be a malfunction. Usually, the temperature is measured by thermistors that are inside the ADC (Analog to Digital converter). Then, a microcontroller is needed to store, organize, and assess the data that arrive from the sensing circuitry.
There are four types of BMS:

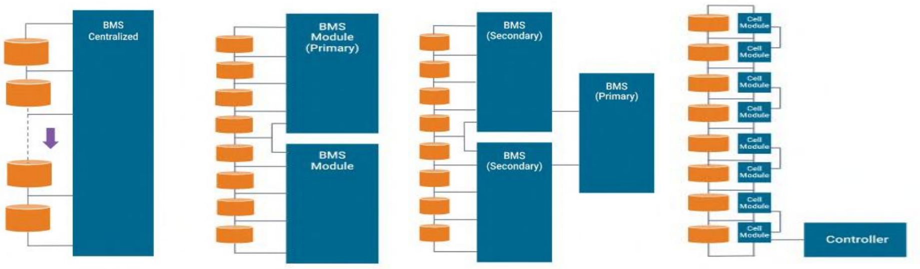
- Centralized: In this configuration, all the battery packages are connected directly with the BMS. It is more compact, and it tends to be the most economical since there is only one BMS. But since all the batteries are connected to the BMS directly, the BMS needs a lot of ports so it is needed a large amounts of wires and connectors that complicates troubleshooting and maintenance.

- Modular: This configuration is like the previous one, but it uses duplicate modules of the primary BMS. Thanks to the duplicated modularity, troubleshooting and maintenance is easier but the costs are higher than the previous one.

- Primary: This topology is similar to the modular one but in this case, the slaves (or secondary) just transferring measurement information to the master, that control and elaborates them. Thanks to the slave, the cost is lower than the modular.

- Distributed: This architecture contains various modules that are connected to each cell and the data are sent to a control board. The cost tends to be higher.

The schematics of these BMS topology are represented below.



(a) Centralized (b) Modular (c) Primary (d) Distributed

Figure 2.8: BMS Topologies
https://www.synopsys.com/glossary/what-is-a-battery-management-system.html

Chapter 3

Equipment and Tests Process

In this chapter, a summary of all the tests performed on 100Ah battery packs is done, and a brief description of the instruments used for the teardown and tests is given.

3.1 Equipment

Battery Cycler

To conduct the tests on the batteries, a cycler, a test system able to perform charge and discharge cycles and register some important parameters - like voltage, current and capacity - has been used throughout the testing process. These parameters were written down in an excel file. For more clarity, see below.

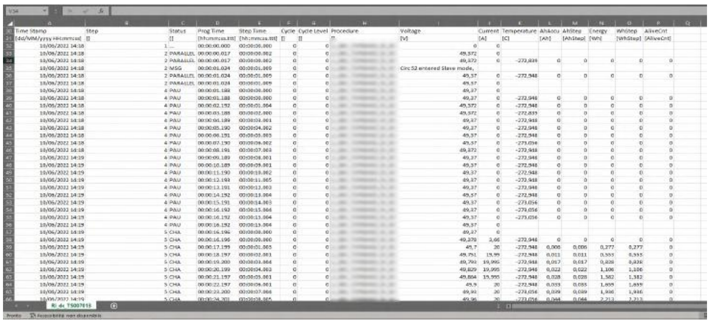


Figure 3.1: Digatron Raw Data

The cycler used for this test belongs to Digatron producer is the BNT ME. In the list below several data regarding the test system are shown.

- Circuit No.: 1-3
- Voltage Range: 10V - 60V (Charge) – 50V - 5V (Discharge)
- Current Range: 0.1A - 100A (charge and discharge)
- Discharge Current Peak: 160A (max 10s)
- Charge Current Peak: 125A (max 10s)
- Time between two discharge/charge peaks: 1min

Hioki

The Hioki Battery Tester BT3554-01, a dedicated tester, is used to measure the internal resistance and the voltage, of the cells and entire battery pack. Range and resolution follow in the table below.

Range [Ω]	Resolution [Ω]	Range [V]	Resolution [V]
3m	1μ	6	1m
30m	10μ	60	10m
300m	100μ		
3	1m		

Table 3.1: Resolutions on different ranges

Figure 3.2: Hioki-3554
www.hioki.com

Pack Battery Software

The producer gives also the software to monitor all battery data. All the software contains the main information about the battery, like the pack voltage, the current and some alarm or protection status.

3.2 Tests Performed

In order to select the best battery pack, some different types of tests are done, at 25°C.

3.2.1 OCV and Internal Resistance

First of all, a measure of the Open Circuit Voltage and the internal DC resistance is done. To perform the measure of the resistance, the Digatron cycler is used, following the IEC62620. The latter is an International Standard for batteries and specifically, this one is related to requirements for lithium-ions secondary cells and batteries, used for industrial applications. The steps for this test are listed below:

1. Discharge with a current of 0,2C to V_{EOD}
2. Charge with a current of 0,2C until V_{EOC}
3. Break of 1h/4h (min/max);
4. Discharge with a current of 0,2C to have 50% of SOC
5. Discharge for 30s with a current of 0.2C;
6. Discharge for 5s with a current of 1C.

The resistance is calculated with the following formula:

$$R_{DC} = \frac{U_1 - U_2}{I_1 - I_2}$$

where:

- U_1 : the voltage at the end the first discharge
- U_2 : the voltage at the end the second discharge
- I_1 : the current during the first discharge
- I_2 : the voltage during the second discharge

When the test start, the OCV is measured to see if the battery pack arrived already discharge.

3.2.2 Capacity tests - Discharge and Charge

In order to know the status of the battery and how much capacity it can charge or discharge, some "capacity tests" are done. These are helpful also to identify some criticalities like the over-temperature of one or more cells during the charging/discharging process, over-voltage, etc... The steps are describes below:

Discharge

1. Charge with a current of 0.2C until V_{EOC} and stop it when the current is lower than 0.01C;
2. Break of 1h;
3. Discharge[1] until V_{EOD};
4. Break of 1h;
5. Charge with a current of 0.2C until V_{EOC} and stop it when the current is lower than 0.01C.

Charge

1. Starting from 100% of SOC, discharge with a current of 0.2C until V_{EOD};

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[1] There are 4 discharge tests, the discharge current are 1C, 0.5C, 0.2C and 0.1C.

2. Break of 1h;
3. Charge with a current of 0.2C until V_{EOC}.

3.2.3 Stress tests

Stress tests are very important to know how the battery behaves in situations as high current rate or a charge and discharge without any break.

Max Charge

1. Starting from 100% of SOC, discharge with a current of 0.2C until V_{EOD};
2. Break of 1h;
3. Charge with the maximum current[2] allowed.

Max Discharge

1. Charge with a current of 0.2C until V_{EOC} and stop it when the current is lower than 0.01C;
2. Break of 1h;
3. Discharge at the maximum current[3] allowed until V_{EOD};
4. Break of 1h;
5. Charge with a current of 0.2C until V_{EOC} and stop it when the current is lower than 0.01C.

Max Discharge followed by a Max Charge

1. Starting from 100% of SOC, discharge with the maximum allowed current until V_{EOD};

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[2] The maximum charging current is stated by the manufacturer and changes from battery to battery.

[3] The maximum discharging current is stated by the manufacturer and changes from battery to battery.

2. Charge with the maximum allowed current:

3. Break of 1h.

3.2.4 Overload tests

During overload test a current greater than the maximum allowed[4], in charge and discharge, is given to the battery in order to test the protection of the BMS. This is useful to know if the delay time declared by the producer, needed to open the mosfets, is correct, and more important, if the protection trigger.

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[4] Some battery packs have two protection for charge and the discharge

Chapter 4

Batteries Teardown

In this chapter the internal design is analyzed in detail. All the batteries are made by LFP prismatic cells, for a total of 48V. The internal design description is focused on the connection between cells and modules, how the thermocouples and sensing cables are connected to the cells. In the end, there is an analysis of the Battery Management System.

	COMPONENTS		**COMPONENTS**
1	Safety mosfet	**13**	Power supply block
2	Mosfet Driver	**14**	Battery button
3	Termocouple	**15**	DC-DC
4	Protection diode	**16**	Electrical connector
5	Passive Balancing	**17**	Anti-theft
6	Shunt	**18**	Display
7	Microcontroller	**19**	SNMP
8	Conditioning pre-processing	**20**	Buzzer
9	Analog Front-end	**21**	Communication port
10	Heat sink	**22**	Polarization resistance
11	Thermic conductive bar	**23**	Transient suppression capacitors
12	Power Connectors	**24**	Reset Button
12a	Connectors to power the board	**25**	Additional Board

Table 4.1: Principal Components of the BMS

1. Safety Mosfets: They have the purpose to connect and disconnect

the battery power to a load or a charger. especially when a critical situation occurs. Usually in a solid state, they are therefore relatively cheap compared to an IC.

2. Mosfets Driver: They control the safety mosfets, so when a critical event occurs, they impose the safety mosfet to open.

3. Thermocouple: It is a sensor for measuring the temperature. It is formed of two metal wires joined at one end, and connected to a device able to measure the temperature. The measurements provided are in a wide range of values.

4. Protection Diode - TVS: TVS stands for Transient Voltage Suppressor, their purpose is to protect the circuit against transients and overvoltage. The working principle is simple: placed in parallel to the load so when voltage exceeds a certain value called breakdown voltage, the TVS starts to conduct and clamp the voltage, preventing damages. It can sustain high amount of current for a short period of time.

5. Passive Balancing: As explained in chapter 2, the BMS has a circuit in order to balance the voltages of the cells. Usually, it is a passive one due to the low cost compared to the active balancing.

6. Shunt Resistor: Shunt resistors are similar to a normal resistor but with a very low value and a high power rating. These type of resistors are placed in a current path in order to measure the current. By measuring the voltage drop across the resistor, the current can be easily calculated.

7. Microcontroller: The brain of the BMS, it captures all the data from the peripherals devices and processes them. Some functions comprehend monitoring and protecting the battery, estimating its state and data logging.

8. Conditioning Pre-Processing Circuit: It cleans up the analog sensor signal and makes it usable for the monitoring process. It is distributed all over the board.

9. Analog Front End (AFE): This is an integrated circuit which is designed to wrap all the analog circuitry required for the design and the operation of the BMS. The principal feature is to measure cell voltages and temperatures to sending the data to the MCU. It also balances the cell voltages

10. Heat Sink: It is useful to dissipate the heat generated when the current flows through safety mosfets.

11. Thermic Conductive Bars: As the heat sinks, they are used to dissipate the heat.

12. Power Connectors: They are used to connect the electrical cables from the battery to the BMS and from the BMS to the external connector where the load is connected. They are welded on board.

13. Power Supply Block

14. Button Battery: Used to maintain the clock of the BMS update correctly.

15. DC-DC Converter: Used to convert the voltage and limit the current.

16. Electrical Connectors: They are used to electrically connect the power board with the control board.

17. Anti-theft: Used to lock the system if the pack is stolen. There are GPS anti-theft devices or/and a gyroscope types.

18. Display: A display is mounted on some battery packs there are a display to visualize some important data like the voltage, the capacity and the current.

19. Simple Network Management Protocol - SNMP: This port is used to receive some parameters through network.

20. Buzzer: It is used to send an audible signal in certain situations like the powering-up.

21. Communication Port: These battery have more type of ports, usually there are the RS232 and the RS485 ports. They are used to connect a computer with the battery pack to monitor it via software.

22. Polarization Resistances

23. Transient Suppression Capacity: Used to attenuate current and voltage transient, generated by the opening and the closing of the mosfets, and the powering on/off.

24. Reset Button: It is mostly present on battery packs and it is used to reset the BMS.

25. Additional Board: Some producers insert an additional board with leds, communication ports, reset button, and dial switch to not have these components on the BMS board.
    Dial switch is used for a parallel connection with multiple packs, in order to have more capacity.
    Dry contacts are passive contacts, no energy is applied to the contacts. These contacts operate like an ordinary switch that opens or closes the circuit. When the contacts are closed the current flows through the contacts and when the contacts are opened no current flows through the contacts.

4.1 Battery Pack n.1

Figure 4.1: Battery Pack n.1

The first battery considered has the following characteristics:

PACK RATE PARAMETERS	Voltage [V]	48
	Capacity [Ah]	100
	Energy [Wh]	4800
	Weight [kg]	39
	Height	3U
PACK FEATURES	Density [Wh/kg]	122.44
	Density [Wh/dm3]	185.35
	Standard charge	0,2C
	Standard discharge	0,2C
	Max charging current	0,5C
	Charge end voltage [V]	53,2 - 54
	Discharge end voltage [V]	46,5 - 47,1 - 47,6 (0,7C - 0,5C - 0,2C)
CELLS CONFIGURATION	Configuration	15s1p
	Series n.	15
	Parallels n.	1
	Modules n.	2
	Cells n.	15

Table 4.2: Battery Pack Specifications

On the *PACK RATE PARAMETERS* it can be seen that the height is expressed in *U*. This unit of measurement is used for batteries when they are hold by a rack. 1U is about 45mm. So this battery pack is about 135mm high.

Another consideration to do is that the V_{EOD} takes different values based on the discharge current. The cell configuration for this battery is *15s1p*: the first part indicated how many cells in series there are, and the second one indicates the number of parallels. So in this case there are 15 cells in series without any parallel.

4.1.1 Design

Inside each battery it can distinguish six main parts: the cells, the modules, cell restraints system, the battery case, the Battery Management System and, if there is, the Anti-Theft. Here are summarized the components of the pack.

	COMPONENTS	QTY	SINGLE ITEM WEIGHT [Kg]	TOT. WEIGHT [Kg]
1.	Cell	15	1.98	29.75
2.	Module	2	16.33	14.29
3.	Cell Restrain System	1	0.57	0.57
4.	Battery case	1	7.54	7.54
5.	BMS	1	0.641	0.64
6.	Anti Theft	1	/	/

Table 4.3: Battery Pack n.1 Components

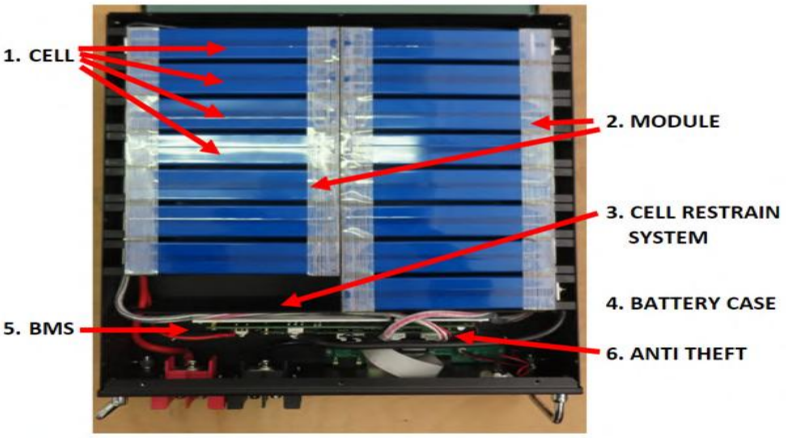
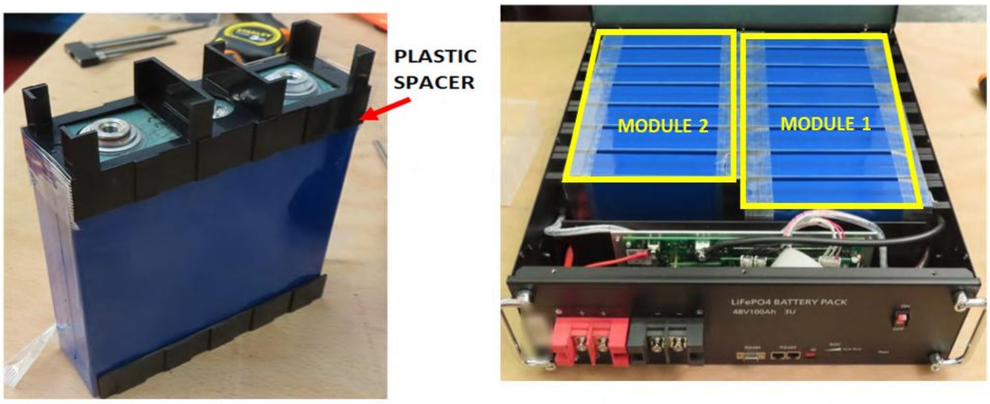


Figure 4.2: Internal of Battery Pack n.1

There are 15 LFP prismatic cells, grouped in 2 modules. All the cells have a plastic spacer that keeps the cells apart from the battery case in order to reduce the risk of contact between the terminals and the metal case.



(a) Cell

(b) Internal of the Battery

Figure 4.3: Internal Design

The modules are held together by an adhesive tape with a cell restraints system. In the image below, it can be noticed a space for the 16th cell for the 51.2V configuration.

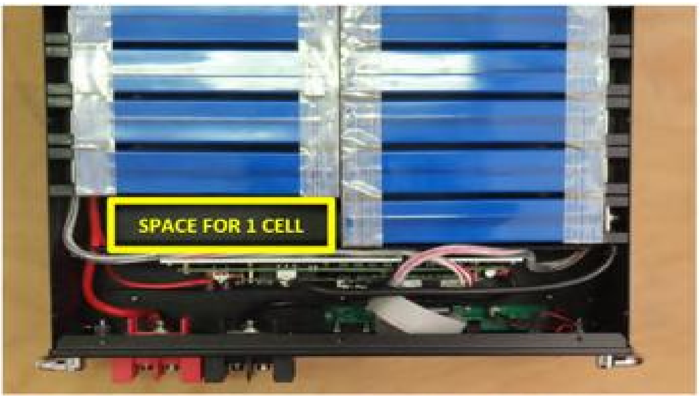


Figure 4.4: Space for the 16th cell

The modules are connected in series via metal busbars, that are short strips of conductive metal for high-current electrical connections. The goal

of a busbar is to maximize the efficiency of a connection by minimizing the electrical resistance.
The more popular metals used for busbars are copper, brass and aluminum. Width and length are based on the battery cell terminal size and position.

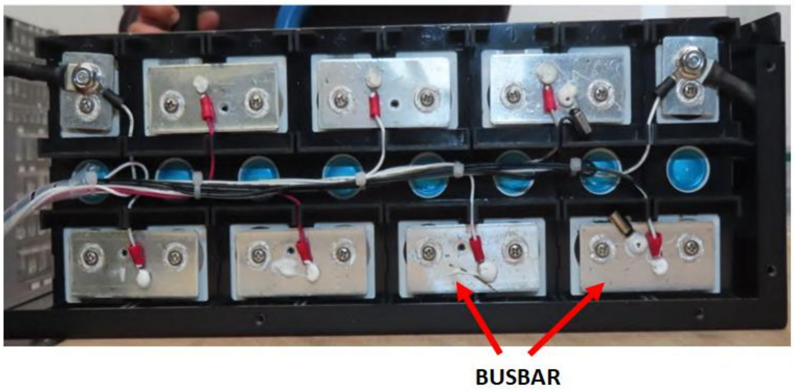


Figure 4.5: Modules Side View

Another important characteristic of a battery pack is its case, especially the front panel.

1	POWER SUPPLY ANODE
2	POWER SUPPLY CATHODE
3	RESET BUTTON
4	DIAL SWITCH
5	RS485 PORT
6	RUNNING LIGHTS
7	ALARM INDICATOR
8	CAPACITY INDICATOR
9	ON/OFF BUTTON

Table 4.4: Front Panel Components

Figure 4.6: Front panel

In the next section, an explanation of the ports is given.

Near the back of the front panel there is the BMS, anchored to a metal barrier with screws. In this pack, there is also the anti-theft that is attached to the BMS.

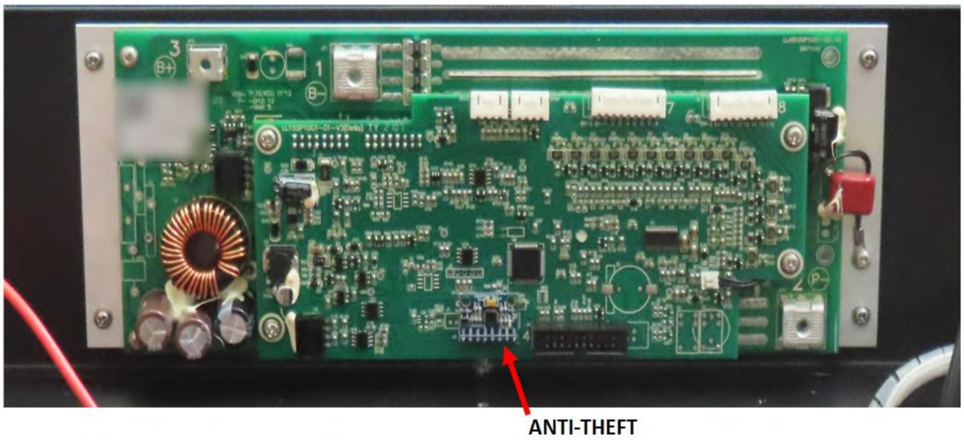


Figure 4.7: BMS

4.1.2 Battery Management System

Here a list of the various components that are present in this BMS.

	COMPONENTS	**QTY**		**COMPONENTS**	**QTY**
1	Safety mosfet	15	**13**	Power supply block	1
2	Mosfet Driver	1	**14**	Battery button	0
3	Termocouple	2	**15**	DC-DC	1
4	Protection diode	4	**16**	Electrical connector	4
5	Passive Balancing	1	**17**	Anti-theft	1
6	Shunt	10	**18**	Display	0
7	Microcontroller	1	**19**	SNMP	0
8	Conditioning pre-processing	1	**20**	Buzzer	0
9	Analog Front-end	1	**21**	Communication port	3
10	Heat sink	2	**22**	Polarization resistance	6
11	Thermic conductive bar	2	**23**	Transient suppression capacitors	1
12	Power Connectors	4	**24**	Reset Button	1
12a	Connectors to power the board	5	**25**	Additional Board	1

Table 4.5: Principal Components of the BMS

1. Safety Mosfets: In this pack mosfets are covered by a thermal pads increasing the heat dissipation.

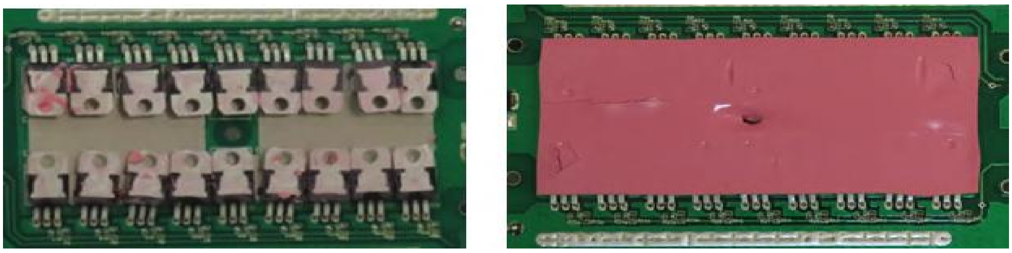


Figure 4.8: Safety Mosfets

2. Mosfet Driver: There is one mosfet for the charge and one for the discharge.

Figure 4.9: Mosfets Driver

3. Thermocouples:

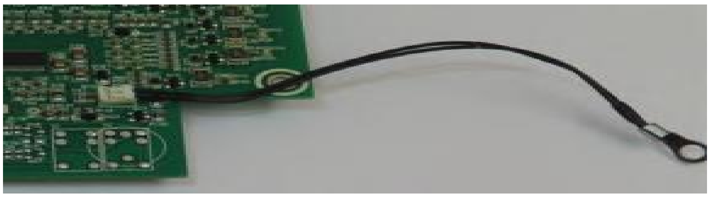


Figure 4.10: Thermocouple

4. Protection Diode - TVS:

Figure 4.11: TVS Diodes

5. Passive Balancing: In this pack there are 15 groups of resistors like the number of cells. It can be notice also the mosfets of the balacing circuit.

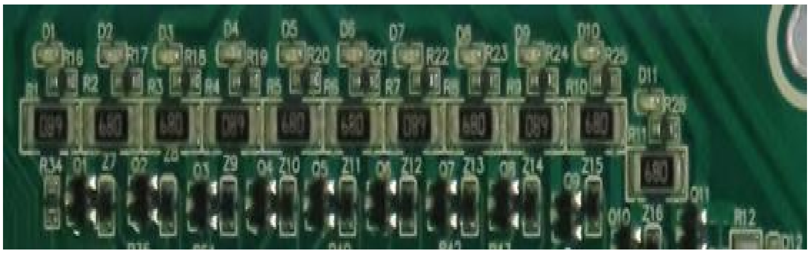


Figure 4.12: Passive Balancing

6. Shunt Resistor:

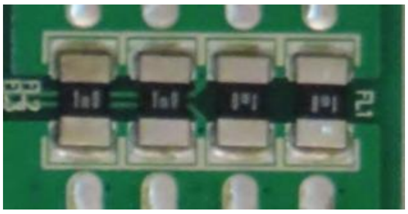


Figure 4.13: Shunt Resistors

7. Microcontroller: The microcontroller mounted on this BMS is the *Microchip PIC 18F7K22 8-bit*:

    - Flash Memory 128KB
    - EEPROM 1024B
    - ADC Channels: 16, Max Resolution: 12b

  - Temperature Range: -40 to 125 °C
  - Voltage Operation Range: 1.8 to 5.5 V

9. Analog Front End (AFE): The AFE model used on this BMS is the TEXAS INSTRUMENT- BQ7694003 with these characteristics:
    - V_{in}(max): 75V
    - Number of series cells (max): 15
    - Features: monitoring, protections, balancing

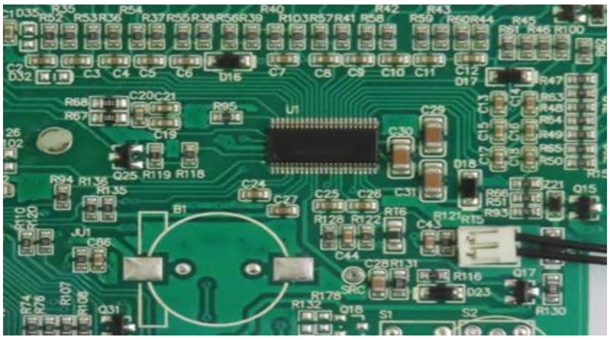


Figure 4.14: AFE with Conditioning Pre-Processing Circuit

10. Heat Sink: It is positioned above the mosftes in order to help the dissipation.

Figure 4.15: Heat Sink

11. Thermic Conductive Bars:

Figure 4.16: Thermic Conductive Bar

12. Power Connectors:

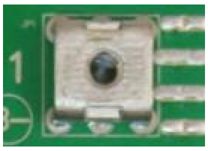


Figure 4.17: Power Connectors

15. DC-DC Converter:

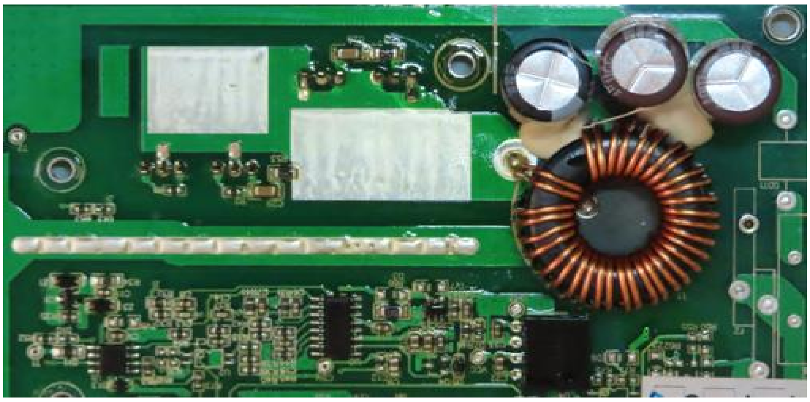


Figure 4.18: DC-DC Converter

16. Electrical Connectors:

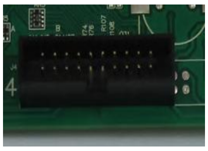


Figure 4.19: Electrical Connectors

17. Anti-theft: On this battery it is installed a gyroscopic anti-theft, the MPU6050, so if the pack is moved after its installation, the gyroscope detects the movement and sends a signal to the BMS to inhibit the battery pack.
18. Display: This pack does not have a display.
19. Simple Network Management Protocol - SNMP: This type of port is not present on the pack.
20. Buzzer: Not present on pack.
23. Transient Suppression Capacity:

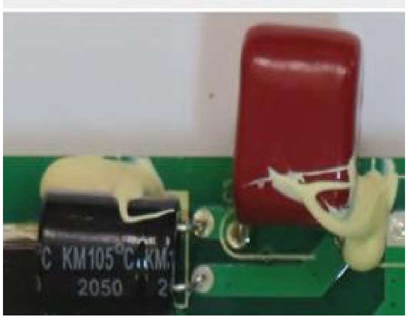


Figure 4.20: Transient Suppression Capacity

25. Additional Board:

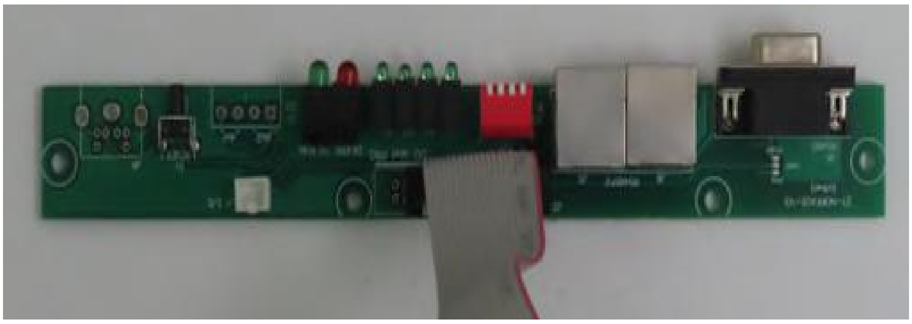


Figure 4.21: Additional Board

The power board and the control board relative to the BMS of the first pack are shown below.

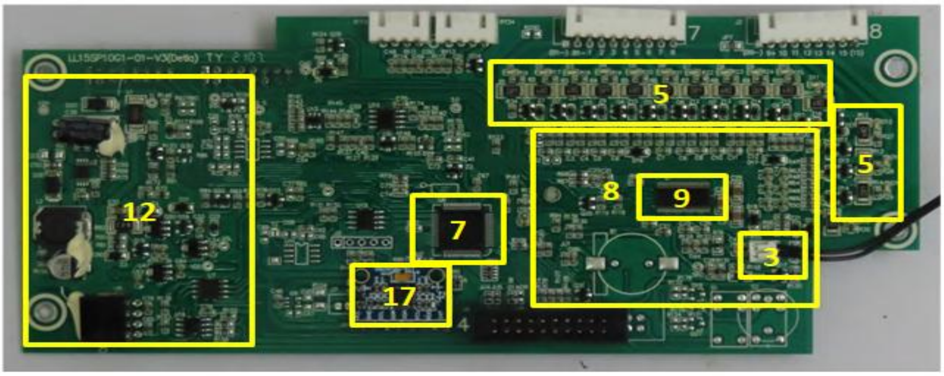


Figure 4.22: Control Board Front View

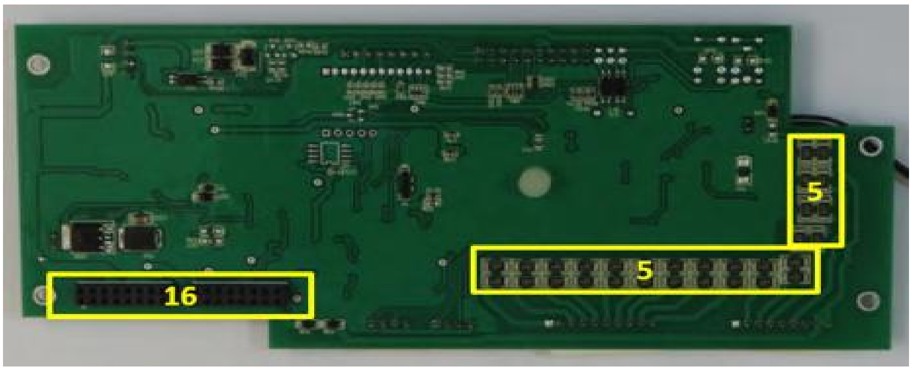


Figure 4.23: Control Board Back View

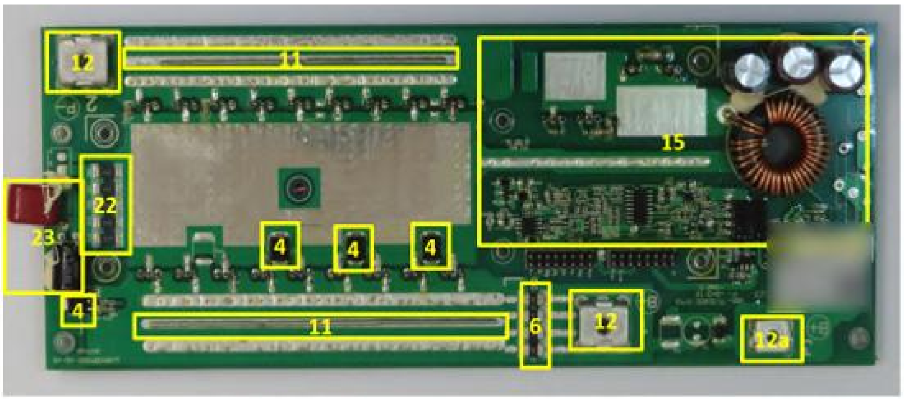


Figure 4.24: Power Board Front View

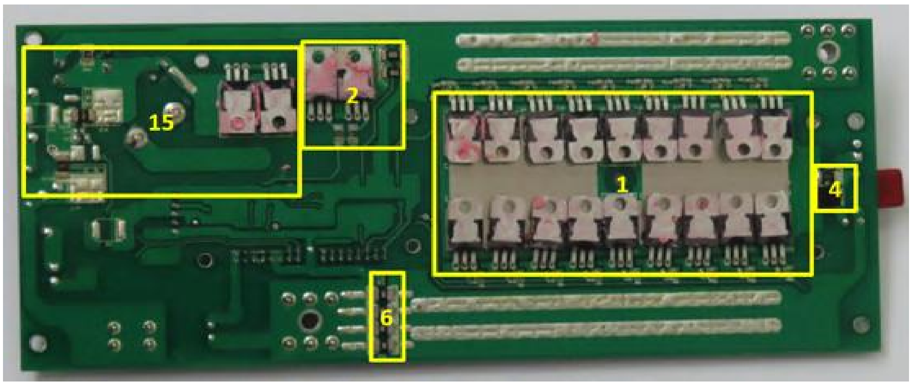


Figure 4.25: Power Board Back View

4.1.3 Internal Resistance and OCV

OCV pack [V]		**RI pack [mΩ]**	
49,4		9.13	
OCV cells [V]		**RI cells [mΩ]**	
1	3,309	1	0,331
2	3,309	2	0,335
3	3,309	3	0,341
4	3,31	4	0,346
5	3,31	5	0,341
6	3,309	6	0,335
7	3,309	7	0,348
8	3,31	8	0,338
9	3,31	9	0,321
10	3,31	10	0,325
11	3,307	11	0,328
12	3,309	12	0,324
13	3,31	13	0,324
14	3,31	14	0,326
15	3,31	15	0,312

Table 4.6: Rint and OCV

It can be noticed that the cells are balanced.

4.2 Battery Pack n.2

Figure 4.26: Battery Pack n.2

The second battery considered has the following characteristics:

PACK RATE PARAMETERS	Voltage [V]	48
	Capacity [Ah]	100
	Energy [Wh]	4800
	Weight [kg]	43
	Height	3U
PACK FEATURES	Density [Wh/kg]	111.82
	Density [Wh/dm3]	173.31
	Standard charge	0,2C
	Standard discharge	0,2C
	Max charging current	0,5C
	Charge end voltage [V]	55
	Discharge end voltage [V]	40.5
CELLS CONFIGURATION	Configuration	15s1p
	Series n.	15
	Parallels n.	1
	Modules n.	2
	Cells n.	15

Table 4.7: Battery Pack Specifications

4.2.1 Design

	COMPONENTS	QTY	SINGLE ITEM WEIGHT [Kg]	TOT. WEIGHT [Kg]
1.	Cell	15	2.24	29.75
2.	Module	2	18.23	14.29
3.	Cell Restrain System	1	0.44	0.44
4.	Battery case	1	7.08	7.08
5.	BMS	1	0.7594	0.7594
6.	Anti Theft	1	/	/

Table 4.8: Battery Pack n.2 Components

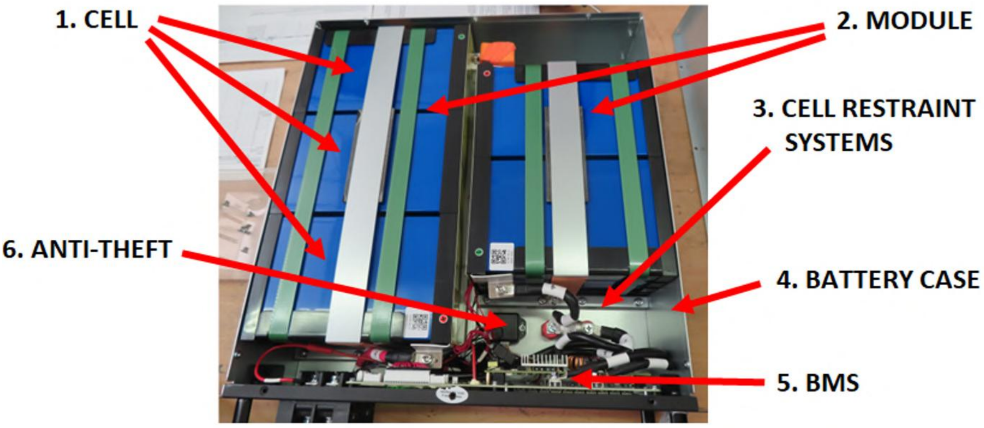


Figure 4.27: Internal of Battery Pack n.2

The cells are 15, grouped into modules. Each module has a plastic foil sheet attached on the upper part to prevent the contact with the case.

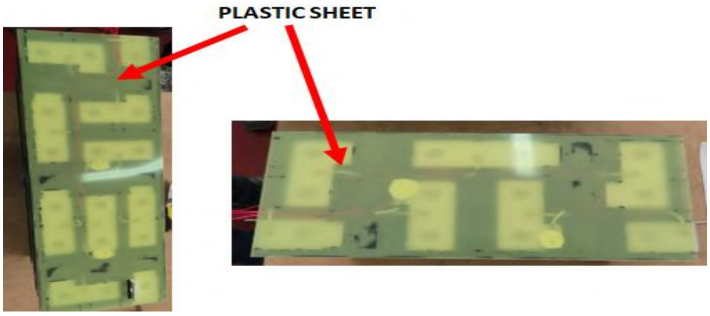


Figure 4.28: Plastic Foil Sheet protection

The two modules have the following configuration

- Module 1: 6s1p - 100Ah
- Module 2: 9s1p - 100Ah

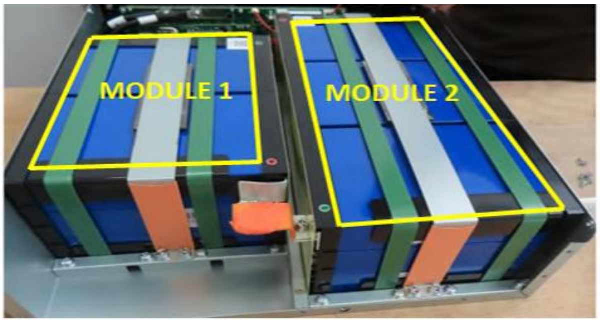


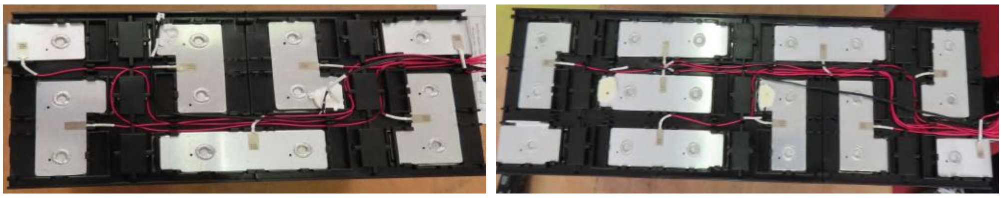
Figure 4.29: Modules Configuration

Each module is contained in a plastic rectangular case, and also to protect them from bumps and to hold the cells together, there is a plastic piece on each edge. As it can seen from the images below, the modules were strapped.

(a) (b)

Figure 4.30: Internal Design

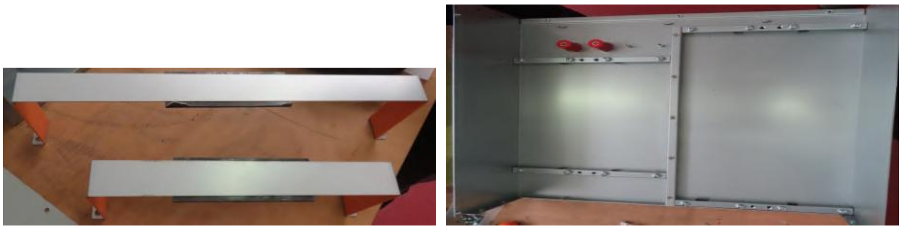
The connections are made by metal busbars that are welded. There are five type of busbars, according to the length.



(a) Module 1 (b) Module 2

Figure 4.31: Busbars

This battery pack has two type of restraint system, the first is anchored with case with screws and the other one is made by two aluminium bars.



(a) Aluminium bars (b) Restraint system anchored

Figure 4.32: Cell Restraint System

The front panel of this battery pack has the following characteristics:

1	POWER SUPPLY ANODE
2	POWER SUPPLY CATHODE
3	RESET BUTTON
4	DIAL SWITCH
5	DRY CONNECTION
6	RS232 PORT
7	RS485 PORT
8	RUNNING LIGHTS
9	ALARM INDICATOR
10	CAPACITY INDICATOR

Table 4.9: Front Panel Components

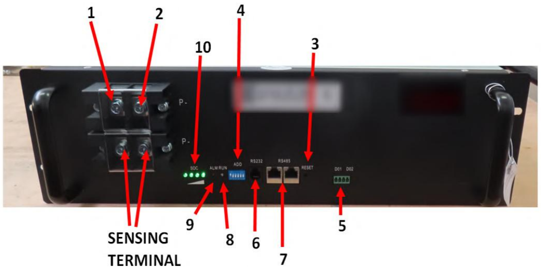


Figure 4.33: Front panel

The Battery Management System is anchored on the back of the front panel.

4.2.2 Battery Management System

The BMS of the second battery is similar to the previous one.

	COMPONENTS	**QTY**		**COMPONENTS**	**QTY**
1	Safety mosfet	20	**14**	Battery button	0
2	Mosfet Driver	1	**15**	DC-DC	1
3	Termocouple	1	**16**	Electrical connector	5
4	Protection diode	11	**17**	Anti-theft	1
5	Passive Balancing	16	**18**	Display	0
6	Shunt	12	**19**	SNMP	0
7	Microcontroller	1	**20**	Buzzer	1
8	Conditioning pre-processing	1	**21**	Communication port	3
9	Analog Front-end	1	**22**	Polarization resistance	6
10	Heat sink	2	**23**	Transient suppression capacitors	1
11	Thermic conductive bar	0	**24**	Reset Button	1
12	Power Connectors	4	**25**	Additional Board	0
13	Power supply block	1			

Table 4.10: Principal Components of the BMS

7. Microcontroller: ST - 32F100xB - ARM Cortex M3 32-bit

   - Flash Memory 128KB
   - 12b ADC
   - Maximum Frequency 24MHz
   - Voltage Operation Range 2.0 to 3.6V

9. AFE: Same as the battery pack n.1

15. DC-DC:

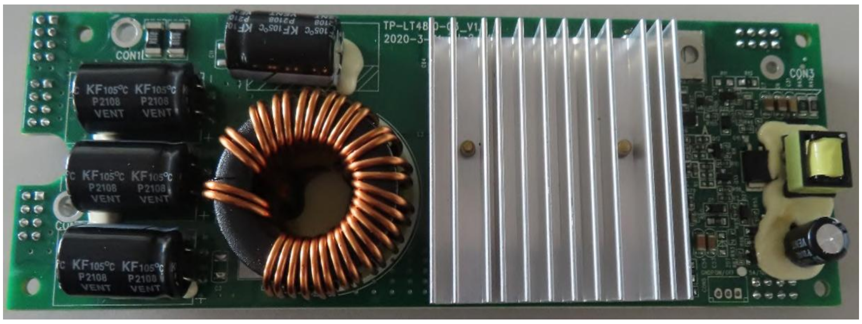


Figure 4.34: DC-DC

17. Anti-theft: Same as the previous pack.

18. Buzzer:

Figure 4.35: Buzzer

21. Communication Ports: In this pack, the communications are three, two RS485 and one RS232. There is also the dial switch.

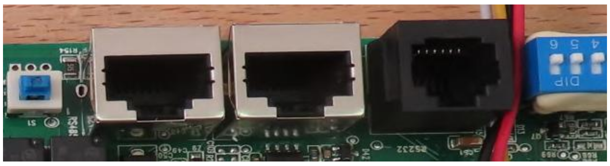


Figure 4.36: Communication Ports

The control board and the power board are shown below.

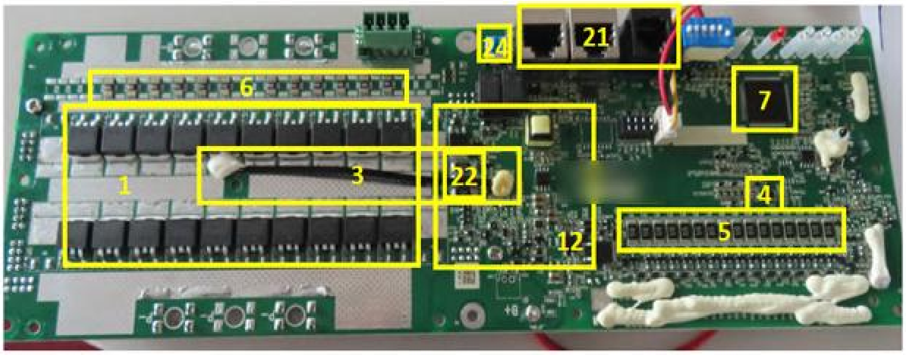


Figure 4.37: Control Board Front View

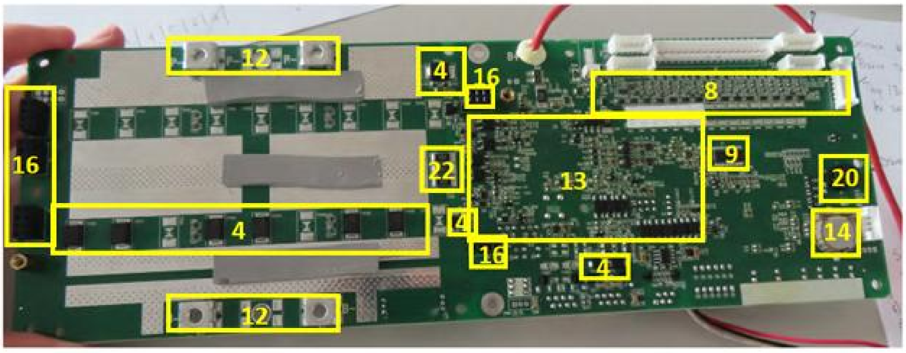


Figure 4.38: Control Board Back View

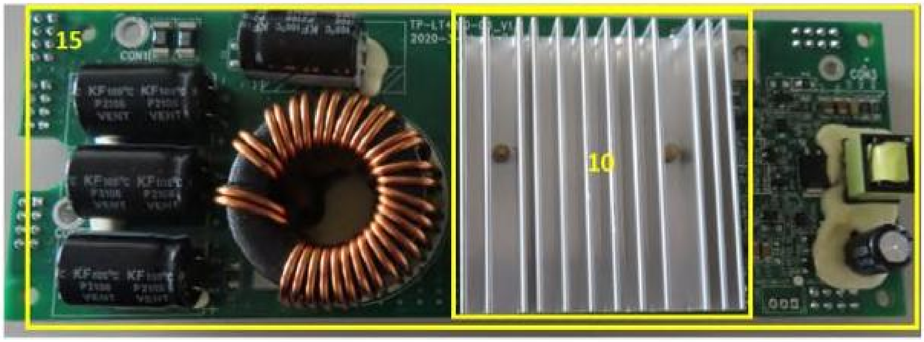


Figure 4.39: Power Board Front View

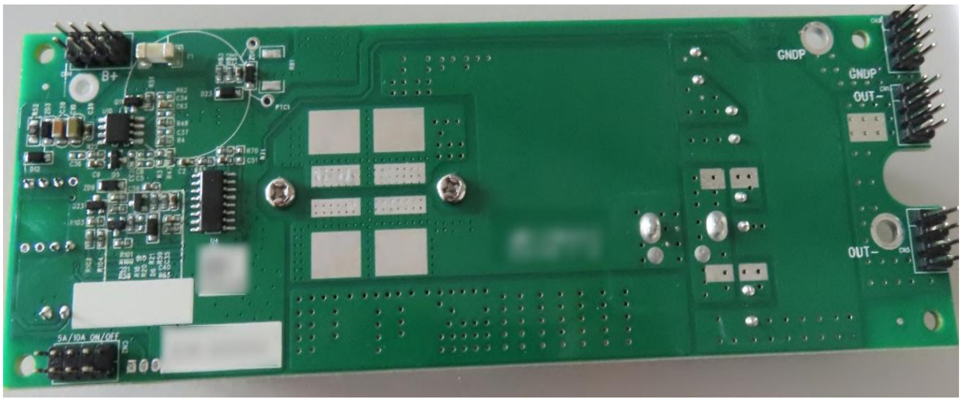


Figure 4.40: Power Board Back View

4.2.3 Internal resistance and OCV

OCV pack [V]		**RI pack [mΩ]**	
49,4		11,6	
OCV cells [V]		**RI cells [mΩ]**	
1	3,366	1	0,358
2	3,333	2	0,35
3	3,331	3	0,356
4	3,332	4	0,371
5	3,332	5	0,347
6	3,331	6	0,351
7	3,332	7	0,346
8	3,332	8	0,354
9	3,337	9	0,348
10	3,332	10	0,363
11	3,332	11	0,356
12	3,332	12	0,361
13	3,333	13	0,357
14	3,333	14	0,355
15	3,332	15	0,359

Table 4.11: Rint and OCV

4.3 Battery Pack n.3

Figure 4.41: Battery Pack n.3

The third battery considered has the following characteristics:

PACK RATE PARAMETERS	Voltage [V]	48
	Capacity [Ah]	100
	Energy [Wh]	4800
	Weight [kg]	44
	Height	4U
PACK FEATURES	Density [Wh/kg]	108.55
	Density [Wh/dm3]	117.21
	Standard charge	0,2C
	Standard discharge	0,2C
	Max charging current	1C
	Charge end voltage [V]	54.75
	Discharge end voltage [V]	37.5
CELLS CONFIGURATION	Configuration	15s1p
	Series n.	15
	Parallels n.	1
	Modules n.	1
	Cells n.	15

Table 4.12: Battery Pack Specifications

4.3.1 Design

	COMPONENTS	QTY	SINGLE ITEM WEIGHT [Kg]	TOT. WEIGHT [Kg]
1.	Cell	15	2.14	32.03
2.	Module	1	33.26	33.26
3.	Cell Restrain System	1	1.13	1.13
4.	Battery case	1	7.35	7.35
5.	BMS	1	0.6354	0.6354
6.	Anti Theft	0	/	/

Table 4.13: Battery Pack n.3 Components

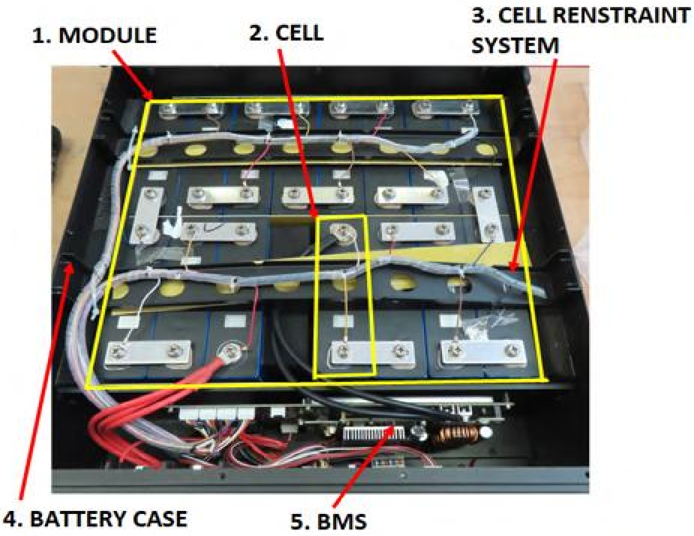


Figure 4.42: Internal of Battery Pack n.3

The cells are 15 grouped into only one module, unlike the previous ones that have two modules. They are separated by a fiber glass plastic foil, which is also placed on the top and bottom side to isolate the entire module from the battery case.

There are also some polystyrene blocks added on the side of the module to prevent damage from bumps, and one positioned in the space for the 16th cell.

(a) Cell (b) Internal of the Battery

Figure 4.43: Internal Design

The module, since it is only one, has the configuration 15s1p. The connections are made by metal busbars that are welded.
This battery pack has two metal bars to the module in position and divide sensing and thermocouple wires.

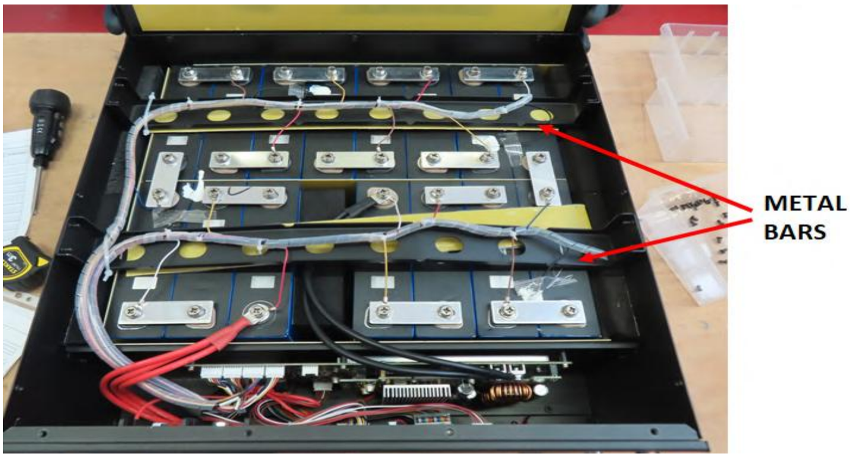


Figure 4.44: Restraint System

The front panel of this battery pack has the following characteristics:

1	POWER SUPPLY ANODE
2	POWER SUPPLY CATHODE
3	RESET BUTTON
4	DIAL SWITCH
5	DRY CONNECTION
6	RS232 PORT
7	RS485 PORT
8	RUNNING LIGHTS
9	ALARM INDICATOR
10	CAPACITY INDICATOR

Table 4.14: Front Panel Components

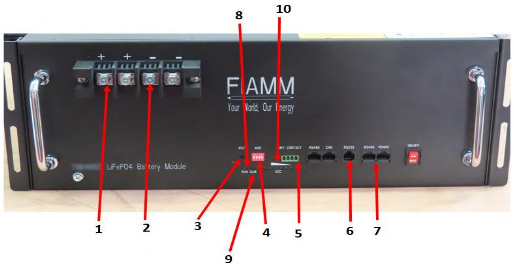


Figure 4.45: Front panel

The Battery Management System is anchored on a metal sheet with some screws.

4.3.2 Battery Management System

The BMS of the second battery is similar to the previous one.

	COMPONENTS	**QTY**		**COMPONENTS**	**QTY**
1	Safety mosfet	18	**14**	Battery button	1
2	Mosfet Driver	2	**15**	DC-DC	1
3	Termocouple	1	**16**	Electrical connector	6
4	Protection diode	12	**17**	Anti-theft	0
5	Passive Balancing	16	**18**	Display	0
6	Shunt	10	**19**	SNMP	0
7	Microcontroller	1	**20**	Buzzer	1
8	Conditioning pre-processing	1	**21**	Communication port	5
9	Analog Front-end	1	**22**	Polarization resistance	6
10	Heat sink	2	**23**	Transient suppression capacitors	0
11	Thermic conductive bar	0	**24**	Reset Button	1
12	Power Connectors	4	**25**	Additional Board	1
13	Power supply block	1			

Table 4.15: Principal Components of the BMS

7. Microcontroller: ST - 32F072VBT6 - ARM Cortex M0 32-bit

    - Flash Memory 128KB
    - 12b ADC
    - Maximum Frequency 48MHz
    - Voltage Operation Range 2.0 to 3.6V

9. AFE: AN9503A

    - Operating Voltage: 12.5 - 85
    - Max Series of Cells: 16
    - Features: Monitoring voltage, current and temperature, protection functions

14. Power Supply Block:

Figure 4.46: Power Supply Block

15. DC-DC: It is mounted separately from the control board.

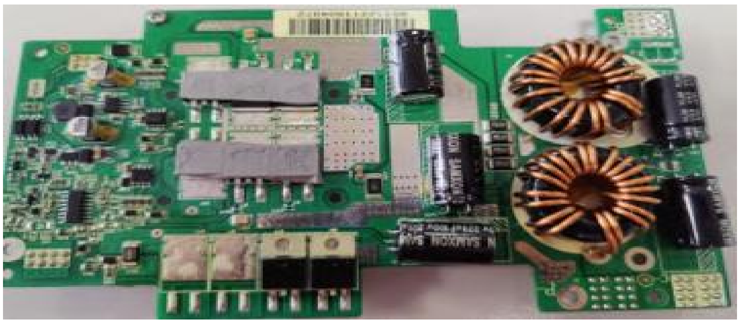


Figure 4.47: DC-DC

21. Communication Ports: In this pack, the communication ports are five, three RS485, one for CAN communication, one for RS232.

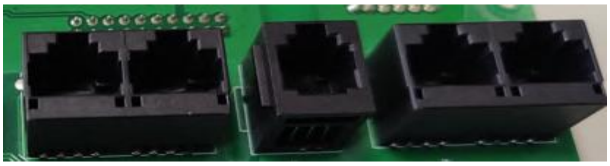


Figure 4.48: Communication Ports

The power board and the control board relative to the BMS of the pack are shown below.

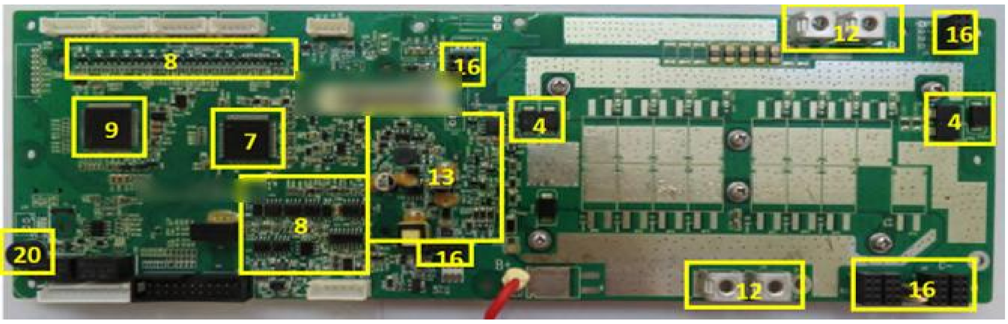


Figure 4.49: Control Board Front View

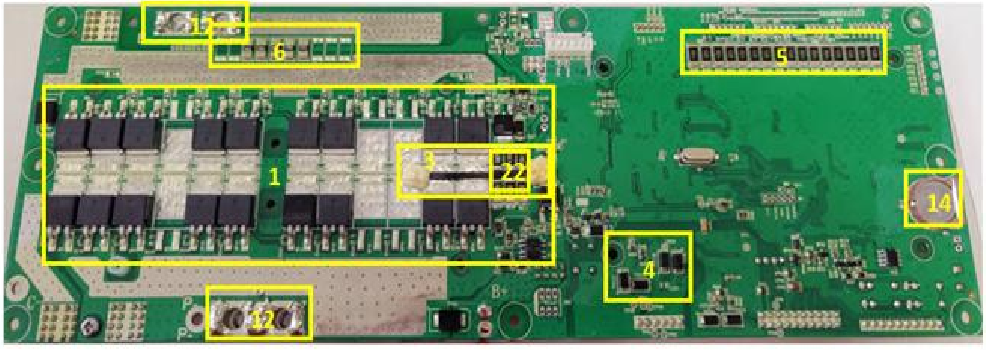


Figure 4.50: Control Board Back View

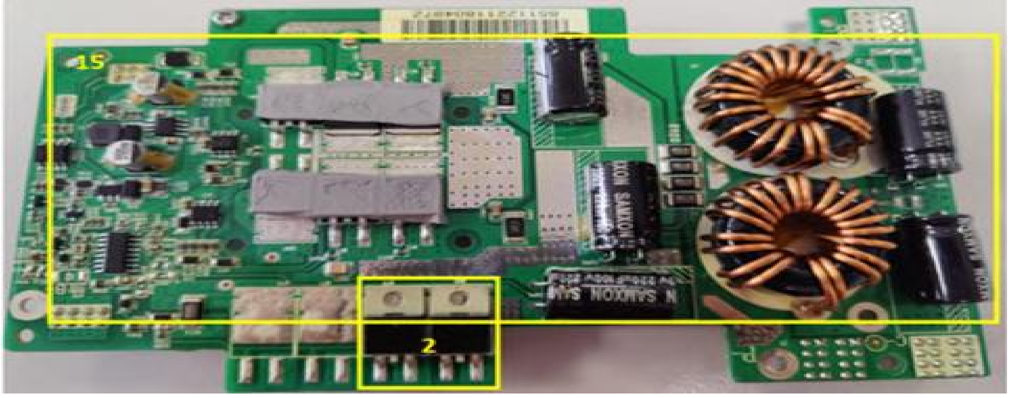


Figure 4.51: Power Board Front View

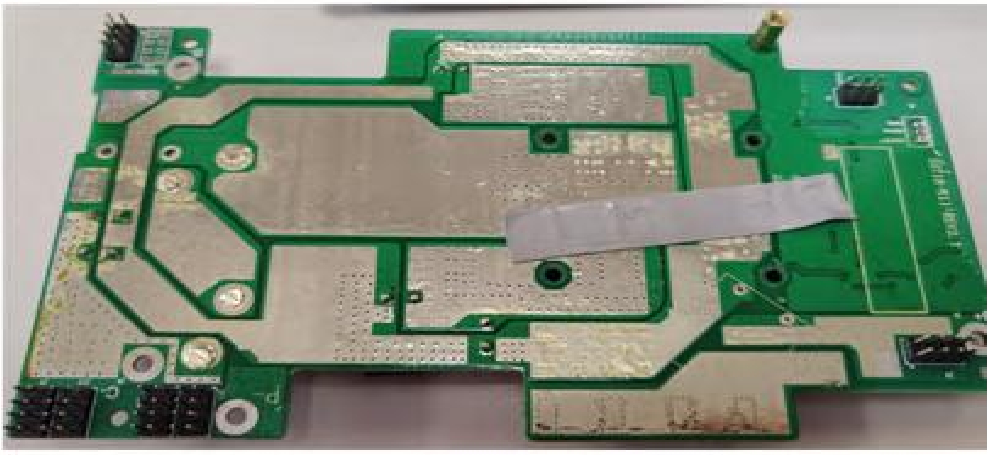


Figure 4.52: Power Board Back View

4.3.3 Internal Resistance and OCV

OCV pack [V]		**RI pack [mΩ]**	
49,4		11,6	
OCV cells [V]		**RI cells [mΩ]**	
1	3,366	1	0,358
2	3,333	2	0,35
3	3,331	3	0,356
4	3,332	4	0,371
5	3,332	5	0,347
6	3,331	6	0,351
7	3,332	7	0,346
8	3,332	8	0,354
9	3,337	9	0,348
10	3,332	10	0,363
11	3,332	11	0,356
12	3,332	12	0,361
13	3,333	13	0,357
14	3,333	14	0,355
15	3,332	15	0,359

Table 4.16: Internal Resistance and OCV

The cells are balanced also in this battery pack.

Chapter 5

Electrical Tests Performances

In this chapter, all the tests done for each battery pack are analyzed, comparing the data from the BMS and the Digatron. The plots[1] that are present in all the tests, except for the internal resistance, are:

- Voltage and Current;
- Cell Voltages;
- SOC and Current
- Temperatures
- A zoom on the principal step of the test.

All these graphs are in function of the time.

The charge of a battery can be done in different ways:

- Constant Voltage - CV: This profile consists in a charge with a constant voltage for the entire period of time. The current depends on the potential difference between the voltage supplied by the charger and the voltage at the battery, so the initial value of the current is high at the start of the charge that decreases gradually with the increase of the battery voltage;

---

[1] On appendix all the plots are shown.

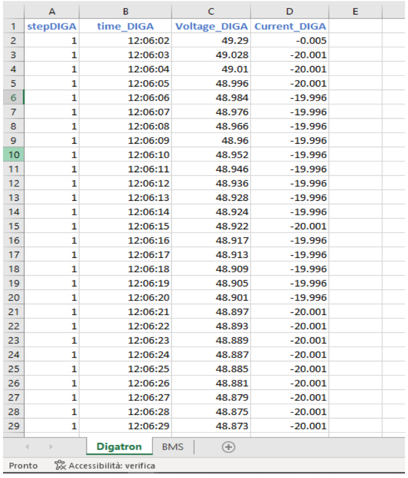
- Constant Current - CC: This profile consists in a constant current for all the period of the charge. It is helpful to limit the initial peak of the current;

- Float Charge: This method is used when the battery is at 100% of SOC to compensate the self-discharge. A current pulse is applied in a way that the battery remains always charged;

- A sequence of these methods.

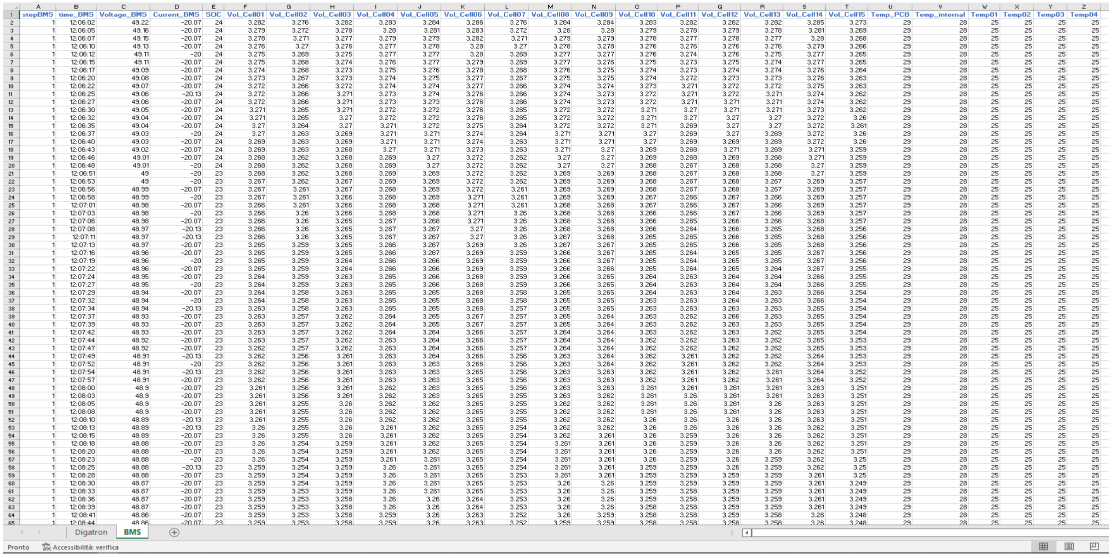
The profile used for these tests are the last one, specifically a Constant Current followed by a Constant Voltage. This means that the current remains constant until the voltage reaches the V_{EOC}. After that, the current starts to decrease and the voltage remains constant.

In order to do the various plots some MATLAB scripts are written. These are shown on *Appendix A*.
The excel file created in order to do the plots is the following. The data registered from the Digatron are the voltage, the current and the time. The BMS, in addition, registered also the cell voltages, the temperature of the cells, PCB and pack, the SOC remaining and the capacity accumulated.



	A	B	C	D	E
1	stepDIGA	time_DIGA	Voltage_DIGA	Current_DIGA	
2	1	12:06:02	49.29	-0.005	
3	1	12:06:03	49.028	-20.001	
4	1	12:06:04	49.01	-20.001	
5	1	12:06:05	48.996	-20.001	
6	1	12:06:06	48.984	-19.996	
7	1	12:06:07	48.976	-19.996	
8	1	12:06:08	48.966	-19.996	
9	1	12:06:09	48.96	-19.996	
10	1	12:06:10	48.952	-19.996	
11	1	12:06:11	48.946	-19.996	
12	1	12:06:12	48.936	-19.996	
13	1	12:06:13	48.928	-19.996	
14	1	12:06:14	48.924	-19.996	
15	1	12:06:15	48.922	-20.001	
16	1	12:06:16	48.917	-19.996	
17	1	12:06:17	48.913	-19.996	
18	1	12:06:18	48.909	-19.996	
19	1	12:06:19	48.905	-19.996	
20	1	12:06:20	48.901	-19.996	
21	1	12:06:21	48.897	-20.001	
22	1	12:06:22	48.893	-20.001	
23	1	12:06:23	48.889	-20.001	
24	1	12:06:24	48.887	-20.001	
25	1	12:06:25	48.885	-20.001	
26	1	12:06:26	48.881	-20.001	
27	1	12:06:27	48.879	-20.001	
28	1	12:06:28	48.875	-20.001	
29	1	12:06:29	48.873	-20.001	

Figure 5.1: Digatron data Sheet for Matlab



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	stepBMS	time_BMS	Voltage_BMS	Current_BMS	SOC	Vol_Cell01	Vol_Cell02	Vol_Cell03	Vol_Cell04	Vol_Cell05	Vol_Cell06	Vol_Cell07	Vol_Cell08	Vol_Cell09	Vol_Cell10	Vol_Cell11	Vol_Cell12	Vol_Cell13	Vol_Cell14	Vol_Cell15	Temp_PCB	Temp_internal	Temp01	Temp02	Temp03	Temp04
2	1	12:06:02	49.22	-20.07	24	3.282	3.276	3.282	3.283	3.284	3.286	3.276	3.284	3.284	3.283	3.282	3.282	3.282	3.285	3.273	29	28	25	25	25	25
3	1	12:06:05	49.16	-20.07	24	3.279	3.272	3.278	3.28	3.281	3.283	3.272	3.28	3.28	3.279	3.278	3.279	3.278	3.281	3.269	29	28	25	25	25	25
4	1	12:06:07	49.15	-20.07	24	3.278	3.271	3.277	3.279	3.279	3.282	3.271	3.279	3.279	3.278	3.277	3.278	3.277	3.28	3.268	29	28	25	25	25	25
5	1	12:06:10	49.13	-20.07	24	3.276	3.27	3.276	3.277	3.278	3.28	3.27	3.278	3.278	3.276	3.276	3.276	3.276	3.279	3.266	29	28	25	25	25	25
6	1	12:06:12	49.11	-20	24	3.275	3.269	3.275	3.277	3.277	3.28	3.269	3.277	3.277	3.276	3.274	3.276	3.275	3.277	3.265	29	28	25	25	25	25
7	1	12:06:15	49.11	-20.07	24	3.275	3.268	3.274	3.276	3.277	3.279	3.269	3.277	3.276	3.275	3.273	3.275	3.274	3.277	3.265	29	28	25	25	25	25
8	1	12:06:17	49.09	-20.07	24	3.274	3.268	3.273	3.275	3.276	3.278	3.268	3.276	3.275	3.274	3.273	3.274	3.274	3.276	3.264	29	28	25	25	25	25
9	1	12:06:20	49.08	-20.07	24	3.273	3.267	3.273	3.274	3.275	3.277	3.267	3.275	3.275	3.274	3.272	3.273	3.273	3.276	3.263	29	28	25	25	25	25
10	1	12:06:22	49.07	-20.07	24	3.272	3.266	3.272	3.274	3.274	3.277	3.266	3.274	3.274	3.273	3.271	3.272	3.272	3.275	3.263	29	28	25	25	25	25
11	1	12:06:25	49.06	-20.13	24	3.272	3.266	3.271	3.273	3.274	3.276	3.266	3.274	3.273	3.272	3.271	3.272	3.271	3.274	3.262	29	28	25	25	25	25
12	1	12:06:27	49.06	-20.07	24	3.272	3.266	3.271	3.273	3.273	3.276	3.266	3.274	3.273	3.272	3.271	3.271	3.271	3.274	3.262	29	28	25	25	25	25
13	1	12:06:30	49.05	-20.07	24	3.271	3.265	3.271	3.272	3.272	3.276	3.265	3.272	3.272	3.271	3.27	3.271	3.271	3.273	3.262	29	28	25	25	25	25
14	1	12:06:32	49.04	-20.07	24	3.271	3.265	3.27	3.272	3.272	3.276	3.265	3.272	3.272	3.271	3.27	3.27	3.27	3.272	3.26	29	28	25	25	25	25
15	1	12:06:35	49.04	-20.07	24	3.27	3.264	3.27	3.271	3.272	3.275	3.264	3.272	3.272	3.271	3.269	3.27	3.27	3.272	3.261	29	28	25	25	25	25
16	1	12:06:37	49.03	-20	24	3.27	3.263	3.269	3.271	3.271	3.274	3.264	3.271	3.271	3.27	3.269	3.27	3.269	3.272	3.26	29	28	25	25	25	25
17	1	12:06:40	49.03	-20.07	24	3.269	3.263	3.269	3.271	3.271	3.274	3.263	3.271	3.271	3.27	3.269	3.269	3.269	3.272	3.26	29	28	25	25	25	25
18	1	12:06:43	49.02	-20.07	24	3.269	3.263	3.268	3.27	3.271	3.273	3.263	3.271	3.27	3.269	3.268	3.271	3.269	3.271	3.259	29	28	25	25	25	25
19	1	12:06:46	49.01	-20.07	24	3.268	3.262	3.268	3.269	3.27	3.272	3.262	3.27	3.27	3.269	3.268	3.269	3.268	3.271	3.259	29	28	25	25	25	25
20	1	12:06:48	49.01	-20	24	3.268	3.262	3.268	3.269	3.27	3.272	3.262	3.27	3.27	3.268	3.267	3.268	3.268	3.27	3.259	29	28	25	25	25	25
21	1	12:06:51	49	-20	23	3.268	3.262	3.268	3.269	3.269	3.272	3.262	3.269	3.269	3.268	3.267	3.268	3.268	3.27	3.259	29	28	25	25	25	25
22	1	12:06:53	49	-20	23	3.267	3.262	3.267	3.269	3.269	3.272	3.262	3.269	3.269	3.268	3.267	3.268	3.267	3.269	3.257	29	28	25	25	25	25
23	1	12:06:56	48.99	-20.07	23	3.267	3.261	3.267	3.268	3.269	3.272	3.261	3.269	3.269	3.268	3.267	3.268	3.267	3.269	3.257	29	28	25	25	25	25
24	1	12:06:58	48.99	-20	23	3.267	3.261	3.266	3.268	3.269	3.271	3.261	3.269	3.269	3.267	3.266	3.267	3.266	3.269	3.257	29	28	25	25	25	25
25	1	12:07:01	48.98	-20.07	23	3.266	3.261	3.266	3.268	3.268	3.271	3.261	3.268	3.268	3.267	3.266	3.267	3.266	3.269	3.257	29	28	25	25	25	25
26	1	12:07:03	48.98	-20	23	3.266	3.26	3.266	3.268	3.268	3.271	3.26	3.268	3.268	3.266	3.266	3.267	3.266	3.269	3.257	29	28	25	25	25	25
27	1	12:07:06	48.98	-20.07	23	3.266	3.26	3.265	3.267	3.268	3.271	3.26	3.268	3.268	3.266	3.265	3.266	3.266	3.268	3.257	29	28	25	25	25	25
28	1	12:07:08	48.97	-20.13	23	3.266	3.26	3.265	3.267	3.267	3.27	3.26	3.268	3.268	3.266	3.264	3.266	3.265	3.268	3.256	29	28	25	25	25	25
29	1	12:07:11	48.97	-20.13	23	3.266	3.26	3.265	3.267	3.267	3.27	3.26	3.267	3.268	3.265	3.265	3.266	3.265	3.268	3.256	29	28	25	25	25	25
30	1	12:07:13	48.97	-20.07	23	3.265	3.259	3.265	3.266	3.267	3.269	3.26	3.267	3.267	3.265	3.265	3.266	3.265	3.268	3.256	29	28	25	25	25	25
31	1	12:07:16	48.96	-20.07	23	3.265	3.259	3.265	3.266	3.267	3.269	3.259	3.266	3.267	3.265	3.264	3.265	3.265	3.267	3.256	29	28	25	25	25	25
32	1	12:07:19	48.96	-20	23	3.265	3.259	3.264	3.266	3.266	3.269	3.259	3.266	3.267	3.265	3.264	3.265	3.265	3.267	3.256	29	28	25	25	25	25
33	1	12:07:22	48.96	-20.07	23	3.265	3.259	3.264	3.266	3.266	3.269	3.259	3.266	3.266	3.265	3.264	3.265	3.264	3.267	3.255	29	28	25	25	25	25
34	1	12:07:24	48.95	-20.07	23	3.264	3.259	3.263	3.265	3.266	3.268	3.259	3.266	3.265	3.264	3.263	3.264	3.264	3.266	3.255	29	28	25	25	25	25
35	1	12:07:27	48.95	-20	23	3.264	3.259	3.263	3.265	3.266	3.268	3.259	3.266	3.265	3.264	3.263	3.264	3.264	3.266	3.255	29	28	25	25	25	25
36	1	12:07:29	48.94	-20.07	23	3.264	3.258	3.263	3.265	3.265	3.268	3.258	3.265	3.265	3.264	3.263	3.264	3.263	3.266	3.254	29	28	25	25	25	25
37	1	12:07:32	48.94	-20	23	3.264	3.258	3.263	3.265	3.265	3.268	3.258	3.265	3.265	3.263	3.263	3.264	3.263	3.266	3.254	29	28	25	25	25	25
38	1	12:07:34	48.94	-20.13	23	3.263	3.258	3.263	3.265	3.265	3.268	3.257	3.265	3.265	3.263	3.263	3.263	3.263	3.265	3.254	29	28	25	25	25	25
39	1	12:07:37	48.93	-20.07	23	3.263	3.257	3.262	3.264	3.265	3.267	3.257	3.265	3.264	3.263	3.262	3.266	3.263	3.265	3.254	29	28	25	25	25	25
40	1	12:07:39	48.93	-20.07	23	3.263	3.257	3.262	3.264	3.265	3.267	3.257	3.265	3.264	3.263	3.262	3.263	3.263	3.265	3.254	29	28	25	25	25	25
41	1	12:07:42	48.93	-20.07	23	3.263	3.257	3.262	3.264	3.264	3.266	3.257	3.264	3.264	3.263	3.262	3.263	3.262	3.265	3.254	29	28	25	25	25	25
42	1	12:07:44	48.92	-20.07	23	3.263	3.257	3.262	3.263	3.264	3.266	3.257	3.264	3.264	3.262	3.262	3.263	3.262	3.265	3.253	29	28	25	25	25	25
43	1	12:07:47	48.92	-20.07	23	3.262	3.257	3.262	3.263	3.264	3.266	3.257	3.264	3.264	3.262	3.262	3.262	3.262	3.265	3.253	29	28	25	25	25	25
44	1	12:07:49	48.91	-20.13	23	3.262	3.256	3.261	3.263	3.264	3.266	3.256	3.263	3.264	3.262	3.261	3.262	3.262	3.264	3.253	29	28	25	25	25	25
45	1	12:07:52	48.91	-20	23	3.262	3.256	3.261	3.263	3.263	3.266	3.256	3.263	3.264	3.262	3.261	3.262	3.262	3.264	3.253	29	28	25	25	25	25
46	1	12:07:54	48.91	-20.13	23	3.262	3.256	3.261	3.263	3.263	3.265	3.256	3.263	3.263	3.262	3.261	3.262	3.261	3.264	3.252	29	28	25	25	25	25
47	1	12:07:57	48.91	-20.07	23	3.262	3.256	3.261	3.263	3.263	3.265	3.256	3.263	3.263	3.262	3.261	3.262	3.261	3.264	3.252	29	28	25	25	25	25
48	1	12:08:00	48.9	-20.07	23	3.261	3.256	3.261	3.262	3.263	3.265	3.256	3.263	3.263	3.261	3.261	3.261	3.261	3.263	3.251	29	28	25	25	25	25
49	1	12:08:03	48.9	-20.07	23	3.261	3.256	3.261	3.262	3.263	3.265	3.255	3.263	3.262	3.261	3.26	3.261	3.261	3.263	3.251	29	28	25	25	25	25
50	1	12:08:05	48.9	-20.07	23	3.261	3.255	3.26	3.262	3.262	3.265	3.255	3.262	3.262	3.261	3.26	3.261	3.26	3.263	3.251	29	28	25	25	25	25
51	1	12:08:08	48.9	-20.07	23	3.261	3.255	3.26	3.262	3.262	3.265	3.255	3.262	3.262	3.261	3.26	3.261	3.26	3.263	3.251	29	28	25	25	25	25
52	1	12:08:10	48.89	-20.13	23	3.261	3.255	3.26	3.262	3.262	3.265	3.255	3.262	3.262	3.26	3.26	3.26	3.26	3.263	3.251	29	28	25	25	25	25
53	1	12:08:13	48.89	-20.13	23	3.26	3.255	3.26	3.261	3.262	3.265	3.254	3.262	3.262	3.26	3.26	3.26	3.26	3.262	3.251	29	28	25	25	25	25
54	1	12:08:15	48.89	-20.07	23	3.26	3.255	3.26	3.261	3.262	3.265	3.254	3.262	3.261	3.26	3.259	3.26	3.26	3.262	3.251	29	28	25	25	25	25
55	1	12:08:18	48.88	-20.07	23	3.26	3.254	3.259	3.261	3.262	3.265	3.254	3.261	3.261	3.26	3.259	3.26	3.26	3.262	3.251	29	28	25	25	25	25
56	1	12:08:20	48.88	-20.07	23	3.26	3.254	3.259	3.261	3.262	3.265	3.254	3.261	3.261	3.26	3.259	3.26	3.26	3.262	3.251	29	28	25	25	25	25
57	1	12:08:23	48.88	-20	23	3.26	3.254	3.259	3.261	3.261	3.265	3.254	3.261	3.261	3.26	3.259	3.26	3.259	3.262	3.25	29	28	25	25	25	25
58	1	12:08:25	48.88	-20.13	23	3.259	3.254	3.259	3.26	3.261	3.265	3.254	3.261	3.261	3.259	3.259	3.26	3.259	3.262	3.25	29	28	25	25	25	25
59	1	12:08:28	48.88	-20.07	23	3.259	3.254	3.259	3.26	3.261	3.265	3.253	3.261	3.261	3.259	3.259	3.259	3.259	3.261	3.25	29	28	25	25	25	25
60	1	12:08:30	48.87	-20.07	23	3.259	3.254	3.259	3.26	3.261	3.265	3.253	3.26	3.26	3.259	3.259	3.259	3.259	3.261	3.249	29	28	25	25	25	25
61	1	12:08:33	48.87	-20.07	23	3.259	3.253	3.259	3.26	3.261	3.265	3.253	3.26	3.26	3.259	3.258	3.259	3.259	3.261	3.249	29	28	25	25	25	25
62	1	12:08:36	48.87	-20.07	23	3.259	3.253	3.258	3.26	3.26	3.264	3.253	3.26	3.26	3.259	3.258	3.259	3.259	3.261	3.249	29	28	25	25	25	25
63	1	12:08:39	48.87	-20.07	23	3.259	3.253	3.258	3.26	3.26	3.264	3.253	3.26	3.26	3.258	3.258	3.259	3.259	3.261	3.249	29	28	25	25	25	25
64	1	12:08:41	48.86	-20.07	23	3.259	3.253	3.258	3.259	3.26	3.263	3.252	3.26	3.259	3.258	3.258	3.259	3.258	3.26	3.248	29	28	25	25	25	25
65	1	12:08:44	48.86	-20.07	23	3.259	3.253	3.258	3.259	3.26	3.263	3.252	3.259	3.259	3.258	3.258	3.258	3.258	3.26	3.248	29	28	25	25	25	25

Figure 5.2: BMS data Sheet for Matlab

To avoid putting all the graphs in the following chapters, it was preferred to include the most important ones here and to include all them in the Appendix B.

The capacity charged or discharged is taken from the Digatron log, because it is more accurate than the battery monitoring system and the sensing of the Digatron is directly connected to the battery terminals.

The BMS data were extrapolated from the software logger. The main window of a software contains several information and features. A screenshot is shown below.

[redacted]

Pack Information
Pack Voltage 53.826 V
Pack Current 18.15 A
SOC 100 %
SOH 100 %
RemainCapacity 95190 mAH
FullCapacity 95190 mAH
Battery Cycle 2

Temperature
Tcell 1 23.8 ℃
Tcell 2 23.7 ℃
Tcell 3 23.9 ℃
Tcell 4 23.9 ℃
MOS_T 25.2 ℃
ENV_T 27.4 ℃

Cell Voltage(mV)
MaxVolt 15 3613
MinVolt 4 3570
VoltDiff 43

Vcell 1 3587
Vcell 2 3583
Vcell 3 3577
Vcell 4 3570
Vcell 5 3580
Vcell 6 3590
Vcell 7 3572
Vcell 8 3579
Vcell 9 3590
Vcell 10 3570
Vcell 11 3610 BL
Vcell 12 3607 BL
Vcell 13 3606 BL
Vcell 14 3592
Vcell 15 3613 BL
Vcell 16

Serial Port
Port COM8
Baud Rate 9600
☐ Auto Display
Pack 1
Pack Qty 1
ADDR 0
Interval(S) 1

System Status
●CHARGING-ON ●CHARGING ●CHG-LIMIT-OFF ●ACin
●DISCHARGING-ON ●DISCHARGING ●HEATER-OFF ●Fully

Alarm Status
Cell OV

Protect Status
None

Fault Status
None

Switch Control
CHG Circuit Close
Sound Alarm Open
DSG Circuit Close
LED Alarm Close
Shutdown Off

Password *****

[redacted] | PACK S/N: | COMM: Normal

08:08:17
2022-10-10

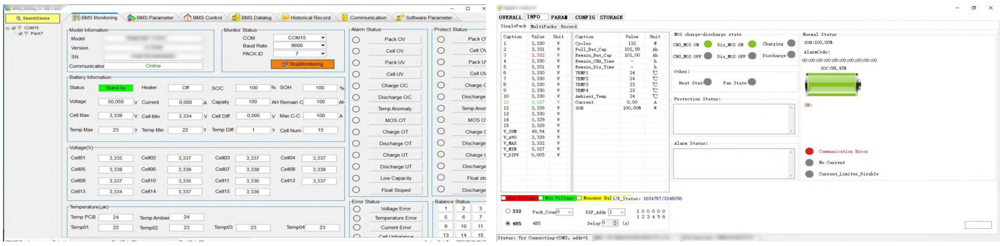
Figure 5.3: Software Main Window Pack n.3

The software of the pack n.3 is one of the most complete. As it can be seen there are multiple box:

- Pack Information: in this box the main informations are present that are voltage, current, state of charge and state of health, the total and remaining capacity and the number of cycles already done;
- Temperature: all the four temperatures taken from the thermocouples, the board one and the internal temperature are present.
- Cell Voltages: the fifteen cell voltages are shown, with the maximum and minimum ones and sometimes with the difference. An important feature, that not all the software have, is the balancing status, highlighted with a color or written near the cell voltages. Thanks to this, it is possible to see which cell is being balanced;
- Alarm/Protect/Fault Status: in these boxes are highlighted if an alarm, protection or fault is ongoing;
- Switch Control: this software feature is not present sometimes, but it is useful in order to switch the status of the mosfets or to shutdown the BMS manually;
- Serial Port: here are reported all the information about the communication.

The software is able to save the data registered. These data is upload in a excel or txt file. Sometimes, an autosave function is present in order to keep all the data saved.

Another possibility that a producer can implement in a software is to change the threshold parameters like the protection ones, the alarm or the limit charging function. This feature sometimes is locked with a password, that is possible to change. In this document are not shown the software of the other two batteries because they are similar to the one analyzed above. The main differences are the presence of the autosave, the switch control box and the way as the data are saved. Below all the other two main windows are shown.



(a) Main Window Pack n.1

(b) Main Window Pack n.2

Figure 5.4: Main Windows

The software of the pack n.1 is not optimized, there are some visual bugs and the informations sometimes are not comprehensive.
All the software, then, are evaluated in order to compare all the packs.

5.1 Battery Pack n.1 Performances

The principal parameters of the battery pack are summarized in this table.

<table>
<tr><th colspan="3">Battery Specification</th></tr>
<tr><td colspan="2">Nominal Voltage</td><td>48V</td></tr>
<tr><td colspan="2">Internal Resistance</td><td><30mΩ</td></tr>
<tr><td colspan="2">Normal Charge Voltage</td><td>52.5V - 54.0V</td></tr>
<tr><td colspan="2">Allowed Max Charge</td><td>50A</td></tr>
<tr><td colspan="2">Charge Current Limitation</td><td>10A</td></tr>
<tr><td colspan="2">End Of Discharge Voltage</td><td>42.2V - 44.0V</td></tr>
<tr><td colspan="2">Cycle Life</td><td>>2000 cycles</td></tr>
<tr><th colspan="3">Electrical Characteristics & Tests Conditions</th></tr>
<tr><td rowspan="3">Over Charge</td><td>Protection</td><td>55.5V</td></tr>
<tr><td>Protection delay time</td><td>1s</td></tr>
<tr><td>Protection release</td><td>54.0V</td></tr>
<tr><td rowspan="3">Over Discharge</td><td>Protection</td><td>40.5V</td></tr>
<tr><td>Protection delay time</td><td>1s</td></tr>
<tr><td>Protection release</td><td>43.5V</td></tr>
<tr><td rowspan="10">Over Current</td><td>Charge Protection</td><td>110A</td></tr>
<tr><td>Protection delay time</td><td>1s</td></tr>
<tr><td>Protection release time</td><td>about 60s</td></tr>
<tr><td>Charge Limitation Current</td><td>10A</td></tr>
<tr><td>Discharge Protection 1</td><td>>110A</td></tr>
<tr><td>Protection delay time</td><td>1s</td></tr>
<tr><td>Protection release time</td><td>about 60s</td></tr>
<tr><td>Discharge Protection 2</td><td>>120A</td></tr>
<tr><td>Protection delay time</td><td>500ms</td></tr>
<tr><td>Protection release time</td><td>about 60s</td></tr>
</table>

Table 5.1: Battery Datasheet

5.1.1 OCV and Internal DC Resistance

First of all, it can be seen that the measurements registered from the BMS are a bit different from the ones taken from Digatron. This happens because the data logging of the BMS is less accurate compared to the cycler. This first test helps to find the best voltage values, V_{EOD} and V_{EOC}, because with 44V, for example, the capacity discharged was under 100Ah, same for the charge with 52.5V. The final values so are respectively for charge and discharge, 53.5V and 43V. During the charge, at the end of it, there is a voltage peak detected from the Digatron (about 65V): this value is not to be taken into account because the opening of the mosfets at end of charge, due to overvoltage, raises the voltage. From Figure 5.6 it can notice that some cells are not balanced, especially the cell n. 2 that reaches almost 3.8V, that is the cell overvoltage value imposed via software by the producer. The results of this test are

$$R_{int} = 16.388 m\Omega$$

from Digatron data, and

$$R_{int} = 10.375 m\Omega$$

from BMS data logger.
The OCV is about 49.41V.

Digatron data		**BMS data**	
U1 (V)	48.849	**U1 (V)**	49.04
U2 (V)	47,538	**U2 (V)**	48.21
I1 (A)	20	**I1 (A)**	20
I2 (A)	100	**I2 (A)**	100
Rdc mesaured (mΩ)	16.388	**Rdc mesaured (mΩ)**	10.375

Table 5.2: Summary Results for the Internal Resistance

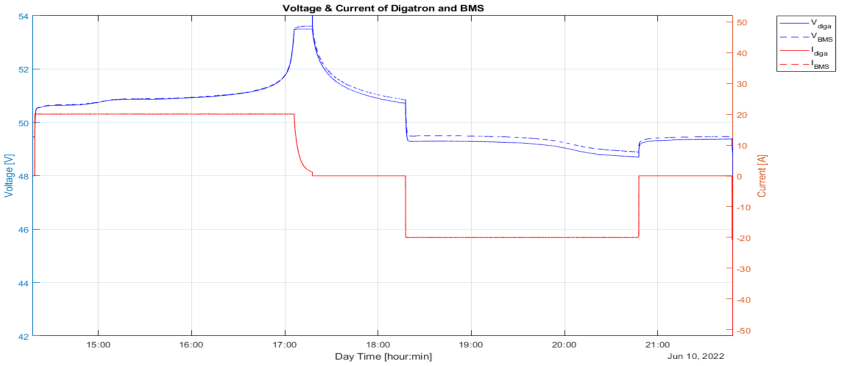


Figure 5.5: V and I

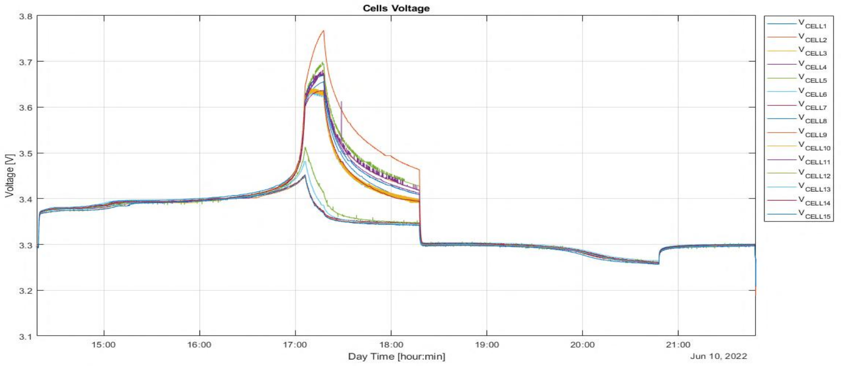


Figure 5.6: Cell Voltages

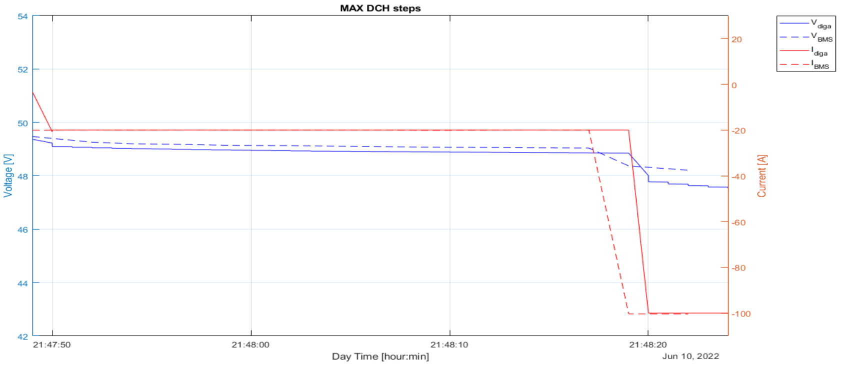


Figure 5.7: Discharge Steps

5.1.2 Capacity Tests

Discharge at 0.5C

The first tests after the internal resistance one, are the capacity tests, in particular the discharge ones.

Like the previous test, some cells are unbalanced with respect to the others. The capacity discharged with a rate of 0.5C is about 102Ah. With a high discharge rate the amount of energy that can be extracted from the battery is less than the one with a standard discharge, so it is expected that with the next tests, the capacity discharged is more than this one.

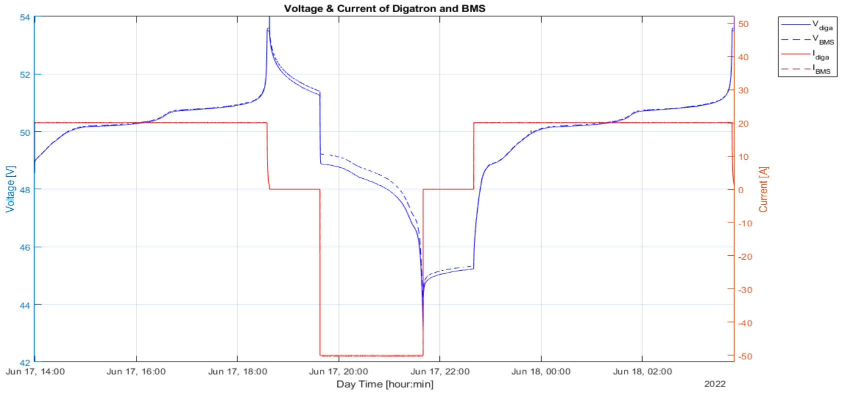


Figure 5.8: DCH05C - V and I

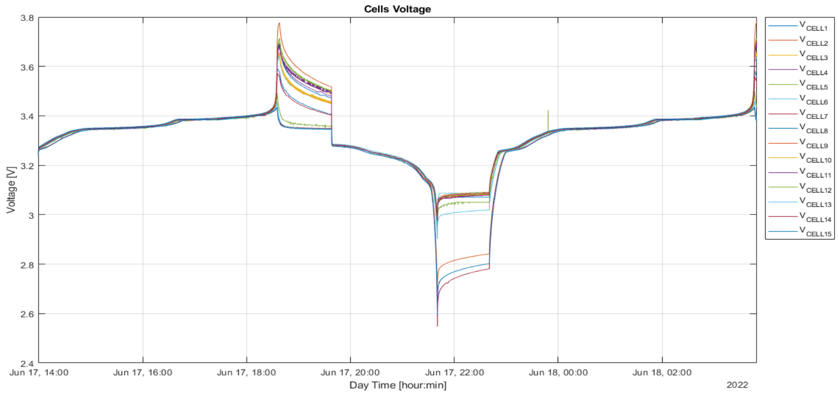


Figure 5.9: DCH05C - Cell Voltages

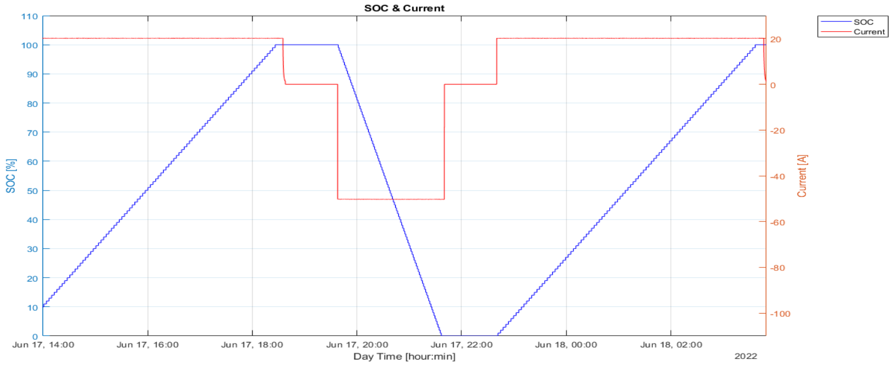


Figure 5.10: DCH05C - SOC and I

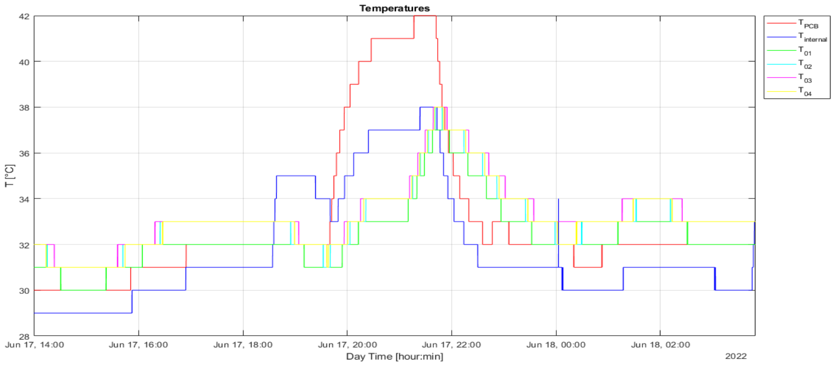


Figure 5.11: DCH05C - Temperatures

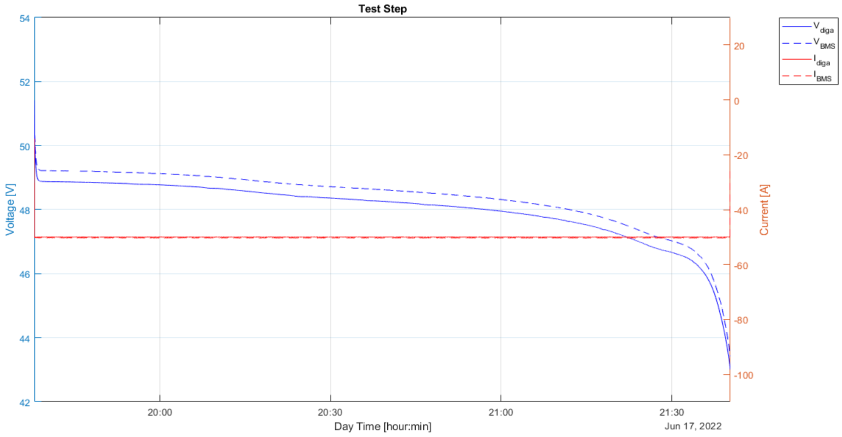


Figure 5.12: DCH05C - Discharge Steps

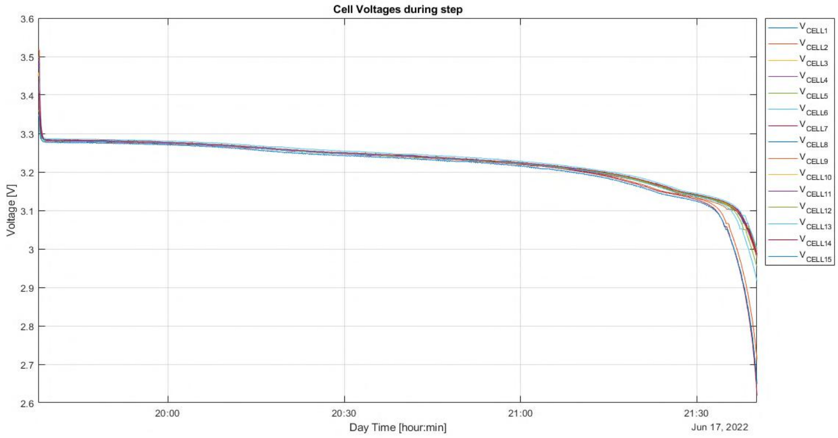


Figure 5.13: DCH05C - Discharge Steps - Cell Voltages

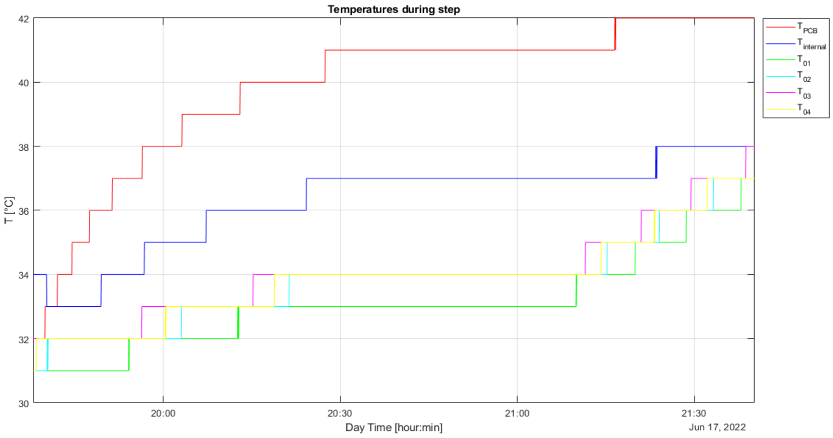


Figure 5.14: DCH05C - Discharge Steps - Temperatures

Discharge at 0.2C

In this test, during the last charge, after the battery was completely discharged (0% SOC), the current did not reach the 20A set. This implies a current limitation. When the voltage drops to 45V or less, the current is limited at about 8A. This is done by the manufacturer in order to preserve the life of the battery. Also the internal resistance at low SOC is higher, and high temperature can deteriorate the battery. However, this condition causes a problem with the Digatron, which enters in an error state whenever this has not been done. To manage this issue, the pack has been charged with an external power supply with a current below 8A until 45V is reached, and then, the BMS released the protection.

Another way to get around this procedure is to remove current limitation via software, but due to an error on the application, it has not been done. This problem occurred in all the tests except for the previous one and for high discharge rate tests in which the relaxation voltage goes up rapidly and reaches 45V.

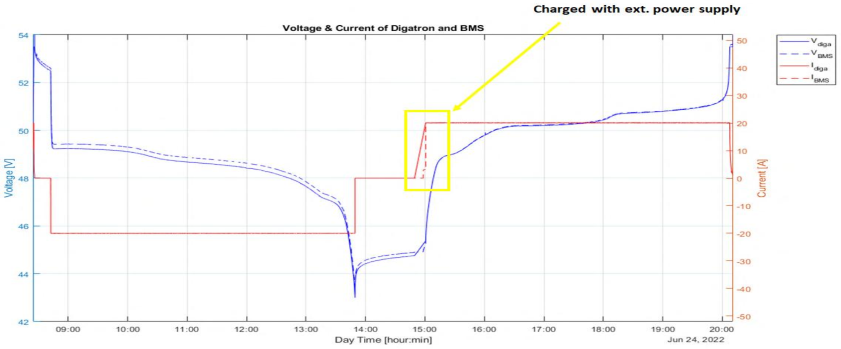

Charged with ext. power supply

Figure 5.15: DCH02C - V and I

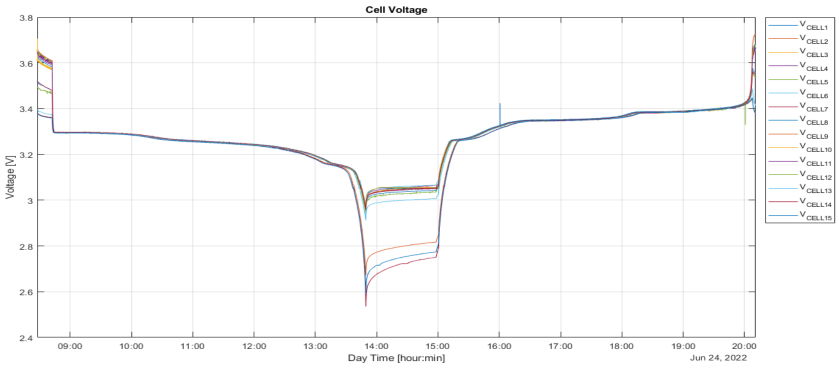


Figure 5.16: DCH02C - Cell Voltages

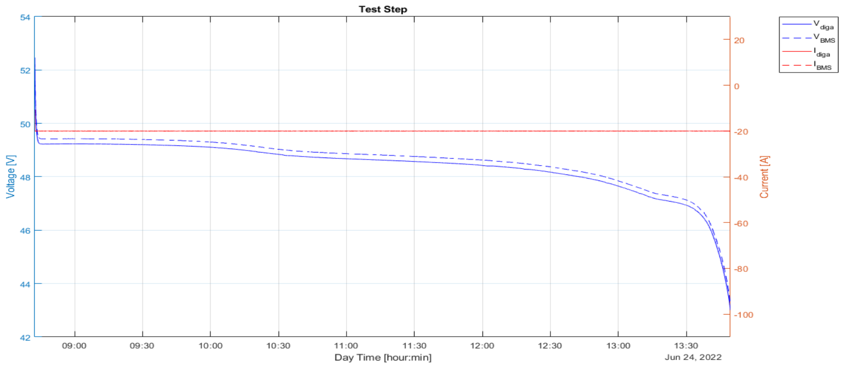


Figure 5.17: DCH02C - Discharge Steps

Discharge at 0.1C

On plot 5.18 the last charge is missing due to the limitation of the current that leads to use an external power supply and restart the Digatron program. This step is shown in Figure 5.21.

The capacity discharged in this test and in the previous ones, is higher than the one discharged with a 0.5C rate, as expected.

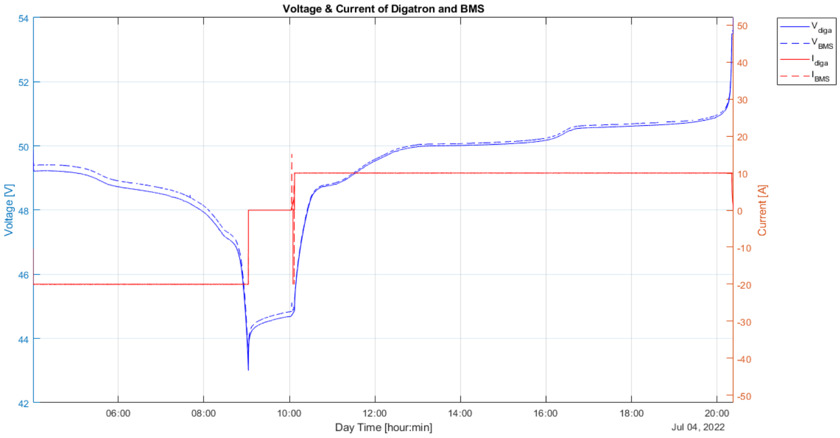


Figure 5.18: DCH01C - V and I

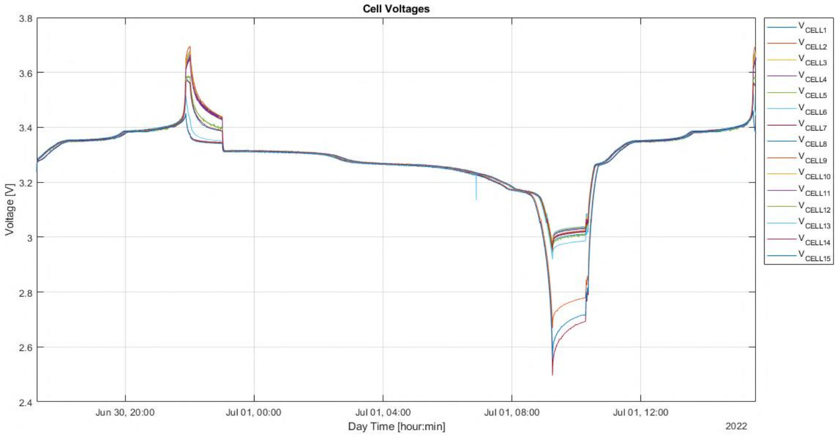


Figure 5.19: DCH01C - Cell Voltages

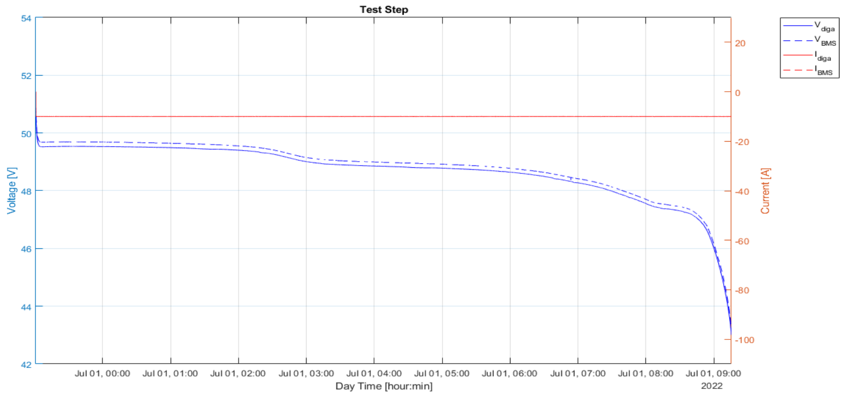


Figure 5.20: DCH01C - Discharge Steps

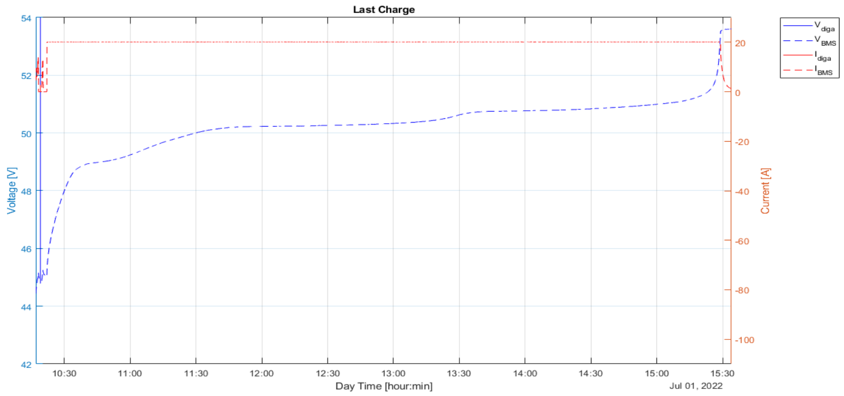


Figure 5.21: DCH01C - Last Charge

Discharge at 1C

In this test the limitation occurred during the first charge, so the Digatron did not register the first charge. Instead after the discharge at 1C, as explained above, the relaxation voltage goes up rapidly at 45V so the limitation did not take place.

On the plot 5.24, the starting value of the SOC is 50%. This value is not correct because before this test, a reset was done, trying to avoid the current limitation. This was done before an external power supply was used.

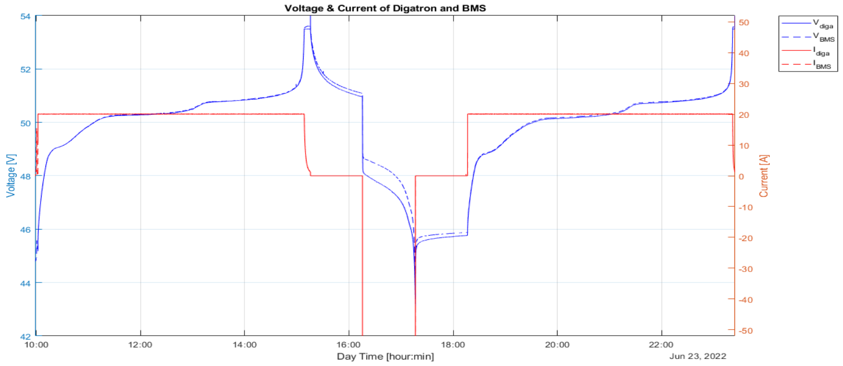


Figure 5.22: DCH1C - V and I

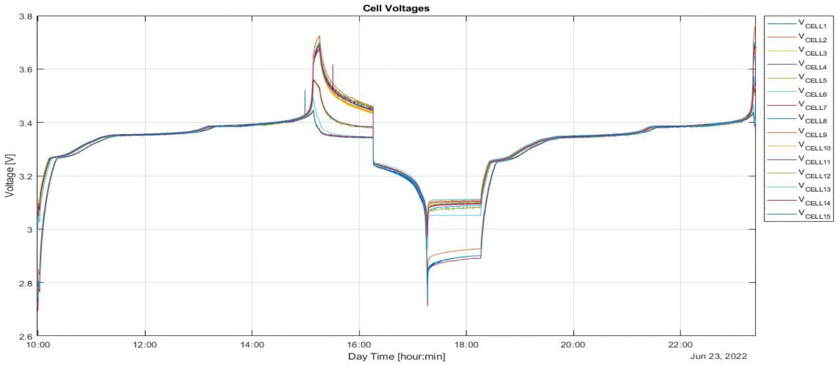


Figure 5.23: DCH1C - Cell Voltages

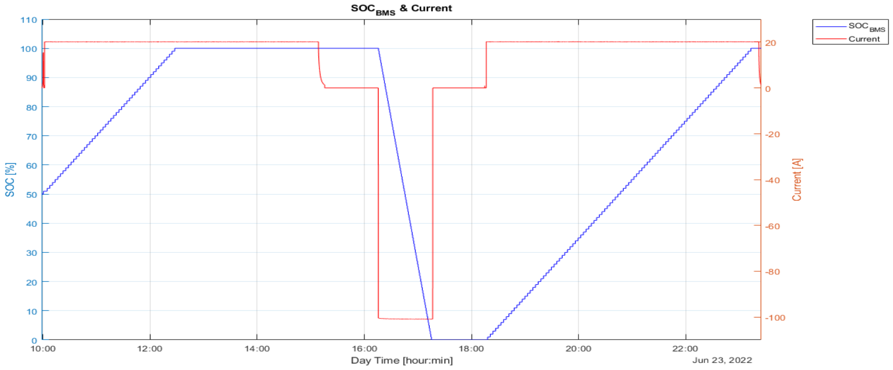


Figure 5.24: DCH1C - SOC and I

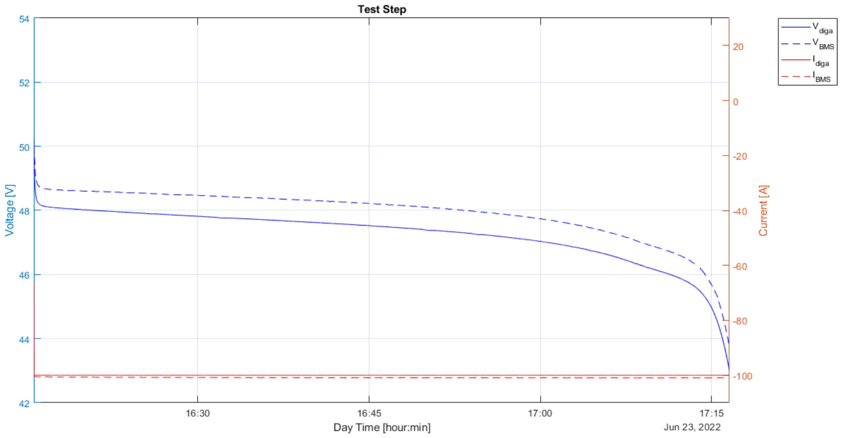


Figure 5.25: DCH1C - Discharge Steps

Charge at 0.5C

The maximum continuous charging current declared from the producer is 50A. Performing the test the first time, the battery went into error. After checking the datasheet and the parameters on the software it is found an incongruence: the activation of current protection was set 42A. In order to do the test and according to the producer, the parameter has been changed to above 50A.

From the graph 5.53 it can be noticed that during the pause there is a peak detected by the Digatron. This is due to the fact that the charge of the battery has been executed at 50A, so Digatron enters into error.

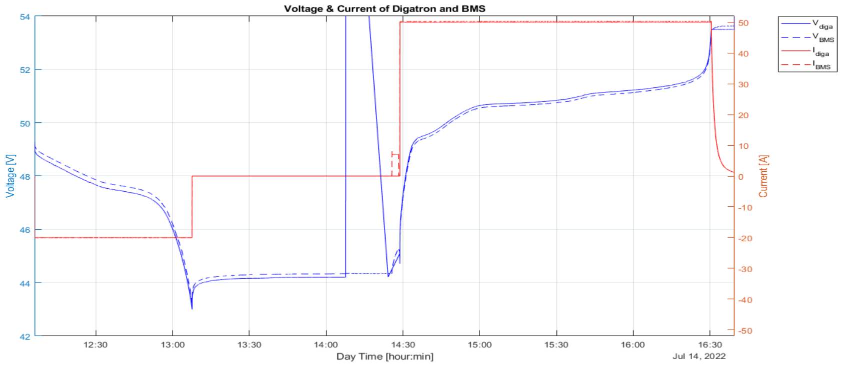


Figure 5.26: CHA05C - V and I

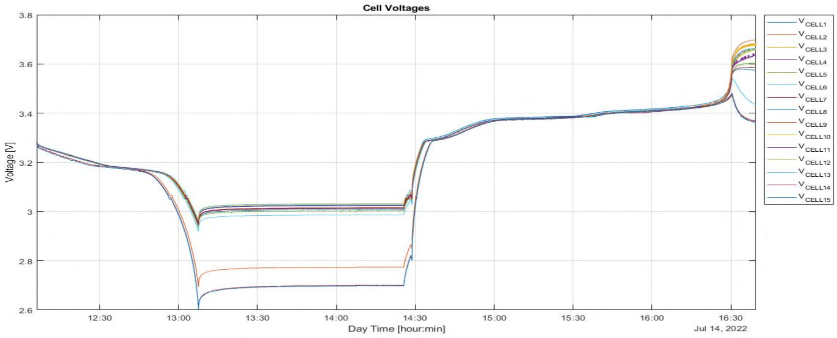


Figure 5.27: CHA05C - Cell Voltages

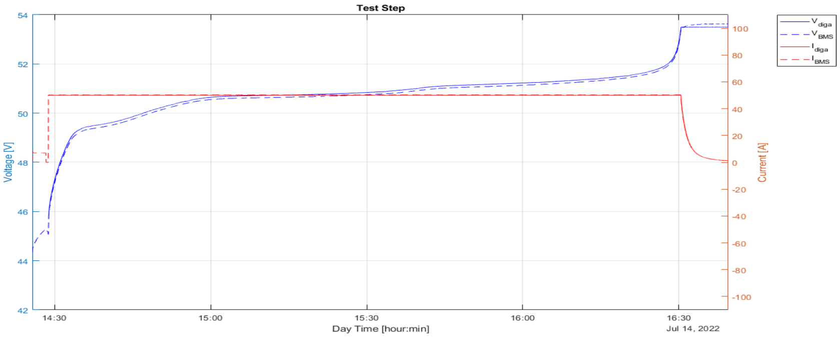


Figure 5.28: CHA05C - Charge Steps

Charge at 0.2C

For this test data and plots are the same of the discharge at 0.2C because the value of the current is the same.

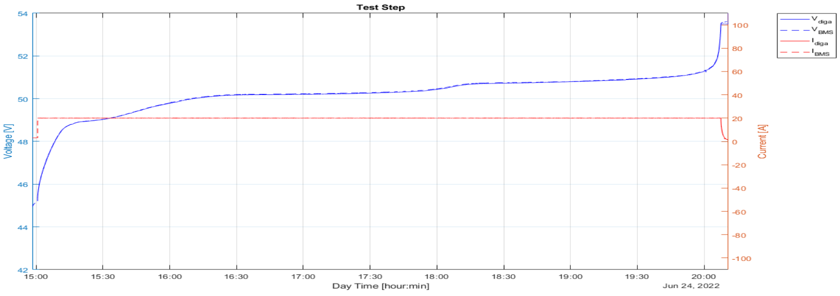


Figure 5.29: CHA02C - Charge Steps

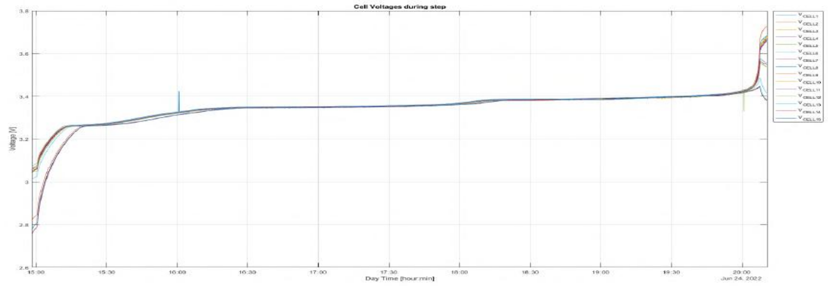


Figure 5.30: CHA02C - Charge Steps - Cell Voltages

Charge at 0.1C

This test consists in a discharge of the battery, as always at the standard current of 20A, and then a charge of 0,1C, therefore with a current of 10A. The test result is positive because charged capacity is above 100Ah.

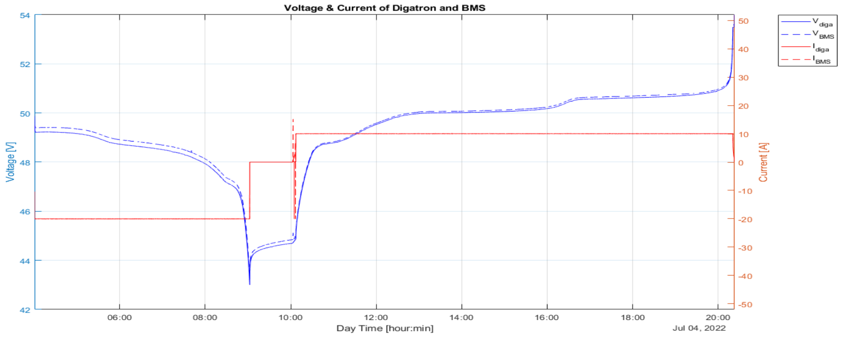


Figure 5.31: CHA01C - V and I

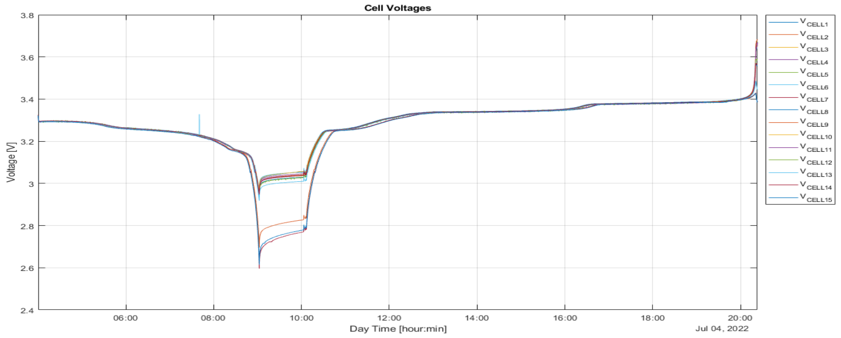


Figure 5.32: CHA01C - Cell Voltages

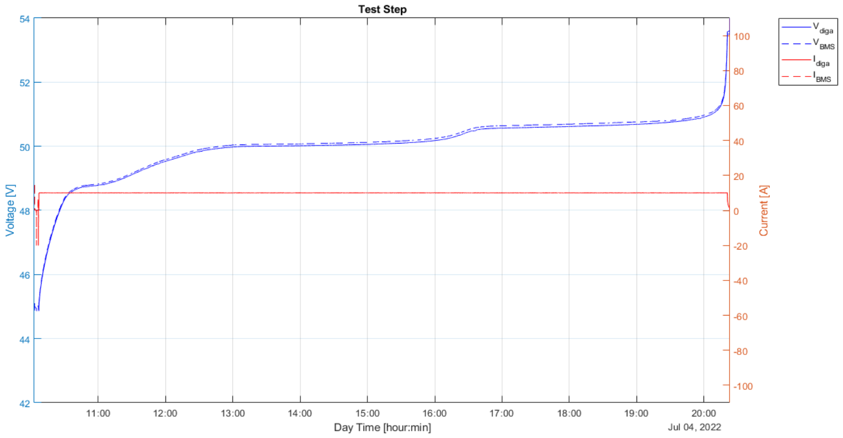


Figure 5.33: CHA01C - Charge Steps

5.1.3 Stress Tests

Charge at Maximum Current

For this test data and plots are the same of the charge at 0.5C because the maximum charging current is 50A.

Discharge at Maximum Current

Test data and plots are the same of the discharge at 1C because the maximum discharge current is 100A.

Maximum Charge and Discharge

The first charge is short because the battery pack was almost charged.

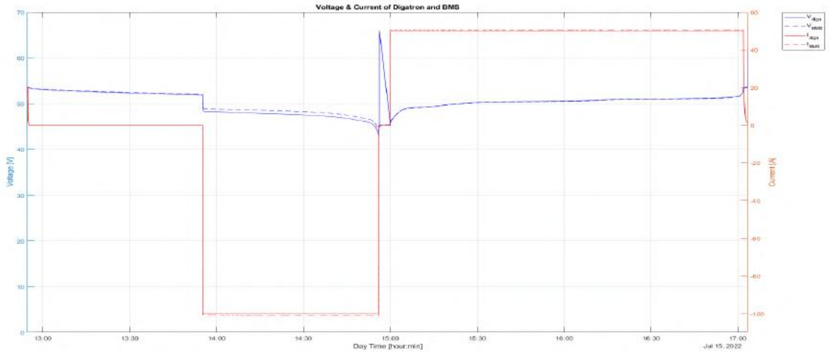


Figure 5.34: MAX DCH/CHA - V and I

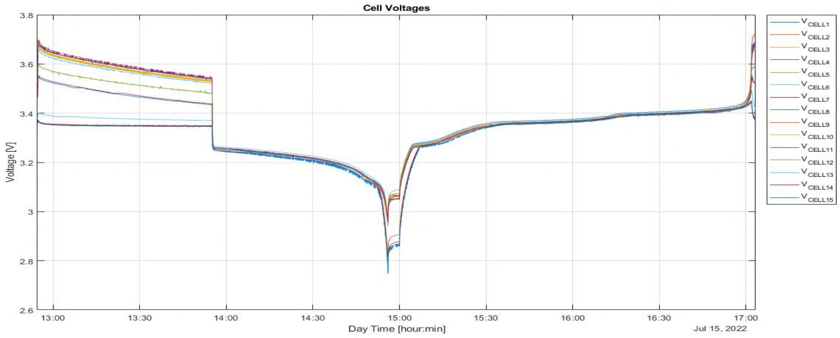


Figure 5.35: MAX DCH/CHA - Cell Voltages

5.1.4 Overload Tests

The test results positive if the delay and release time follow the values stated by the producer. The problem met during this test is that the cycler goes into error, stopping the program. Thus, the delay time is counted until the error appears, instead the release time is counted after the error shows up, until the voltage returns to nominal.
The delay time of the overcharge and overdischarge is different from the times declared by producer.

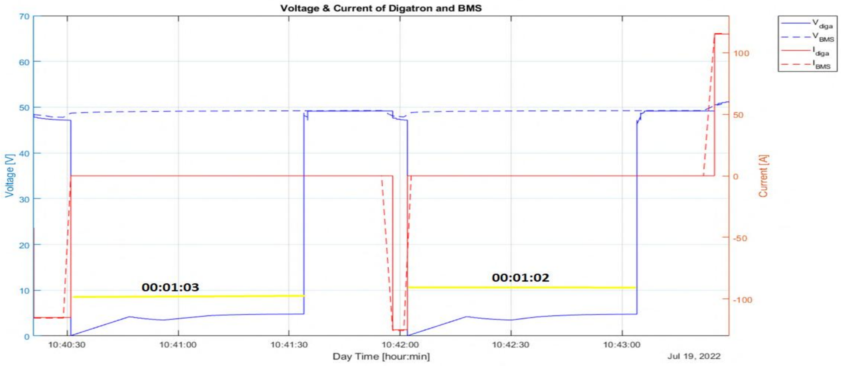


Figure 5.36: Overprotection test - V and I

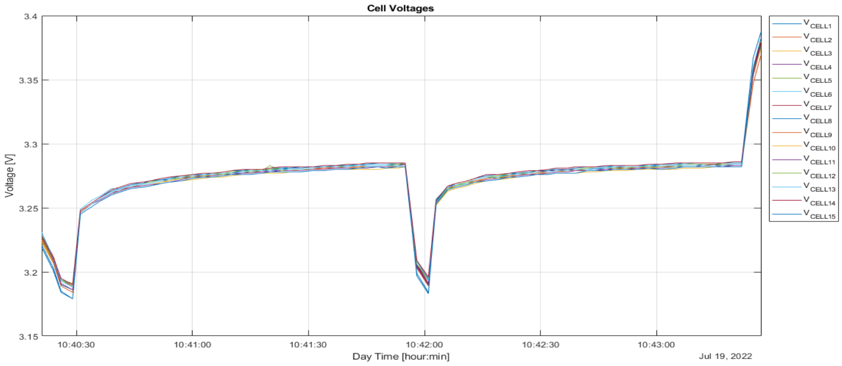


Figure 5.37: Overprotection test - Cell Voltages

5.1.5 Summary of the Test

A table with the most important results are shown in the next page.
The results of the tests are very satisfactory, especially from the point of view of capacity tests that the battery, in both charge and discharge, can always achieve more than 100% of nominal capacity. The end of charge current reaches almost 1A. Outside the numerical results, the PC software is not so good, the values registered are not accurate, the capacity remaining is shown as a simple percentage, the value of the temperatures values are integer.

			Value
Internal Resistance		**Digatron**	16.388mΩ
		BMS	10.375mΩ
Capacity tests	**DCH05C**	**DCH capacity**	101.927Ah
		OV/UV	/
		OT/UT	/
	DCH02C	**DCH capacity**	102.332Ah
		OV/UV	/
		OT/UT	/
	DCH01C	**DCH capacity**	101.524Ah
		OV/UV	/
		OT/UT	/
	DCH1C	**DCH capacity**	101.524Ah
		OV/UV	/
		OT/UT	/
	CHA05C	**CHA capacity**	102.597Ah
		OV/UV	/
		OT/UT	/
	CHA02C	**CHA capacity**	102.554Ah
		OV/UV	/
		OT/UT	/
	CHA01C	**CHA capacity**	101.362Ah
		OV/UV	/
		OT/UT	/
Stress tests	**Max CHA**	**CHA capacity**	102.597Ah
		OV/UV	/
		OT/UT	/
Stress tests	**Max DCH**	**DCH capacity**	101.994Ah
		OV/UV	/
		OT/UT	/

Table 5.3: Summary Table tests Pack n.1

Overload tests	**DCH1**	**Delay Time**	10.7s
		Release Time	1.03 min
	DCH 2	**Delay Time**	3.8s
		Release Time	1.02 min
	CHA	**Delay Time**	3.5s
		Release Time	/

Table 5.4: Summary Table tests Pack n.1

5.2 Battery Pack n.2 Performances

The principal parameters from the datasheet of the battery pack are summarized in this table.

Battery Specification		
Nominal Voltage		48V
Internal Resistance		not declared
Normal Charge Voltage		55.0V
Allowed Max Charge		50A
Charge Current Limitation		Not Present
End Of Discharge Voltage		40.5V
Cycle Life		>2500 cycles (100%DOD)
Electrical Characteristics & tests Conditions		
Over Charge	**Protection**	55V
	Protection delay time	3s
	Protection release	not declared
Over Discharge	**Protection**	40.5V
	Protection delay time	3s
	Protection release	not declared
Over Current	**Charge Protection 1**	55A
	Protection delay time	2s
	Charge Protection 2	80A
	Protection delay time	500ms
	Release time	2.30min
	Discharge Protection 1	110A
	Protection release time	5s
	Discharge Protection 2	120A
	Protection delay time	1s
	Protection release	after a charge

Table 5.5: Battery Datasheet

5.2.1 OCV and Internal DC Resistance

As the battery pack n.1, data logging of the BMS is less accurate than the Digatron, infact the software of the BMS registered only two values of the last discharge step, that are useless. Thus, the value taken into account is the one from Digatron.

Digatron data		**BMS data**	
U1 (V)	48.807	**U1 (V)**	48.89
U2 (V)	47.230	**U2 (V)**	47.53
I1 (A)	20	**I1 (A)**	20
I2 (A)	100	**I2 (A)**	100
Rdc mesaured (mΩ)	15.790	**Rdc mesaured (mΩ)**	13.600

Table 5.6: Summary Results for the Internal Resistance

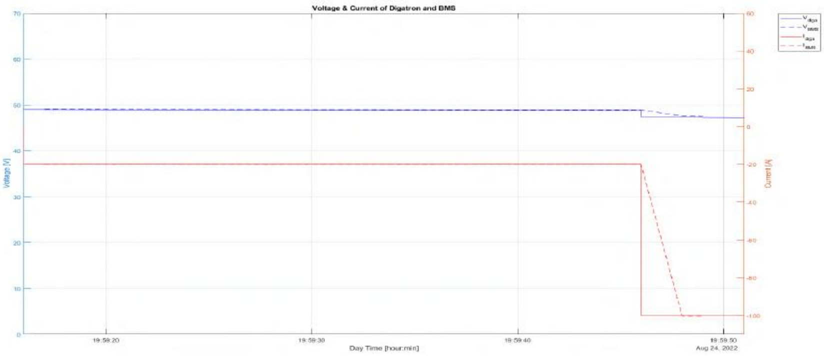


Figure 5.38: V and I

The OCV is about 50V.

5.2.2 Capacity Tests

Discharge at 0.5C

The SOC recorded by the BMS at the end of the charge or discharge, goes

from 0 or 100% with a step. This means that the BMS software is not accurate.
During this test and the following ones, there are some voltage peaks due to the opening of the mosfets, in charge or discharge. This brings to a voltage higher that the limit of the Digatron, that brings it into error.

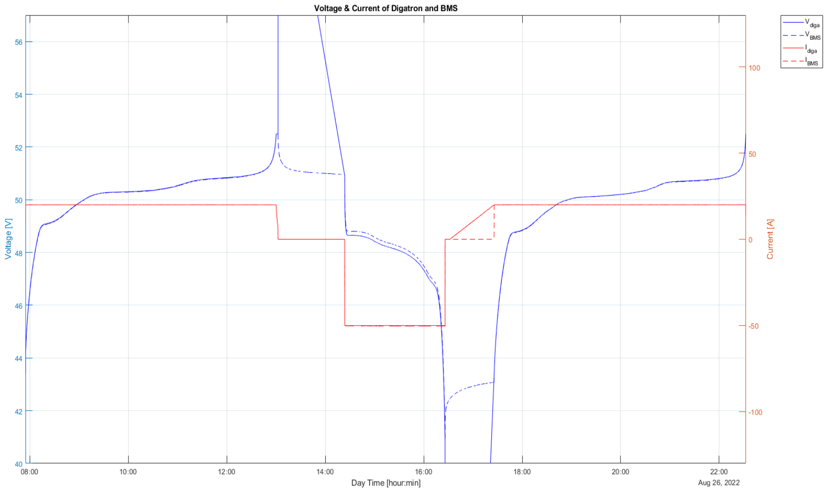


Figure 5.39: DCH05C - V and I

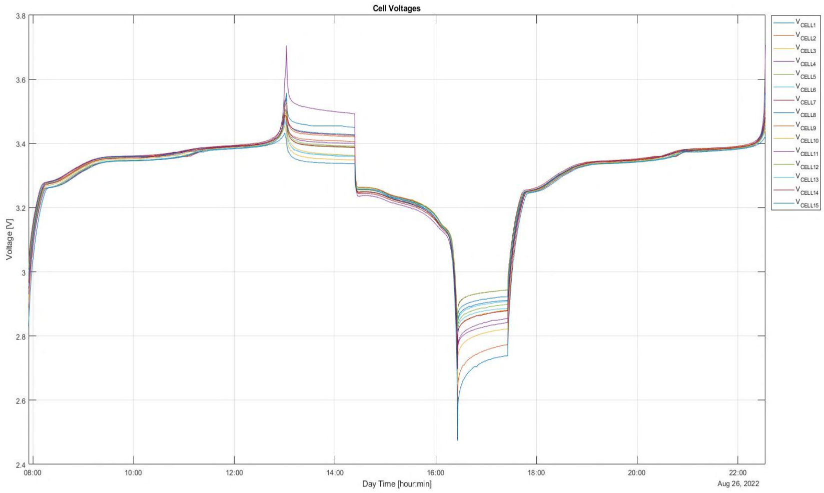


Figure 5.40: DCH05C - Cell Voltages

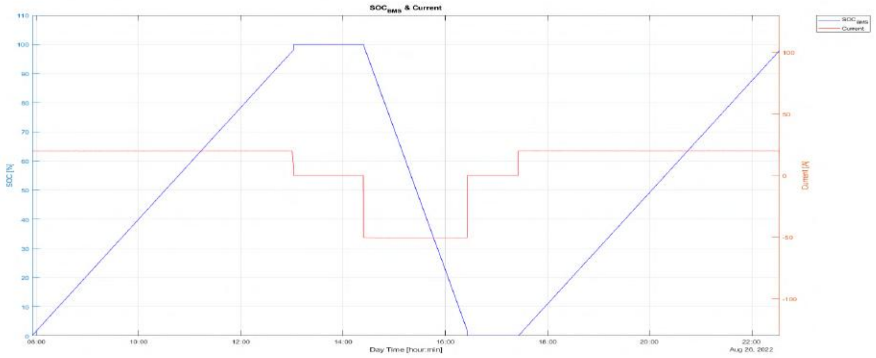


Figure 5.41: DCH05C - SOC and I

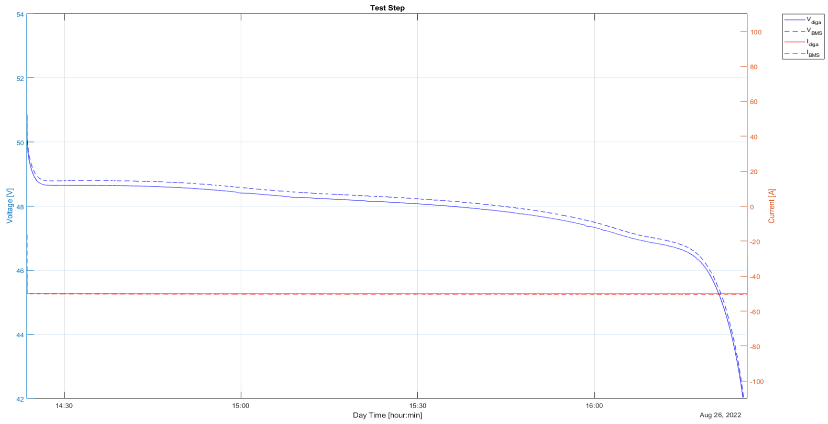


Figure 5.42: DCH05C - Discharge Steps

Discharge at 0.2C

The first charge lasted for less than one minute because the battery pack was completely charged. Then, as can be seen from the plot 5.43, the second pause lasted ten hours instead of only one because Digatron went into error for undervoltage, during night, after the complete discharge.

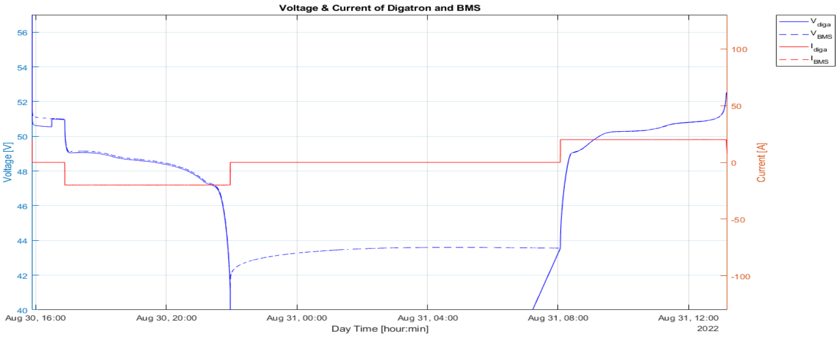


Figure 5.43: DCH02C - V and I

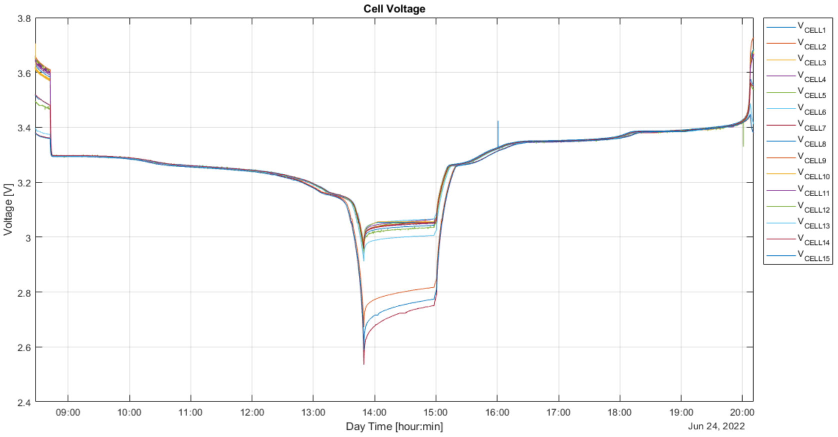


Figure 5.44: DCH02C - Cell Voltages

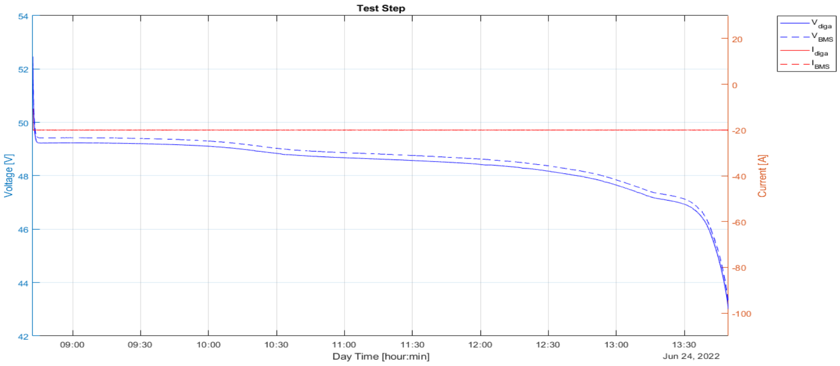


Figure 5.45: DCH02C - Discharge Steps

Discharge at 0.1C

In this test, as it can be notice, there are two peaks due to the same problem with the cycler: when the BMS opens the mosfet the Digatron enters into error, due to the high voltage. The cells that enter into overvoltage or undervoltage, respectively, are the 11th and 15th. The discharge capacity is 101.660Ah.

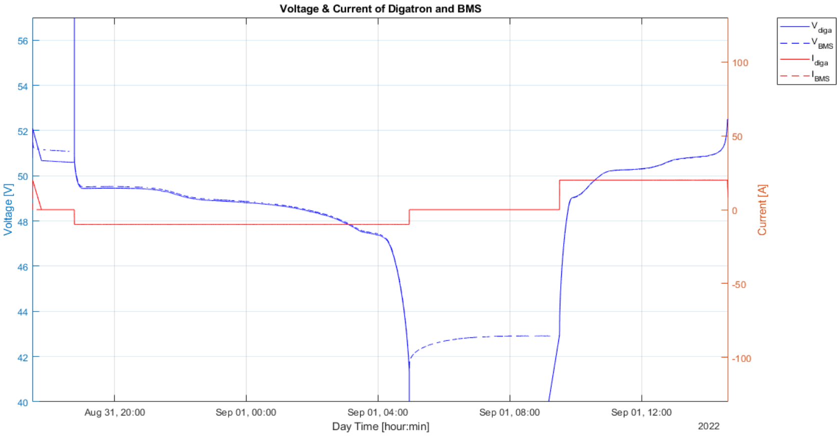


Figure 5.46: DCH01C - V and I

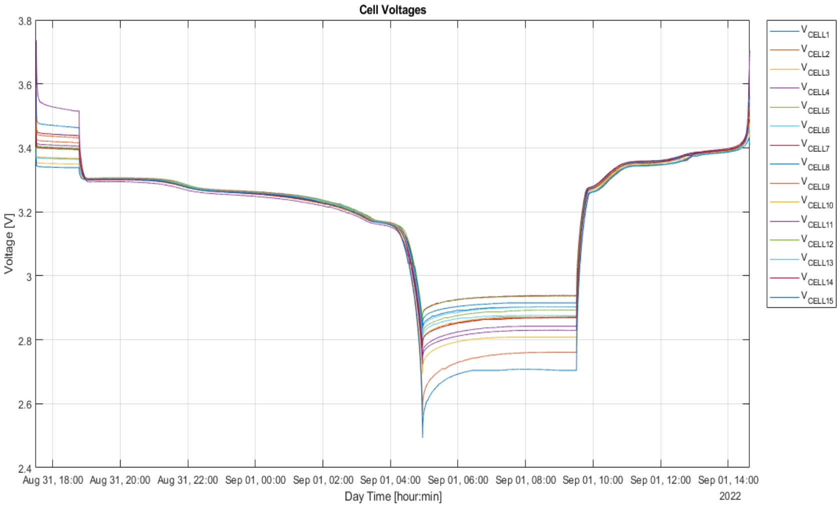


Figure 5.47: DCH01C - Cell Voltages

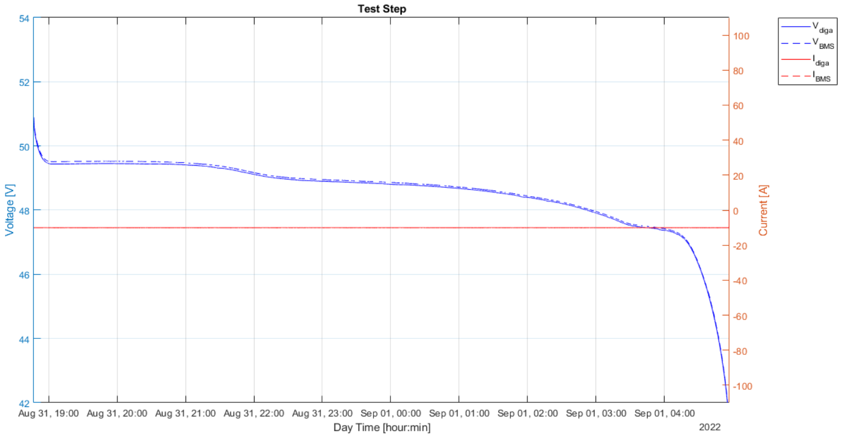


Figure 5.48: DCH01C - Discharge Steps

Discharge at 1C

During the discharge at 1C current, no cells went into undervoltage, due to the high discharge rate. Instead, in the charge process always the same cell (n.11) goes into overvoltage. It can also be seen that the percentage of the SOC is not correctly read from the software.

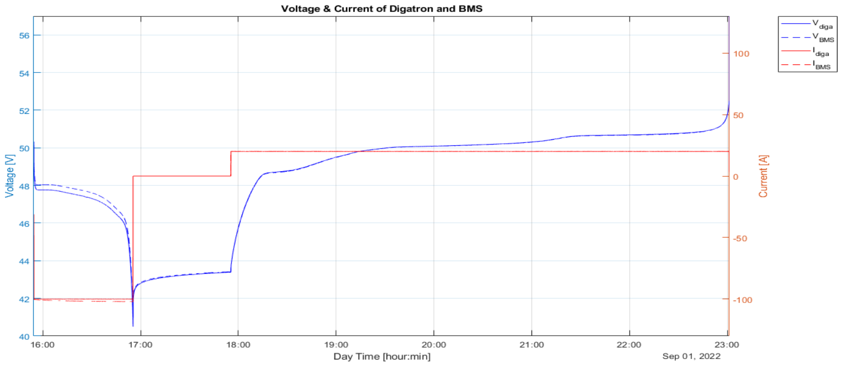


Figure 5.49: DCH1C - V and I

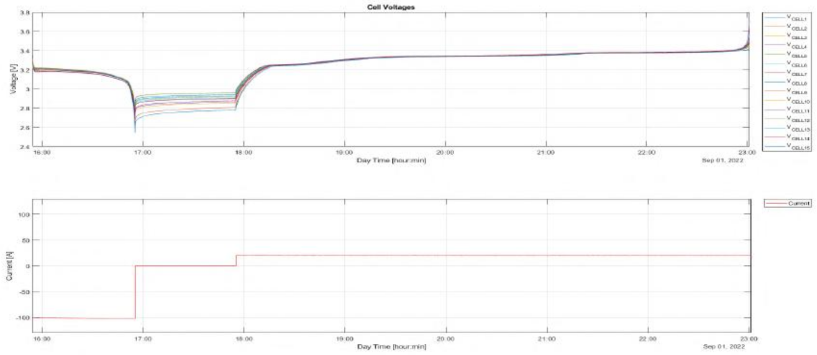


Figure 5.50: DCH1C - Cell Voltages

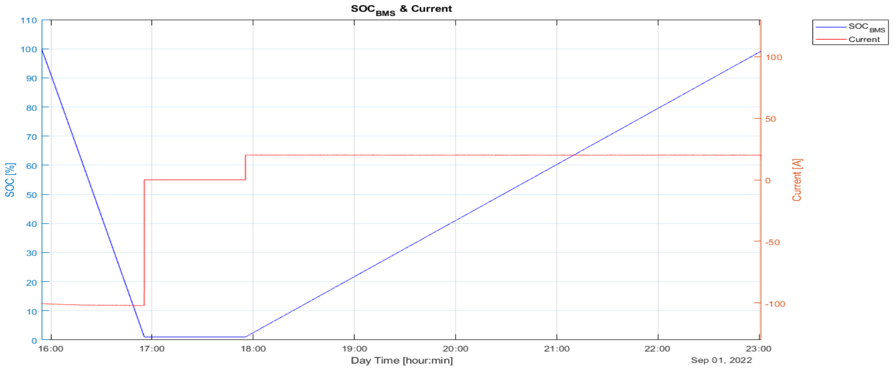


Figure 5.51: DCH1C - SOC and I

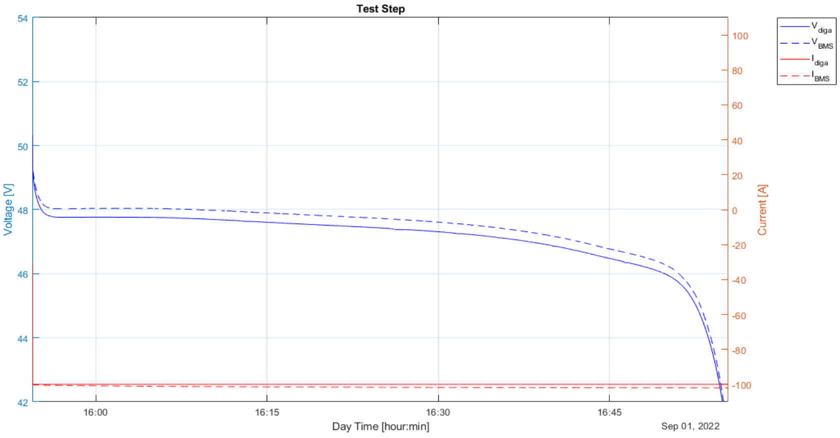


Figure 5.52: DCH1C - Discharge Steps

Charge at 0.5C

The first part of the charge is missing because the data logger of the BMS didn't register it. Same as the previous test, the Digatron went in error because of the overvoltage/undervoltage.

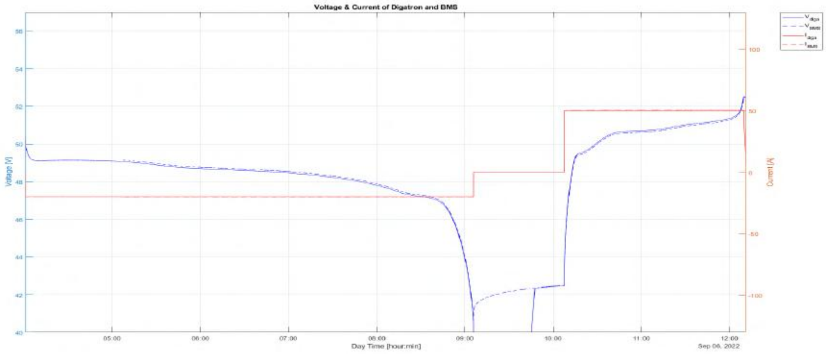


Figure 5.53: CHA05C - V and I

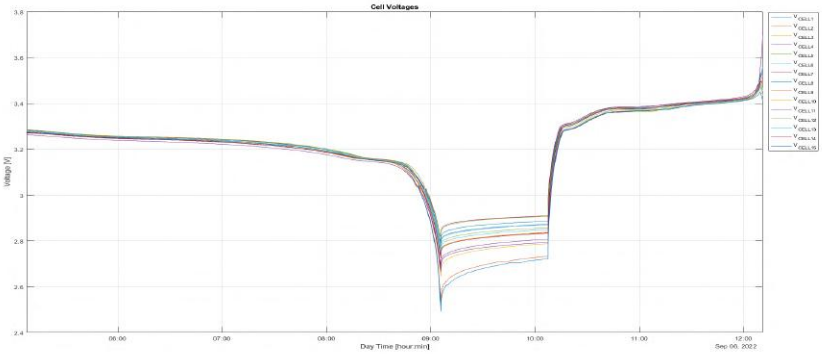


Figure 5.54: CHA05C - Cell Voltages

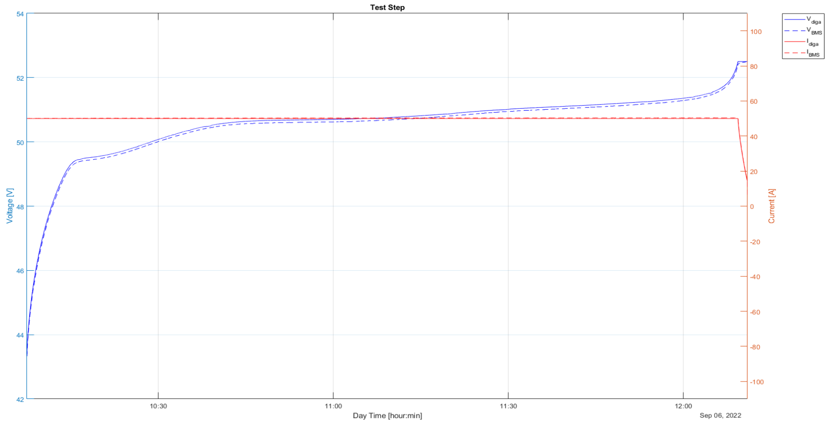


Figure 5.55: CHA05C - Charge Steps

Charge at 0.2C

The charged capacity with a 0.2C rate, so with a current of 20A, is 101.295Ah, 1Ah less than the previous test but above 100Ah, so the result is positive.

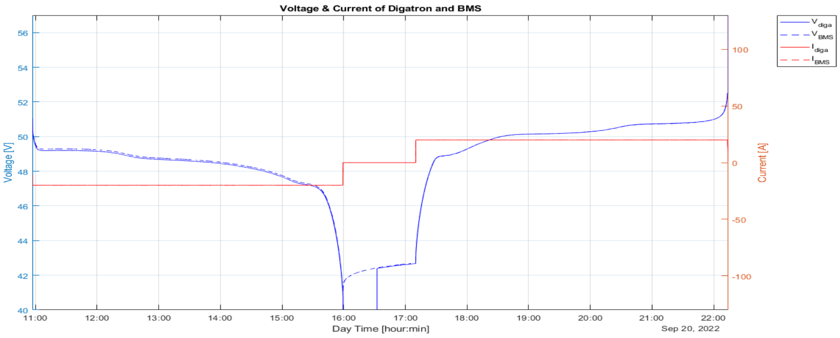


Figure 5.56: CHA02C - V and I

Charge at 0.1C

The test consists into a total discharge, followed by a charge at 0.1C, that, for a 100Ah battery represents a current of 10A. The result of the test is positive.

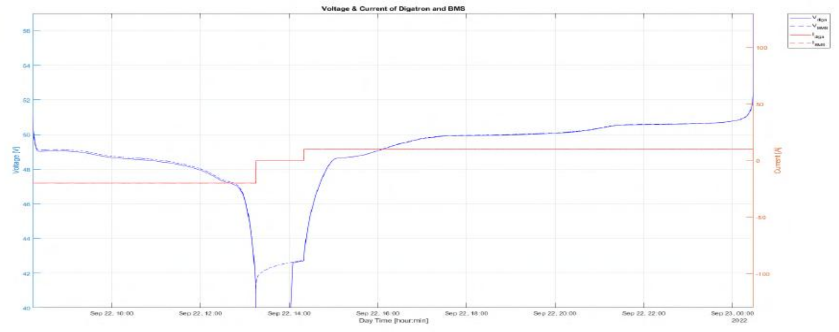


Figure 5.57: CHA01C - V and I

5.2.3 Stress Tests

Charge at Maximum Current

Also for this battery, this test is the same of the charge at 0.5C because the maximum current is 50A.

Discharge at Maximum Current

The data and the plots are the same of the discharge at 1C because the maximum current is 100A.

Maximum Charge and Discharge

The battery pack at the start of the test was charged, so the charge step on the graph isn't visible.

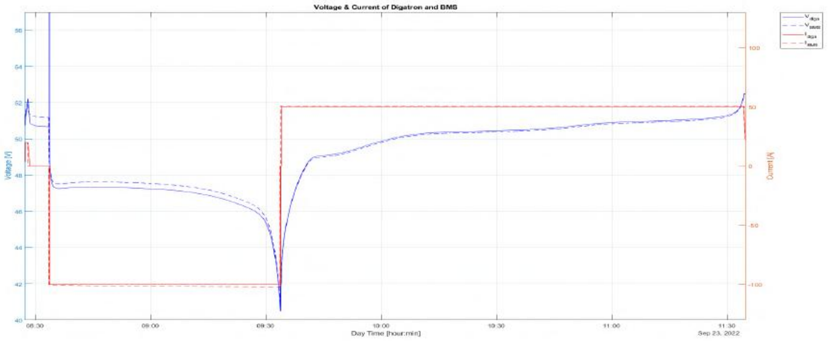


Figure 5.58: MAX DCH/CHA - V and I

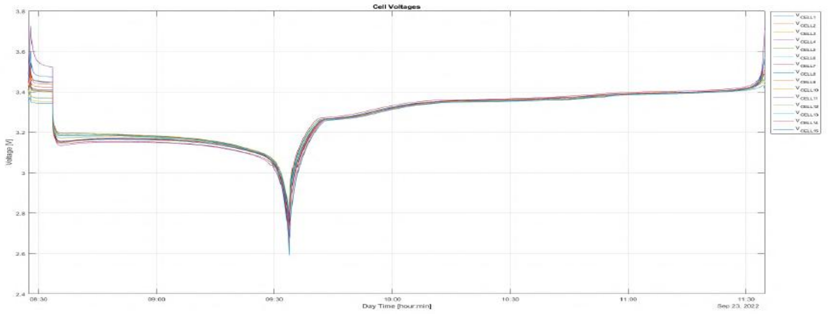


Figure 5.59: MAX DCH/CHA - Cell Voltages

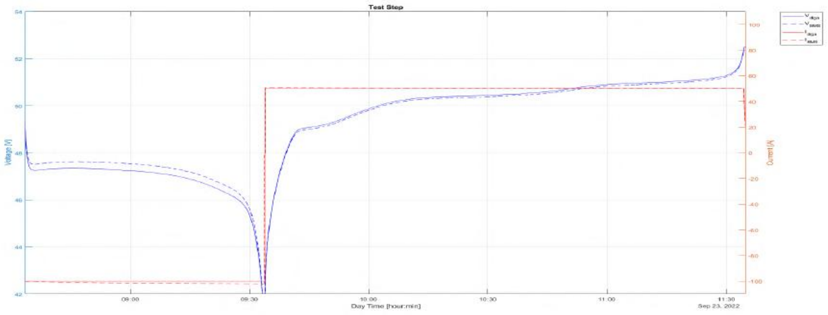


Figure 5.60: MAX DCH/CHA - DCH/CHA steps

5.2.4 Overload Tests

From the datasheet given by the producer, the delay time needed to open the mosfets when the current overcomes the limit value, and the time needed to release the protection are missing. The first one is instead present in the parameter settings window of the software.
On datasheet there is only one protection for charge, instead on the software there are two. The discharge current protection are two also in the datasheet.
After a discharge, there is no release time, to avoid a possible short circuit. So, in order to unlock the protection, the battery needs a short charge. Instead the release time of the battery after an overcurrent in charge lasts about 2.30min.
To test the protection a current bigger than 5A was set.

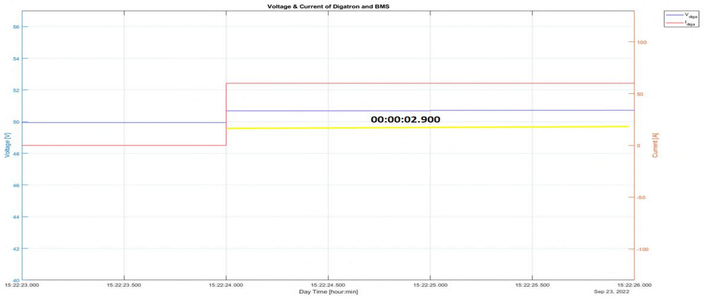


Figure 5.61: Overprotection test - Charge at 60A

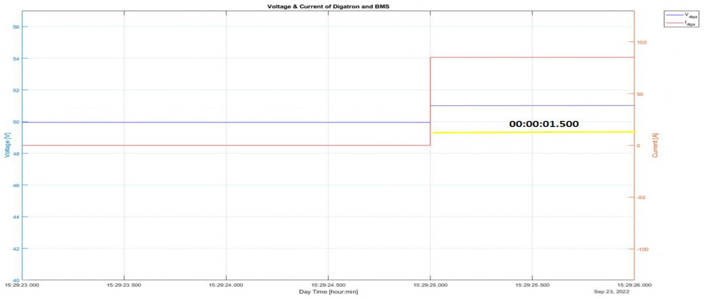


Figure 5.62: Overprotection test - Charge at 85A

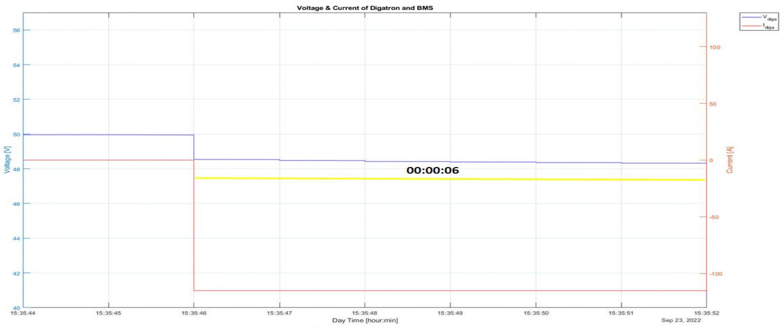


Figure 5.63: Overprotection test - Discharge at 115A

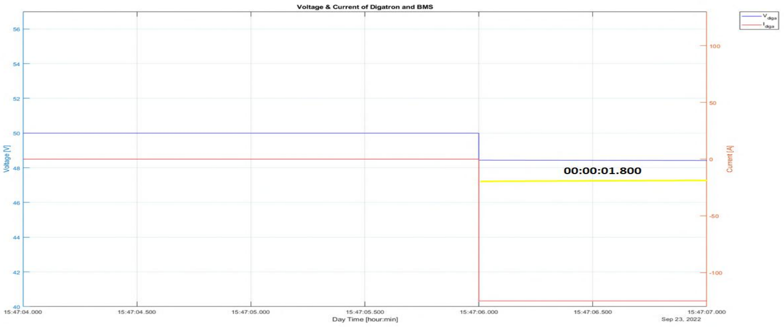


Figure 5.64: Overprotection test - Discharge at 125A

5.2.5 Summary of the tests

A table with most important results are shown on next page. The results of the tests are good especially for the capacity tests because the Ah charged and discharged are above 100Ah.

The only problem encountered was the Digatron went into error with overvoltage or undervoltage, that has been solved restarting the program.

The end of charge current is not good as the previous pack because the current never dropped much from its charge value.

			Value
Internal Resistance		**Digatron**	15.790mΩ
		BMS	13.600mΩ
Capacity tests	**DCH05C**	**DCH capacity**	101.896Ah
		OV/UV	11/15
		OT/UT	/
	DCH02C	**DCH capacity**	101.301Ah
		OV/UV	11/15
		OT/UT	/
	DCH01C	**DCH capacity**	101.660Ah
		OV/UV	11/15
		OT/UT	/
	DCH1C	**DCH capacity**	101.521Ah
		OV/UV	11/-
		OT/UT	/
	CHA05C	**CHA capacity**	102.352Ah
		OV/UV	11/15
		OT/UT	/
	CHA02C	**CHA capacity**	101.295Ah
		OV/UV	11/15
		OT/UT	/
	CHA01C	**CHA capacity**	101.309Ah
		OV/UV	11/15
		OT/UT	/
Stress tests	**Max CHA**	**CHA capacity**	102.352Ah
		OV/UV	11/15
		OT/UT	/
Stress tests	**Max DCH**	**DCH capacity**	101.521Ah
		OV/UV	11/15
		OT/UT	/

Table 5.7: Summary Table tests Pack n.2

Overload tests	**CHA 60A**	**Delay Time**	2.9s
		Release Time	2.30 min
	CHA 85A	**Delay Time**	1.5s
		Release Time	2.30 min
	DCH 115A	**Delay Time**	6s
		Release Time	in charge
	DCH 125A	**Delay Time**	1.8s
		Release Time	in charge

Table 5.8: Summary Table tests Pack n.2

5.3 Battery Pack n.3 Performances

The principal parameters of the battery pack are summarized in this table.

Battery Specification		
Nominal Voltage		48V
Internal Resistance		<100mΩ
Normal Charge Voltage		54.0V
Allowed Max Charge		100A
Charge Current Limitation		20A (not set up)
End Of Discharge Voltage		37.5V
Cycle Life		not declared
Electrical Characteristics & tests Conditions		
Over Charge	**Protection**	55.5V
	Protection delay time	4s
	Protection release	50.7V
Over Discharge	**Protection**	37.5V
	Protection delay time	1s
	Protection release	43.5V
Over Current	**Charge Protection**	110A
	Protection delay time	1s
	Protection release time	1min
	Charge Limitation Current	20A (not set up)
	Discharge Protection 1	110A
	Protection delay time	1s
	Protection release time	1min
	Discharge Protection 2	>150A
	Protection delay time	100ms
	Protection release time	1min

Table 5.9: Battery Datasheet

5.3.1 OCV and Internal DC Resistance

The data were taken only from the cycler, as the previous packs. The test consist in a charge of 0.2C, then a discharge of 50Ah, followed by a discharge with 0.2C rate for 30s and another one at 1C for 5s. To measure the direct current internal resistance it was necessary to take the voltages at the end of these last two discharges.
The voltage peak detected from the digatron is due to the opening of the mosfets for overvoltage.

Digatron data		**BMS data**	
U1 (V)	48.521	**U1 (V)**	48.80
U2 (V)	47,019	**U2 (V)**	47.67
I1 (A)	20	**I1 (A)**	20
I2 (A)	100	**I2 (A)**	100
Rdc mesaured (mΩ)	15.020	**Rdc mesaured (mΩ)**	11.200

Table 5.10: Summary Results for the Internal Resistance

The OCV is about 49.43V so the battery arrived at Fiamm with a good state of charge.
The plot that represents the voltage and the current in function of time is the following.

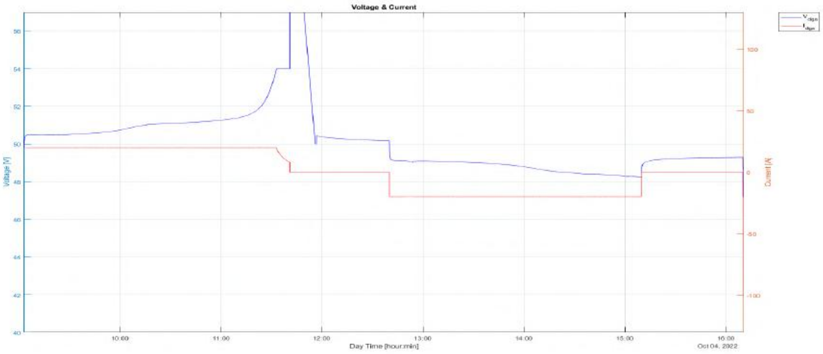


Figure 5.65: V and I

5.3.2 Capacity Tests

Discharge at 0.5C

The test consists in five steps: a charge at standard charge current in order to have the battery fully charged, a pause, the discharge at 0.5C rate that is 50A, followed by another break and a charge at standard charge.

The first charge lasted for a small period of time because the pack was almost charged. When the battery reached the end of charge or discharge voltage, the cycler went into error because of the opening of the mosfets that raises the voltage over the Digatron limits. After the fully discharge, the battery turned off and the only way to wake up the battery was to charged with a very low current, with an external power supply.

During the first pause, it can be seen a straight line from the peak, this is due to the fact that the Digatron did not register data because it was in error. The noisy, instead, in the charge phase, is due to a loosened screw at the negative terminal.

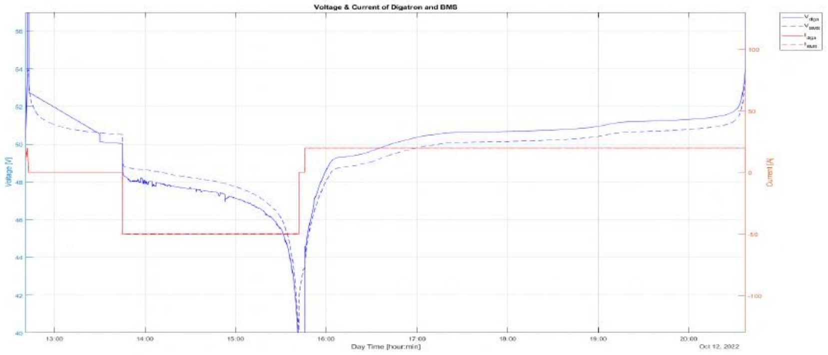


Figure 5.66: DCH05C - V and I

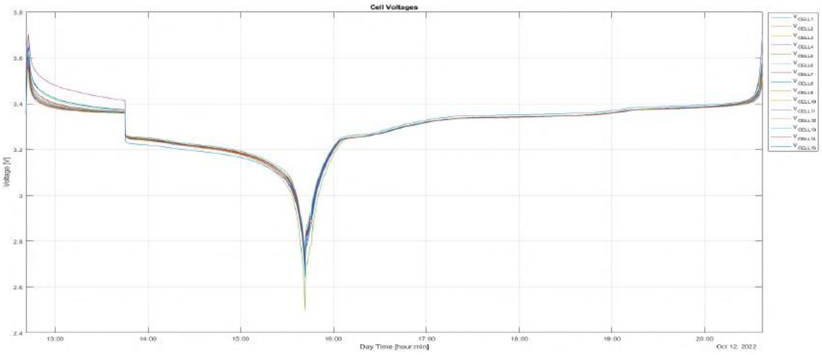


Figure 5.67: DCH05C - Cell Voltages

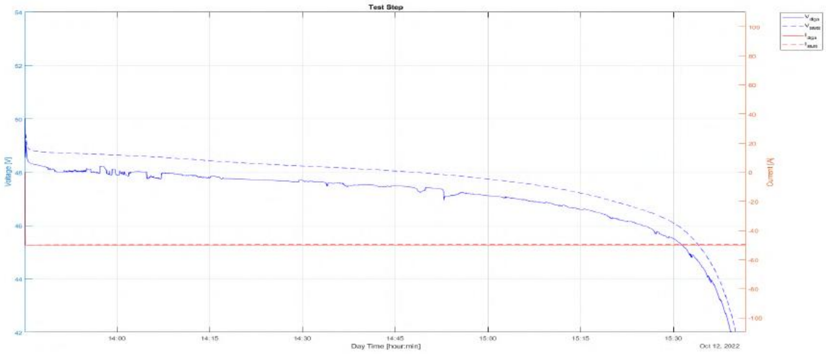


Figure 5.68: DCH05C - Discharge Steps

Discharge at 0.2C

This test has the same steps of the previous one but with a discharge current of 20A. For this pack, the unervoltage value is 2.5V. As it can be seen from plot 5.70, there is the cell n. 5 that is quite unbalanced compared to the others and goes into undervoltage condition. This brings the battery to enter into sleep mode. In order to continue the test, it was needed to charged the pack with a current of 0.1A. The moment of shutdown can be seen from plot 5.71. From the shutdown to the charge time, half an hour has passed, so the temperatures of board and BMS dropped.

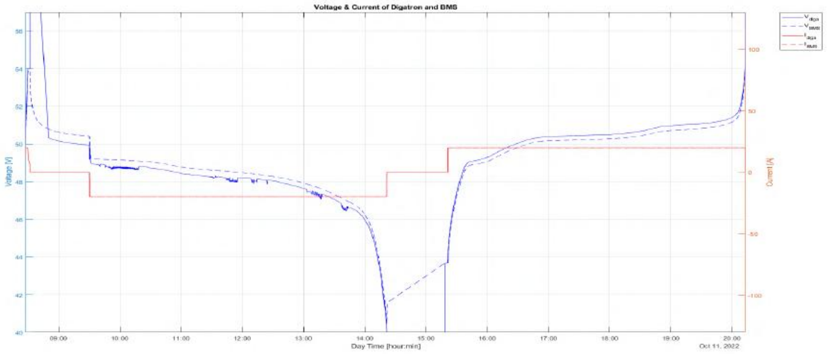


Figure 5.69: DCH02C - V and I

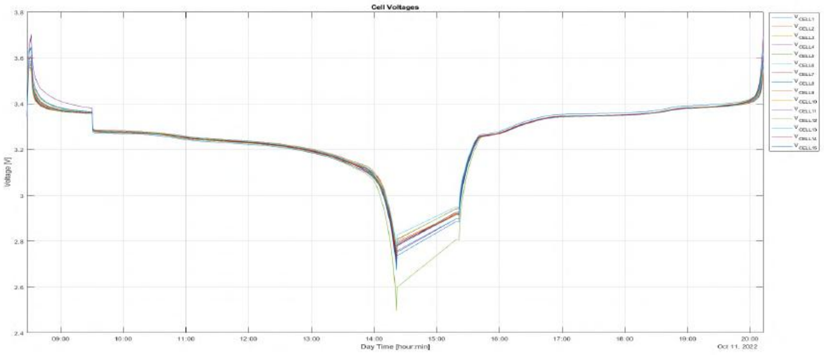


Figure 5.70: DCH02C - Cell Voltages

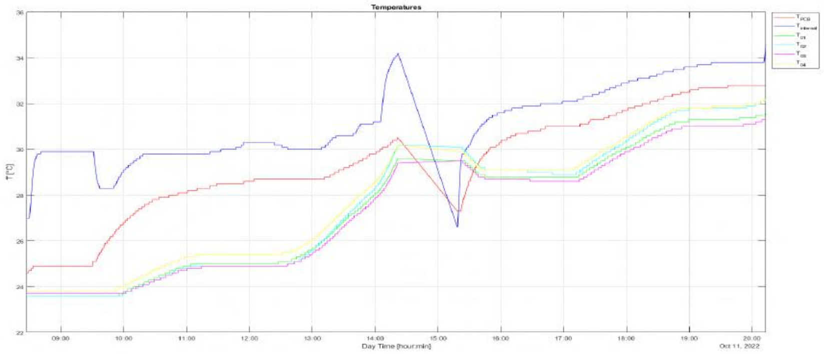


Figure 5.71: DCH02C - Temperatures

Discharge at 0.1C

During this test, the same problems of the previous ones were met. From the first plot it can be seen clearly that an external power supply was used in order to turn on the battery.
As it can be seen from the first plot, in the first pause there is a step of the cycler voltage. This voltage raise comes from the charging mosfet that, after a fully charge, prevents a further charge.

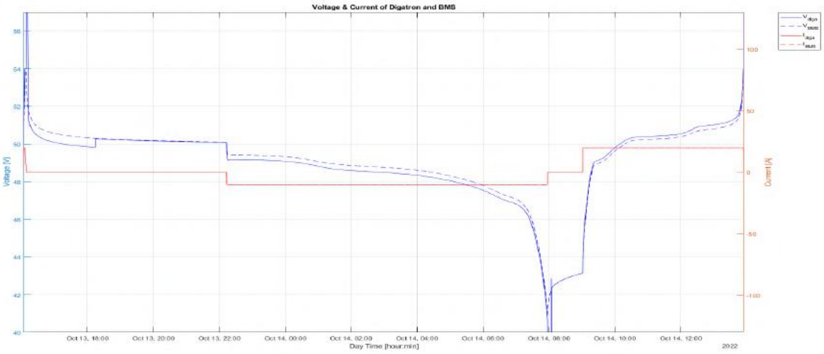


Figure 5.72: DCH01C - V and I

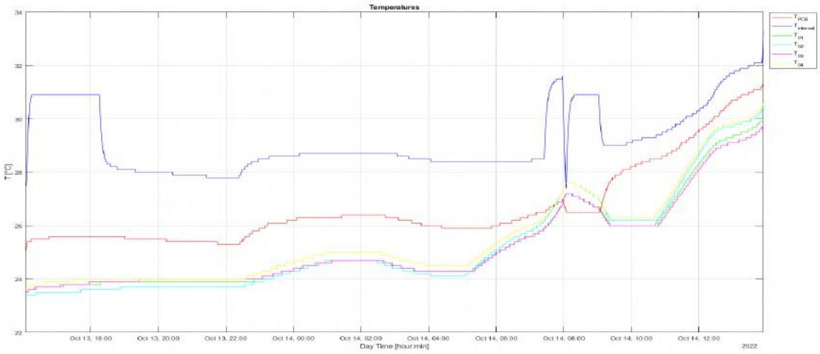


Figure 5.73: DCH01C - Temperatures

Discharge at 1C - Maximum Discharge

The maximum continuous discharging current of this pack is 100A, so 1C. This test and the one with the maximum discharge current are the same. From the plot **??**, it can be seen the using of the external power supply. The state of charge, furthermore, starts from 95%, because the total capacity read from the BMS is about 95Ah.

The capacity discharged, in order to pass the test, has to be above 95%. This test results positive because it is about 97%.

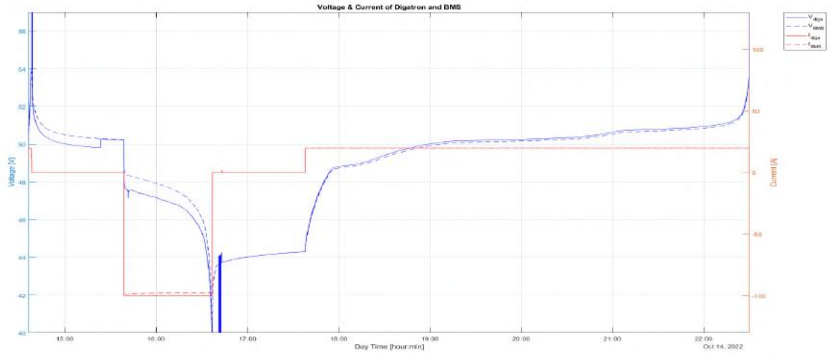


Figure 5.74: DCH1C - V and I

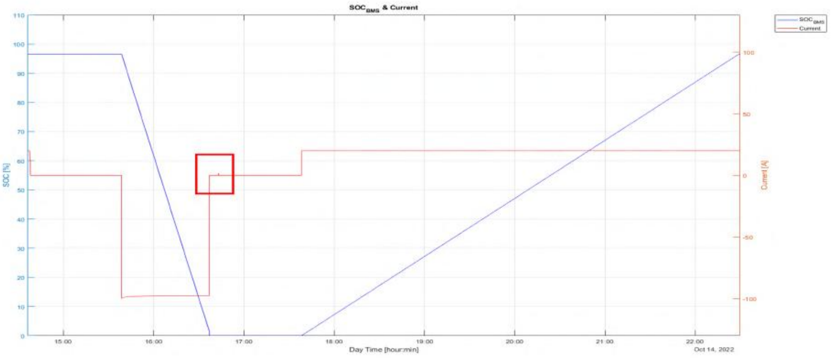


Figure 5.75: DCH1C - SOC and I

Charge at 0.5C

The result of the test is negative because the capacity charged is about 96%, instead of 100%.

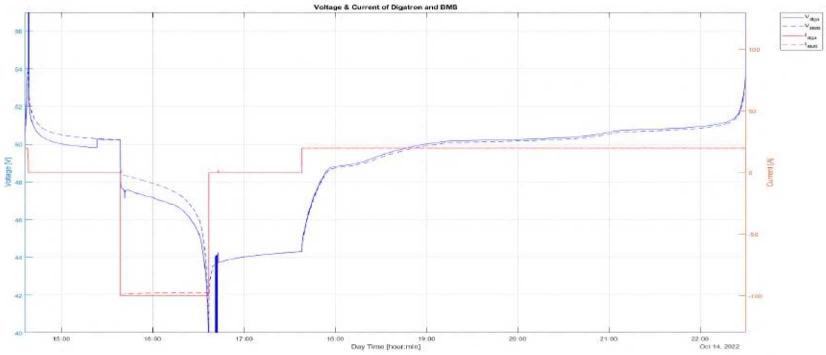


Figure 5.76: CHA05C - V and I

Charge at 0.2C

This test is incorporate with the discharge at 0.2C rate, so it has the same data and plots.

Charge at 0.1C

The pause was not respected: instead of one hour, it lasted more than two hours. Also this test results negative.

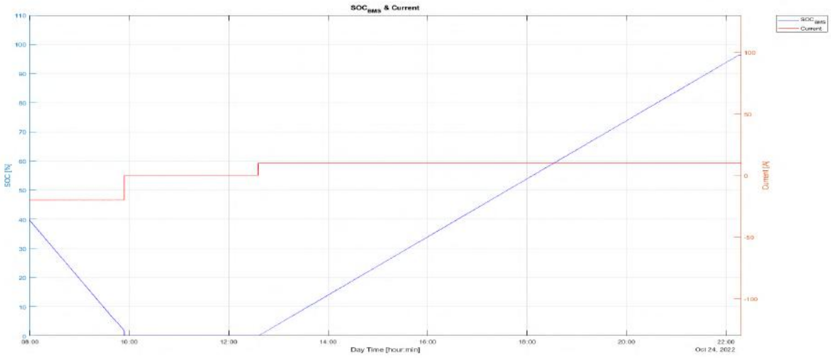


Figure 5.77: CHA01C - V and I

5.3.3 Stress Tests

Maximum Charge

As the previous tests, the cycler went into error when the BMS opened the mosfets, so the program was restarted manually.

During the charge at 1C rate, the cell n.8 reaches high voltage value, but and the end of it the cell that went into overvoltage is the n.11.
The capacity charged with 100A is 96.302Ah, so the test is negative.

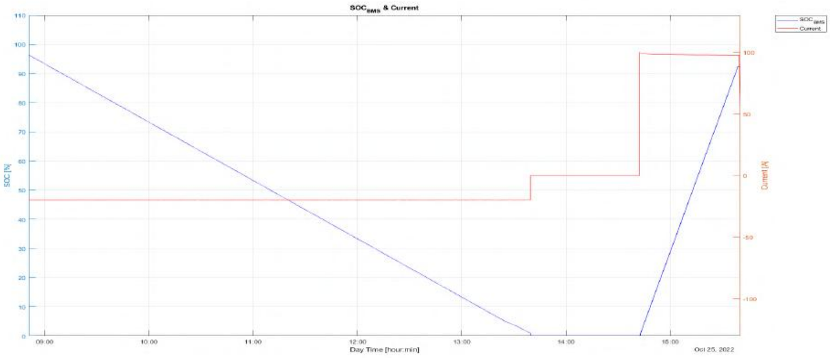


Figure 5.78: MAX CHA - V and I

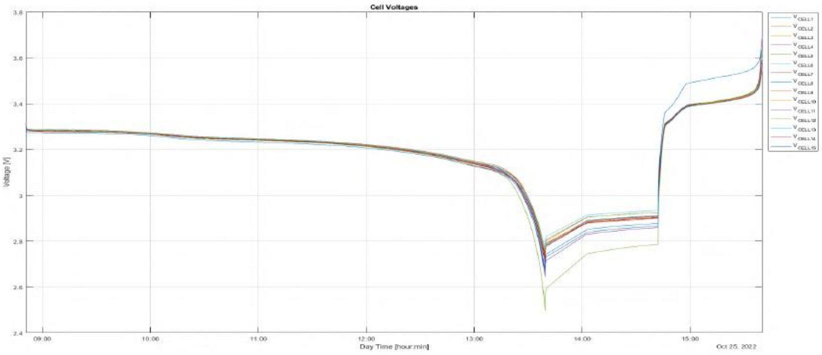


Figure 5.79: MAX CHA - Cell Voltages

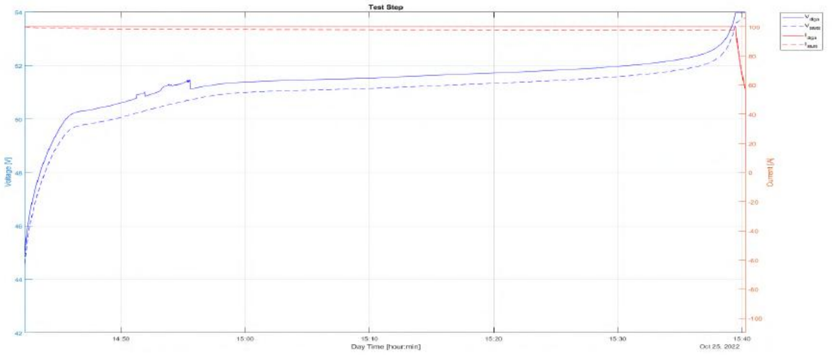


Figure 5.80: MAX CHA - Charge step

Maximum Discharge and Charge

The result of this test is negative. During the discharge, the capacity discharged is about 94%. During the charging process, the capacity is 49% due to the early overvoltage.

The state of charge and so the total capacity results at about 16% from the BMS data. This because the policy of the BMS is to update that value when an OV occurs. During the charge, the voltage of the cell n.15 increases a lot with respect to the other cells, and goes into OV rapidly.

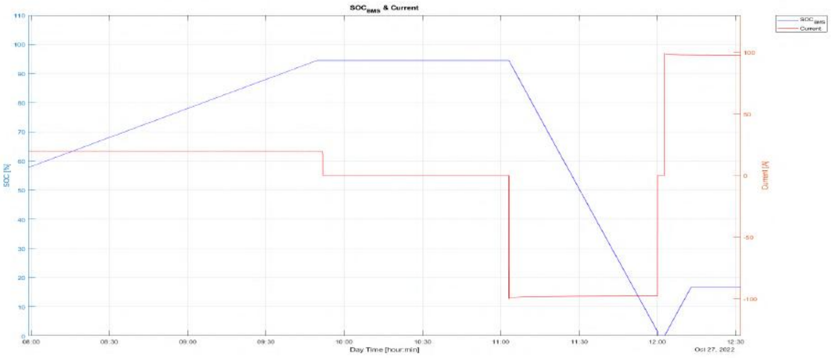


Figure 5.81: MAX DCH - CHA - V and I

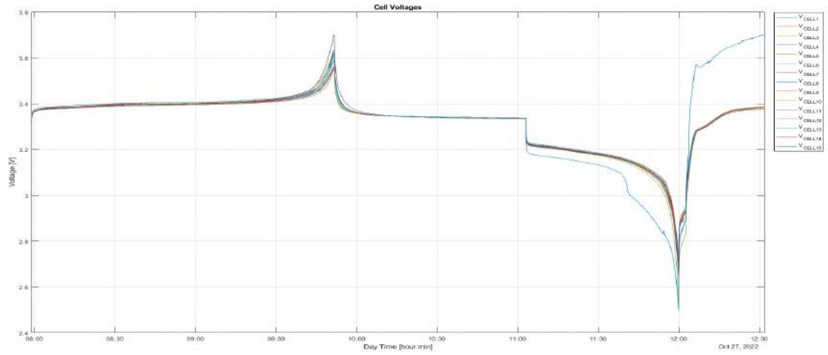


Figure 5.82: MAX DCH - CHA - SOC and I

5.3.4 Overload Tests

The protections present are two for the discharge, and only one for the charge. The time values declared by the producer were met. For the overcharge, the release time was not analyzed, due to the setting error of the cycler.

After the discharge process, the voltage goes to about 5V in order to block a load to absorb current. The producer states that after 10 times a current exceeds the limit, the battery is no longer unlock automatically but it is needed to charge/discharge manually.

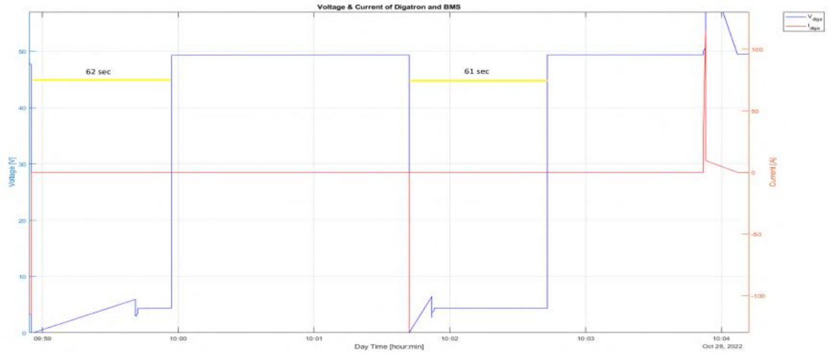


Figure 5.83: Overload test

5.3.5 Summary of the tests

During the tests, the main problems encountered are the noise in some steps and the same of the previous pack that is due to the limits of the Digatron cycler. The noise was due to a screw that was not tightened properly, in particular the one of the negative terminal of the battery.

The results of the tests are not the best, for the capacity tests only the discharge at 1C is positive, so also the maximum discharge. The overload test is positive.

The results are summarized on the following table.

			Value
Internal Resistance		**Digatron**	15.02mΩ
		BMS	11.20mΩ
Capacity tests	**DCH05C**	**DCH capacity**	97.08Ah
		OV/UV	11/5
		OT/UT	/
	DCH02C	**DCH capacity**	97.09Ah
		OV/UV	11/5
		OT/UT	/
	DCH01C	**DCH capacity**	97.34Ah
		OV/UV	11/5
		OT/UT	/
	DCH1C	**DCH capacity**	97.106Ah
		OV/UV	11/5
		OT/UT	/
	CHA05C	**CHA capacity**	96.437Ah
		OV/UV	11/5
		OT/UT	/
	CHA02C	**CHA capacity**	97.158Ah
		OV/UV	11/5
		OT/UT	11/5
	CHA01C	**CHA capacity**	97.19Ah
		OV/UV	11/15
		OT/UT	/
Stress tests	**Max CHA**	**CHA capacity**	96.302Ah
		OV/UV	11/15
		OT/UT	/
Stress tests	**Max DCH**	**DCH capacity**	97.106Ah
		OV/UV	11/15
		OT/UT	/

Table 5.11: Summary Table tests Pack n.2

Overload tests	**CHA 115A**	**Delay Time**	1s
		Release Time	1 min
	DCH 115A	**Delay Time**	1s
		Release Time	1min
	DCH 125A	**Delay Time**	100ms
		Release Time	1min

Table 5.12: Summary Table tests Pack n.2

Chapter 6

Comparison: Database

The purpose of the project is to find a supplier that can cooperate with Fiamm to enter the Lithium batteries business. To decree what battery pack is the best, three databases were created. The first database to be described in this thesis is the one related to the teardown. Each pack is summarized in terms of the design, BMS and a brief weight comparison. After that, in another database, all the electrical performances are presented, therefore, for each pack are summarized all the tests done with a small description of it and, if there were, the problems met. The last database created, but not described in this document, is the software comparison. In this file are summarized all the pros and cons of each battery software, as the possibility to switch the mosfets manually or to shutdown the pack through a button.
All the grade assigned on the following databases was given as objectively as possible.

6.1 Teardown Comparison

The database file contains the information about all the batteries analyzed. The first comparison is about size and weights, giving more importance to energy density, cells configuration, and maximum current allowed in charge or discharge. Next, a comparison about the internal design, therefore re-

garding the connections between cells and the restraint system, and then compare each BMS and analyze the differences.
The battery management systems are all similar to each other, except for some components. Of these, the first elements are the thermal conductive bars, that, as mentioned in previous chapters, are used to dissipate the heat. Only in two packs they are present, but in all the batteries, at least one heat sink is present. Some components like the display or the SNMP port are add-ons, that the producer can put in the battery later, after the purchase.
Another difference between packs is that some producers added an additional board for the communication ports, leds and switches, in order to separate the BMS, therefore the control board of the battery, from the external communications.

The features taken into account for the internal design are listed below, and the rating goes from 1 to 7, where 7 indicates that the quality is high:

- the energy density;
- quality of the assembling;
- led and cables connection;
- the electrical protection, so, if there is insulating paint or not.
- the presence of the conformal coating, that is a thin polymeric film applied sometimes to protect boards;
- quality of the shunt resistors, if they are in form of integrated circuit or not;
- quality of the integrated circuits;
- if there are components for the heat dissipation like the heat sinks or thermic bars;
- quality of the connector and welding;
- the presence of the DC-DC converter;

- the presence of the anti-theft;
- the overall quality of the electronics circuit and components.

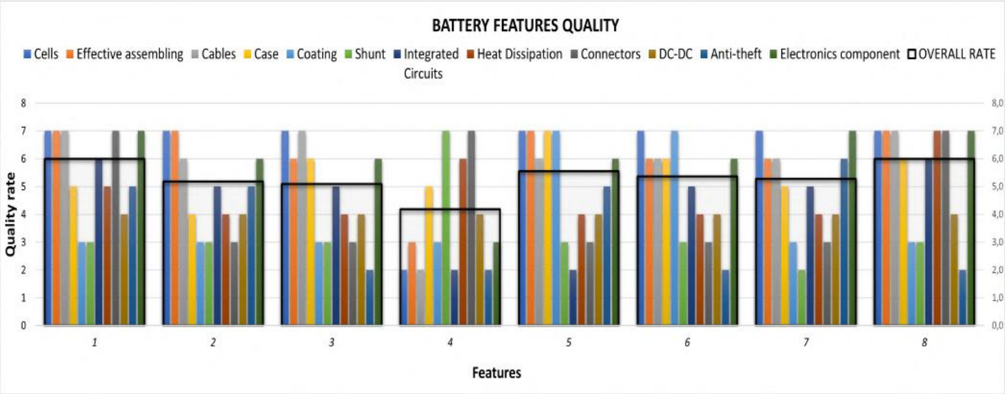


Figure 6.1: Database of Internal Design

The best design seems to be the one of the pack n.1 and n.8. The first different between the two is the lack of the anti-theft in the pack n.8. The other important difference is the heat dissipation: the last pack has more dissipation components than the other one and it has also an heat sink attached on the whole surface of the board. Another difference is in term of weight because the first pack is lighter than the n.8. The last one has a weight of about 60kg, with a white electrical insulated paint.

6.2 Electrical Performances Comparison

To compare all the tests done, a database was created. This file contains a table with all the numerical results and a brief description of the test, especially if there were any mismatches with the datasheet or problems met, then all the test plans are present, and finally some comparison graphs.
As written on the chapter 3, the tests done for this master thesis project are capacity tests, stress tests, and overload tests, all at ambient temperature, about 25 °C.
The comparison regards the following points, and the rating given goes from 1 to 4, where 4 indicates that the test is above the requirements:

- Capacity test: Discharge 0.5C;
- Capacity test: Discharge 0.2C;
- Capacity test: Discharge 0.1C;
- Stress test: Max Charge;
- Stress test: Max Discharge;
- Overload test;
- Maximum charging current acceptability;
- Maximum discharging current acceptability;

The capacity tests considered for the comparison are the discharge ones because for the stationary batteries, the discharging rate is more important than the charging one.
Another parameter for the comparison is the rate of charging or discharging, in order to see which batteries can support the highest rate. The criteria with which a grade are different for each category tests. For the capacity tests 1 is assigned with a discharged capacity less than 98% of the nominal one and 4, with a capacity greater than 102%. For the stress tests, 1 is assigned when overtemperature occurs, and 4 with a capacity greater than 101%. The maximum grade is assigned to the overload protection if the time declared by the producer is respected. The maximum current acceptability needs to be greater than 1C rate in charge and greater than 1.5C in discharge, for the highest grade.

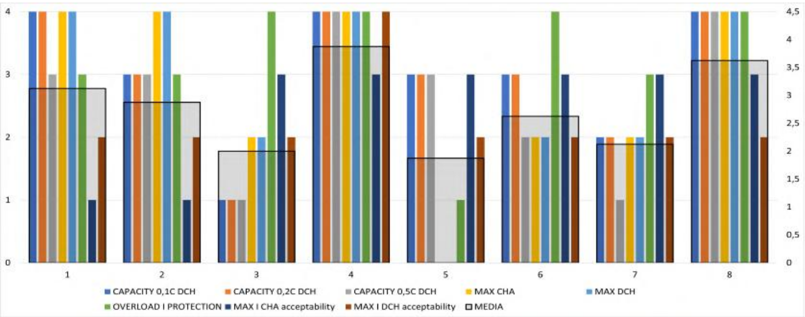


Figure 6.2: Database of Electrical Performances

As it can be seen from the graph the best battery pack for the electrical performances results to be the n.4, followed by n.8. These two packs have the same electrical characteristic, except for the maximum continuous discharge current that for the pack n.4 the maximum current is 150A, instead for the other one is 100A. The nominal voltage of the pack n.8 is 51.2V, so the configuration with one more cell because the producer sends the pack with this specific configuration. The capacity discharged and charged, for this pack, is about 120% if the limit voltage range is used. This because the cells have a capacity of about 120Ah. This suggests that the producer has oversized the battery in order to do more cycles than a normal 100Ah usually do, using the recommended voltage range.

6.3 Software Comparison

The comparison between the different software is done taken into account the main characteristics of them, that are:

- Front Panel Connection and Communications: how the producer organize the front panel and what types of communication ports are present;
- Graphical Interface: what data are visible in the main window and how is the translation and the interaction with buttons and menu;
- User-Friendliness: this takes into account how the connection between the computer and BMS is done, how the stability and fluency of the software is;
- Functionality: what adds-on are present like the possibility to modify the threshold parameters;
- Data Saving: the quality of the saved data, the sampling period and what informations are saved.

Below the comparison plot is shown[1].

---

[1] The software of pack n.5 was not analyzed for business reasons, instead the one of the n.6 will be analyzed in the next future.

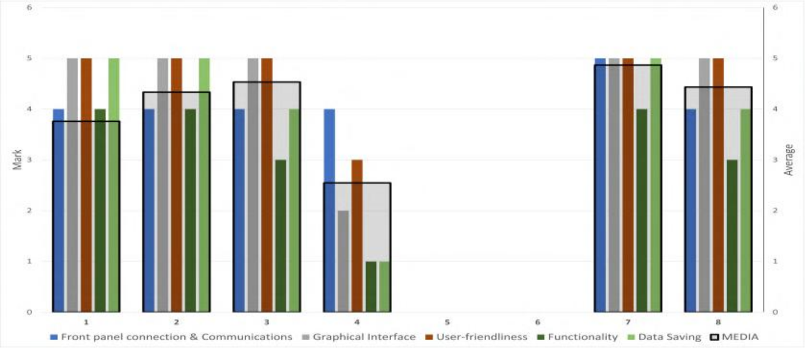
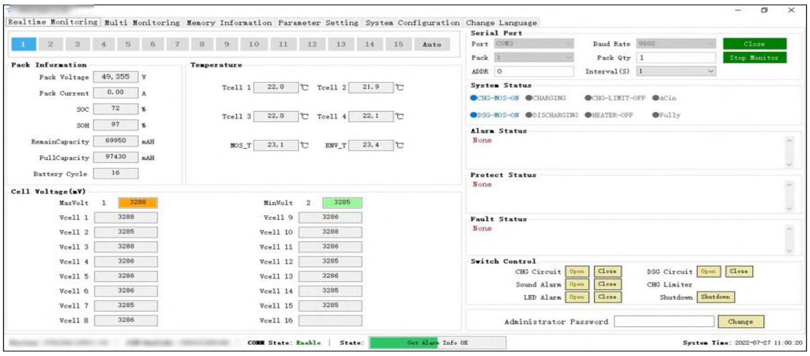


Figure 6.3: Database of Software

The best software results to be the one of the n.7. The main window is represented in the next image.



Pack Information

Pack Voltage 49,355 V
Pack Current 0,00 A
SOC 72 %
SOH 97 %
RemainCapacity 69950 mAH
FullCapacity 97430 mAH
Battery Cycle 16

Temperature

Tcell 1 22.0 ℃ Tcell 2 21.9 ℃
Tcell 3 22.0 ℃ Tcell 4 22.1 ℃
MOS_T 23.1 ℃ ENV_T 23.4 ℃

Cell Voltage(mV)

MaxVolt 1 3288
Vcell 1 3288
Vcell 2 3285
Vcell 3 3288
Vcell 4 3286
Vcell 5 3286
Vcell 6 3286
Vcell 7 3285
Vcell 8 3286

MinVolt 2 3285
Vcell 9 3286
Vcell 10 3288
Vcell 11 3286
Vcell 12 3285
Vcell 13 3286
Vcell 14 3285
Vcell 15 3285
Vcell 16

Serial Port

Port COM3
Baud Rate 9600
Pack 1
Pack Qty 1
ADDR 0
Interval(S) 1

System Status

● CHG-MOS-ON ● CHARGING ● CHG-LIMIT-OFF ● ACin
● DSG-MOS-ON ● DISCHARGING ● HEATER-OFF ● Fully

Alarm Status
None

Protect Status
None

Fault Status
None

Switch Control

CHG Circuit Open Close
Sound Alarm Open Close
LED Alarm Open Close
DSG Circuit Open Close
CHG Limiter
Shutdown Shutdown

Administrator Password

[redacted] [redacted] COMM State: Enable | State: Get Alarm Info OK System Time: 2022-07-27 11:00:20

Figure 6.4: Software pack n.7

This software has all the features presented in chapter 3. The producer also gave the password in order to change some parameters, if it was necessary for the purpose of testing.

Chapter 7

Conclusions

The work done for this thesis was the analysis of three lithium-ion battery packs from the point of view of internal design and electrical performance. Their nominal voltage is 48V with 100Ah of total capacity.

The project started with the purpose to enlarge the company market in the lithium-ions batteries, for telecommunication applications.Therefore, the company initiated a study of ten packs of different manufacturers in order to find the best one.

In the first chapter a description of the lithium-ions batteries is done, explaining the basics of the working principal, the REDOX reaction. The components that are present in a battery are anode, cathode, separator and the electrolyte. Based on the cathode material, there are various type of lithium batteries with different characteristics. The batteries tested for this project are LFP that stands for Lithium Iron Phosphate or LiFePO and all the cells are prismatic. Typically the anode is made up by a graphite. Another predominant cathode type is the NMC, Nickel, Manganese and Cobalt. LFP chemistry is much better for telecom applications for price, safety reasons and cycles. At the end of the chapter there is a brief description of the BMS (Battery Management System) that is the brain of the battery.

In the second chapter all the main equipment used are briefly described, that are a cycler used to charge and discharged the battery, that is able also to registered the data, and a battery tester used to perform internal resistance and voltage measurements.

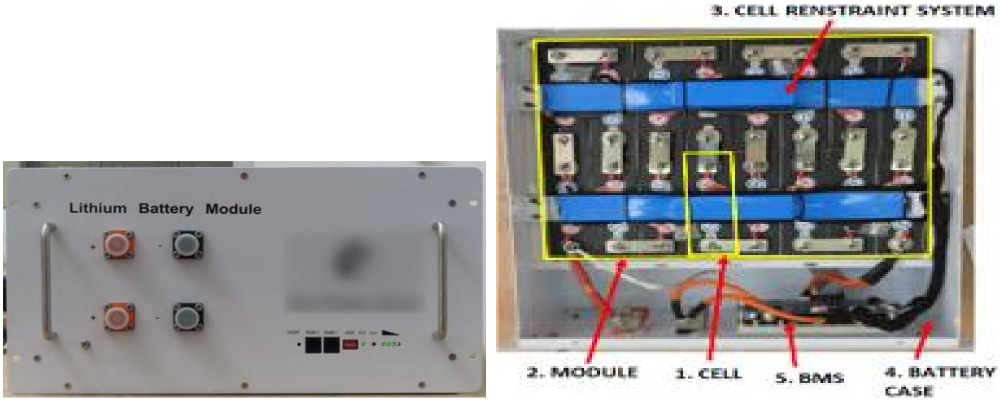
The electrical performances are listed and described. The first two measurements are the internal resistance and the OCV, to know the status of the battery. Then, capacity tests are done with different C rate, at ambient temperature. What is expected from this type of test is to reach at least the nominal capacity. Others important tests are the stress ones, useful to verify if, at high C rate, the overtemperature protection triggered. The last type of test is the overload one, in order to test the protection of the BSM.

The three database with all the informations regarding the design, the electrical performances and the software are created with the goal to identify the best battery pack. In order to do this, it is assigned a weight for each evaluation: the electrical tests have the greatest impact and the software analysis the least one. Doing the average of these three values with their weight, the best battery, at this point of the project, is the pack n.8.

The characteristic of this pack, not present on this document, has sixteen cells, so one more as the previous analysed. This implies that the nominal voltage is 51.2V.

The battery pack presents the following characteristics:

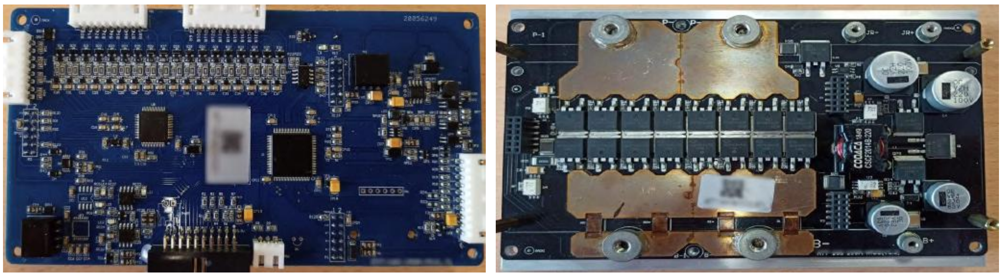
- Nominal Voltage: 51.2V;
- Nominal Capacity: 100Ah;
- Height: 6U;
- Specific Energy: 86.14 Wh/kg;
- Standard Charge/Discharge: 0.5C;
- VEOC: 58.4V;
- VEOD: 40V;
- Configuration: 16s1p;



(a) Front Panel (b) Internal Internal Design

Figure 7.1: Design Pack n.8

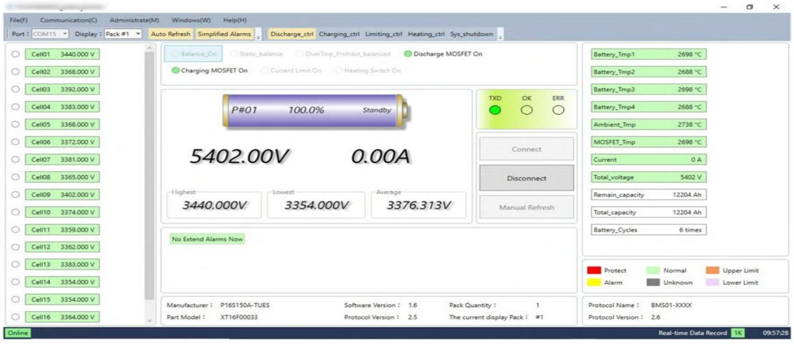
The BMS is a little bit different from the others and with a heat sink on on the back of the power board. There are also some thermic conductive bars to help the dissipation process.



(a) Control Board (b) Power Board

Figure 7.2: BMS Pack n.8

For the electrical tests all the capacity tests reaches more than the nominal value in charge/discharge. The battery is oversized by the producer in order to do more than a 100Ah can do. The internal resistance is about 15mΩ.
The main window of the software is shown below:



Port : COM15
Display : Pack #1

○ Cell01 3440.000 V
○ Cell02 3368.000 V
○ Cell03 3392.000 V
○ Cell04 3383.000 V
○ Cell05 3368.000 V
○ Cell06 3372.000 V
○ Cell07 3381.000 V
○ Cell08 3365.000 V
○ Cell09 3402.000 V
○ Cell10 3374.000 V
○ Cell11 3359.000 V
○ Cell12 3362.000 V
○ Cell13 3383.000 V
○ Cell14 3354.000 V
○ Cell15 3354.000 V
○ Cell16 3364.000 V

● Discharge MOSFET On
● Charging MOSFET On

P#01 100.0% Standby

5402.00V 0.00A

Highest 3440.000V
Lowest 3354.000V
Average 3376.313V

No Extend Alarms Now

Battery_Tmp1	2698 °C
Battery_Tmp2	2688 °C
Battery_Tmp3	2698 °C
Battery_Tmp4	2688 °C
Ambient_Tmp	2738 °C
MOSFET_Tmp	2698 °C
Current	0 A
Total_voltage	5402 V
Remain_capacity	12204 Ah
Total_capacity	12204 Ah
Battery_Cycles	6 times

Manufacturer : P16S150A-TUES
Part Model : XT16F00033
Software Version : 1.6
Protocol Version : 2.5
Pack Quantity : 1
The current display Pack : #1
Protocol Name : BMS01-XXXX
Protocol Version : 2.6

Online
Real-time Data Record 1K 09:57:28

Figure 7.3: Main Window SW Pack n.8

One of the main problem of this software is the wrong position of the comma. The features described in the previous chapters are all present except for the changing threshold parameters that needs a password not declared by the producer.
Fiamm has planned to evaluate others two batteries within the next months so the partial result obtained and described in this chapter could be different from the final one.

Appendix A

Matlab Scripts

Script to extrapolate data

To rapidly take the data from the Digatron and the BMS log, a new excel file with two sheets is created in order to have a general script to use for all the tests. Below the script for the charge with a charge of 0.5C.

```
clc
clear all
close all

%% data

% read data from a specific tab of the excel file
% each column is identified by the name of the first row
CHA05Cdigatron = readtable('CHA05C.xlsx', 'Sheet', 'Digatron');
% data taken from each column
time_digatron = CHA05Cdigatron.time_DIGA;
voltage_digatron = CHA05Cdigatron.Voltage_DIGA;
current_digatron = CHA05Cdigatron.Current_DIGA;
step_digatron = CHA05Cdigatron.stepDIGA;

CHA05Cbms = readtable('CHA05C.xlsx', 'Sheet', 'BMS');
time_bms = CHA05Cbms.time_BMS;
voltage_bms = CHA05Cbms.Voltage_BMS;
current_bms = CHA05Cbms.Current_BMS;
step_bms = CHA05Cbms.stepBMS;

SOC = CHA05Cbms.SOC;

voltage_cell1 = CHA05Cbms.Vol_Cell01;
voltage_cell2 = CHA05Cbms.Vol_Cell02;
voltage_cell3 = CHA05Cbms.Vol_Cell03;
```

```
voltage_cell4 = CHA05Cbms.Vol_Cell04;
voltage_cell5 = CHA05Cbms.Vol_Cell05;
voltage_cell6 = CHA05Cbms.Vol_Cell06;
voltage_cell7 = CHA05Cbms.Vol_Cell07;
voltage_cell8 = CHA05Cbms.Vol_Cell08;
voltage_cell9 = CHA05Cbms.Vol_Cell09;
voltage_cell10 = CHA05Cbms.Vol_Cell10;
voltage_cell11 = CHA05Cbms.Vol_Cell11;
voltage_cell12 = CHA05Cbms.Vol_Cell12;
voltage_cell13 = CHA05Cbms.Vol_Cell13;
voltage_cell14 = CHA05Cbms.Vol_Cell14;
voltage_cell15 = CHA05Cbms.Vol_Cell15;

tempPCB = CHA05Cbms.Temp_PCB;
tempINT = CHA05Cbms.Temp_internal;
temp01 = CHA05Cbms.Temp01;
temp02 = CHA05Cbms.Temp02;
temp03 = CHA05Cbms.Temp03;
temp04 = CHA05Cbms.Temp04;
```

Script for plots

```
% Axes limit varies from plot to plot
% V & I
figure
yyaxis left   % double axis
plot(time_digatron, voltage_digatron, 'b', time_bms, voltage_bms, '--b');
ylabel('Voltage [V]');
% ylim([42 54]);
ylim([0 70]);

yyaxis right
plot(time_digatron, current_digatron, 'r', time_bms, current_bms, '--r');
% ylim([-52 52]);
ylim([-130 130]);
ylabel('Current [A]');

title('Voltage & Current of Digatron and BMS');
legend('V_{diga}', 'V_{BMS}', 'I_{diga}', 'I_{BMS}')
xlabel('Day Time [hour:min]');
grid on
xlim tight
legend('Location','bestoutside');

% Cell voltages
figure
plot(time_bms, voltage_cell1, time_bms, voltage_cell2, time_bms,
    voltage_cell3, time_bms, voltage_cell4, time_bms, voltage_cell5,
    time_bms, voltage_cell6, time_bms, voltage_cell7, time_bms,
    voltage_cell8, time_bms, voltage_cell9, time_bms, voltage_cell10,
```

```
    time_bms, voltage_cell11, time_bms, voltage_cell12, time_bms,
    voltage_cell13, time_bms, voltage_cell14, time_bms, voltage_cell15);
xlabel('Day Time [hour:min]');
ylabel('Voltage [V]');
title('Cell Voltages');
legend('V_{CELL1}', 'V_{CELL2}', 'V_{CELL3}', 'V_{CELL4}', 'V_{CELL5}', '
    V_{CELL6}', 'V_{CELL7}', 'V_{CELL8}', 'V_{CELL9}', 'V_{CELL10}', 'V_{
    CELL11}', 'V_{CELL12}', 'V_{CELL13}', 'V_{CELL14}', 'V_{CELL15}')
grid on
xlim tight
legend('Location','bestoutside');

% SOC
figure
yyaxis left
plot(time_bms, SOC, 'b');
xlabel('Day Time [hour:min]');
ylabel('SOC [%]');
ylim([0 110]);

yyaxis right
plot(time_bms, current_bms, 'r');
ylim([-120 120]);
ylabel('Current [A]');

title('SOC_{BMS} & Current');
legend('SOC_{BMS}', 'Current');
grid on
xlim tight
legend('Location','bestoutside');

% Temperatures
figure
plot(time_bms, tempPCB, 'r', time_bms, tempINT, 'b', time_bms, temp01, 'g
    ', time_bms, temp02, 'c', time_bms, temp03, 'm', time_bms, temp04, 'y
    ');
xlabel('Day Time [hour:min]');
ylabel('T [Â°C]');
title('Temperatures');
legend('T_{PCB}','T_{internal}', 'T_{01}', 'T_{02}', 'T_{03}', 'T_{04}');
grid on
xlim tight
legend('Location','bestoutside');

% % Temperatures for MAX_DCH_CHA
% figure
% plot(time_bms, tempPCB, 'r', time_bms, tempINT, 'b');
% xlabel('Day Time [hour:min]');
% ylabel('T [Â°C]');
% title('Temperatures');
```

```
% legend('T_{PCB}','T_{internal}', 'T_{01}', 'T_{02}', 'T_{03}', 'T_{04}')
    ;
% grid on
% xlim tight
% legend('Location','bestoutside');
% figure
% plot(time_bms, temp01, 'g', time_bms, temp02, 'c', time_bms, temp03, 'm
    ', time_bms, temp04, 'y');
% xlabel('Day Time [hour:min]');
% ylabel('T [Â°C]');
% title('Temperatures');
% legend('T_{PCB}','T_{internal}', 'T_{01}', 'T_{02}', 'T_{03}', 'T_{04}')
    ;
% grid on
% xlim tight
% legend('Location','bestoutside');
```

Script for specific steps

This script is used to zoom on specific step of the test, to see better some problem or how the test is gone.

```
% declaration of all the vectors
stringVecName = [];
stepName = [];
% input from keyboard
Nstep = input('How much step do you want to plot? (must be consecutive):
    ');
for i = 1 : Nstep
    stepName(i) = input('Digit the number of the step:  ');
    stringVecName = [stringVecName, stepName(i)];
end

count = 0;
CurrentVectorBMS = [];
VoltageVectorBMS = [];
CellV1 = [] ;
CellV2 = [] ;
CellV3 = [] ;
CellV4 = [] ;
CellV5 = [] ;
CellV6 = [] ;
CellV7 = [] ;
CellV8 = [] ;
CellV9 = [] ;
CellV10 = [] ;
CellV11 = [] ;
CellV12 = [] ;
CellV13 = [] ;
CellV14 = [] ;
```

```
CellV15 = [] ;
tInt = [];
tPCB = [];
t1 = [];
t2 = [];
t3 = [];
t4 = [];
StepTimeBMS =[];
k = stepName(1);
i = 1;

% looping and save all the data corresponding to the step desired
% BMS loop
while i <= length(step_bms)
    if step_bms(i) == k
        CurrentVectorBMS = [CurrentVectorBMS, current_bms(i)];
        VoltageVectorBMS = [VoltageVectorBMS, voltage_bms(i)];
        CellV1 = [CellV1, voltage_cell1(i)];
        CellV2 = [CellV2, voltage_cell2(i)];
        CellV3 = [CellV3, voltage_cell3(i)];
        CellV4 = [CellV4, voltage_cell4(i)];
        CellV5 = [CellV5, voltage_cell5(i)];
        CellV6 = [CellV6, voltage_cell6(i)];
        CellV7 = [CellV7, voltage_cell7(i)];
        CellV8 = [CellV8, voltage_cell8(i)];
        CellV9 = [CellV9, voltage_cell9(i)];
        CellV10 = [CellV10, voltage_cell10(i)];
        CellV11 = [CellV11, voltage_cell11(i)];
        CellV12 = [CellV12, voltage_cell12(i)];
        CellV13 = [CellV13, voltage_cell13(i)];
        CellV14 = [CellV14, voltage_cell14(i)];
        CellV15 = [CellV15, voltage_cell15(i)];
        tInt = [tInt, tempINT(i)];
        tPCB = [tPCB, tempPCB(i)];
        t1 = [t1, temp01(i)];
        t2 = [t2, temp02(i)];
        t3 = [t3, temp03(i)];
        t4 = [t4, temp04(i)];
        StepTimeBMS = [StepTimeBMS, time_bms(i)];
    elseif step_bms(i) ~= k && ~isempty(CurrentVectorBMS)
        k = k + 1;
        i = i - 1;
    end
    if k > stepName(length(stepName))
        k = k - 1;
        i = length(step_bms)+1;
    end
    i = i + 1;
end
```

```
count = 0;
VoltageVectorDiga = [];
CurrentVectorDiga = [];
StepTimeDiga = [];
k = stepName(1);
i = 1;

% Digatron loop
while i <= length(step_digatron)
    if step_digatron(i) == k
        VoltageVectorDiga = [VoltageVectorDiga, voltage_digatron(i)];
        CurrentVectorDiga = [CurrentVectorDiga, current_digatron(i)];
        StepTimeDiga = [StepTimeDiga, time_digatron(i)];
    elseif step_digatron(i) ~= k && ~isempty(VoltageVectorDiga)
        k = k + 1;
        i = i - 1;
    end
    if k > stepName(length(stepName))
        k = k - 1;
        i = length(step_digatron)+1;
    end
    i = i + 1;
end

%%
figure
yyaxis left
plot(StepTimeDiga, VoltageVectorDiga, 'b', StepTimeBMS, VoltageVectorBMS,
    '--b');
ylabel('Voltage [V]');
ylim([42 54]);

yyaxis right
plot(StepTimeDiga, CurrentVectorDiga, 'r', StepTimeBMS, CurrentVectorBMS,
    '--r');
ylim([-110 110]);
ylabel('Current [A]');

title('Test Step');
legend('V_{diga}', 'V_{BMS}', 'I_{diga}', 'I_{BMS}')
xlabel('Day Time [hour:min]');
grid on
xlim tight
legend('Location','bestoutside');


% Cell voltages
figure
plot(StepTimeBMS, CellV1,StepTimeBMS, CellV2,StepTimeBMS, CellV3,
```

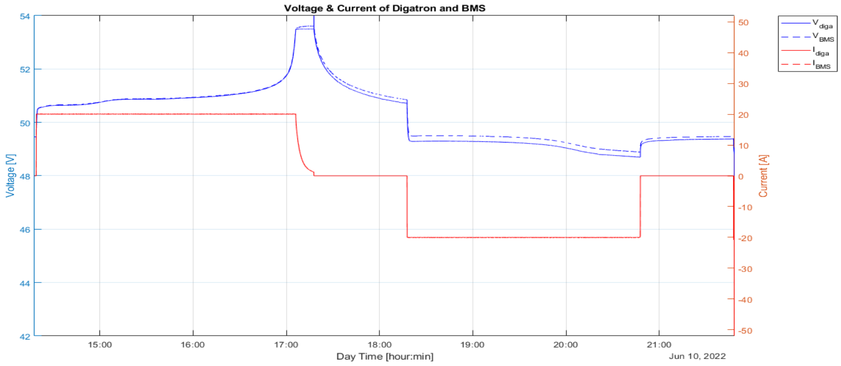
```
    StepTimeBMS, CellV4, StepTimeBMS, CellV5, StepTimeBMS, CellV6,
    StepTimeBMS, CellV7, StepTimeBMS, CellV8, StepTimeBMS, CellV9,
    StepTimeBMS, CellV10, StepTimeBMS, CellV11, StepTimeBMS, CellV12,
    StepTimeBMS, CellV13, StepTimeBMS, CellV14, StepTimeBMS, CellV15);
xlabel('Day Time [hour:min]');
ylabel('Voltage [V]');
title('Cell Voltages during step');
legend('V_{CELL1}', 'V_{CELL2}', 'V_{CELL3}', 'V_{CELL4}', 'V_{CELL5}', '
    V_{CELL6}', 'V_{CELL7}', 'V_{CELL8}', 'V_{CELL9}', 'V_{CELL10}', 'V_{
    CELL11}', 'V_{CELL12}', 'V_{CELL13}', 'V_{CELL14}', 'V_{CELL15}')
grid on
xlim tight
legend('Location','bestoutside');

% temp
figure
plot(StepTimeBMS, tPCB, 'r', StepTimeBMS, tInt, 'b', StepTimeBMS, t1, 'g',
     StepTimeBMS, t2, 'c', StepTimeBMS, t3, 'm', StepTimeBMS, t4, 'y');
xlabel('Day Time [hour:min]');
ylabel('T [Â°C]');
title('Temperatures during step');
legend('T_{PCB}','T_{internal}', 'T_{01}', 'T_{02}', 'T_{03}', 'T_{04}');
grid on
xlim tight
legend('Location','bestoutside');
```

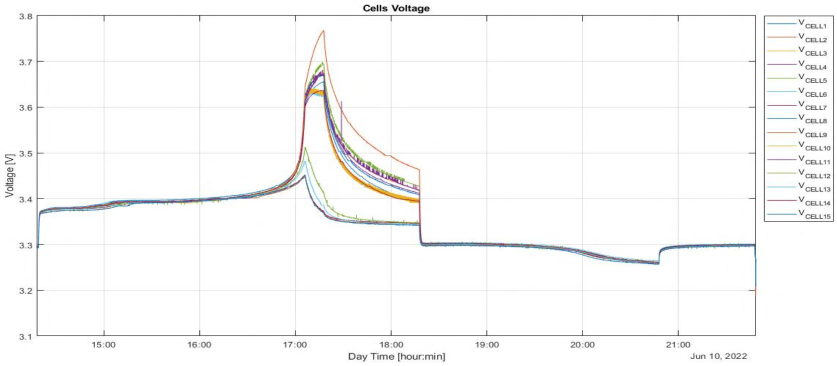
Appendix B

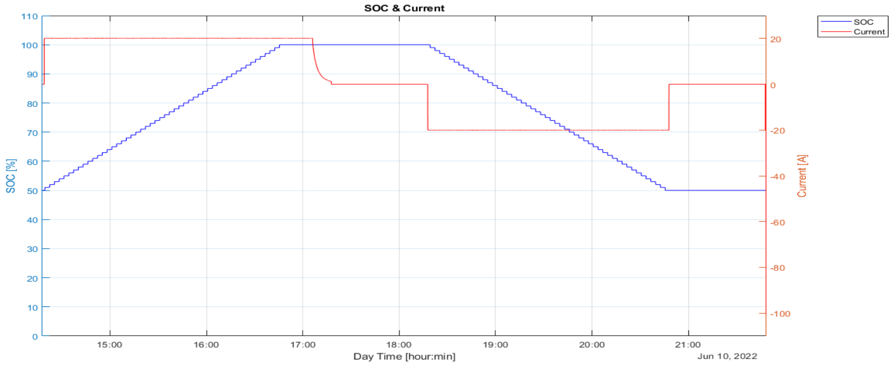
Plots

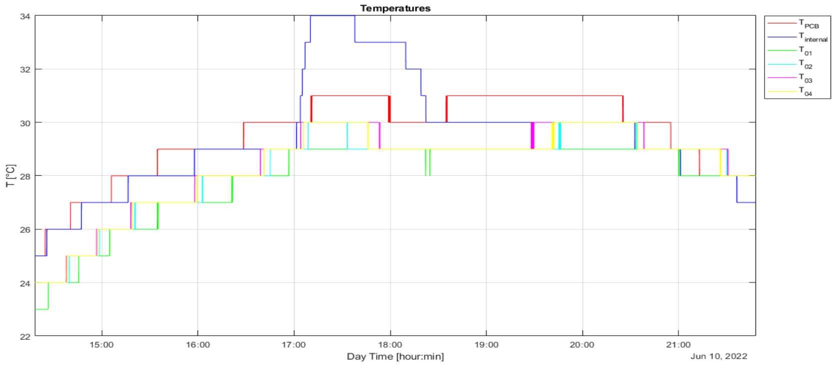
Battery Pack n.1

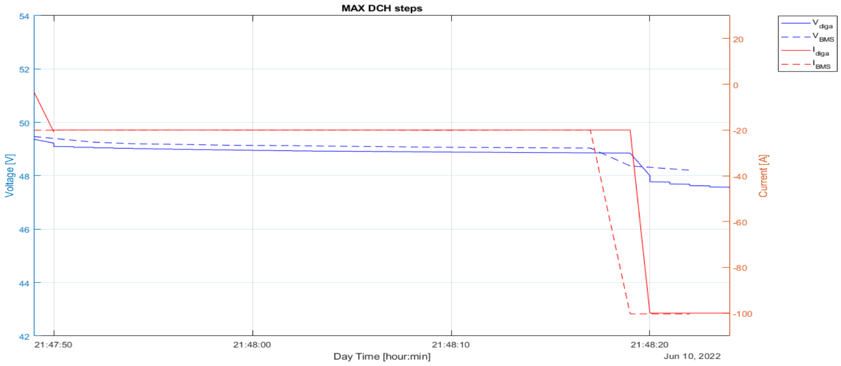
Internal Resistance



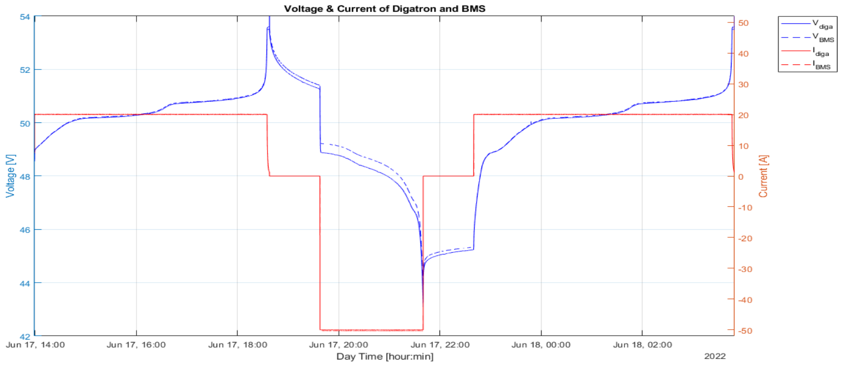

Cells Voltage
Voltage [V]
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Day Time [hour:min]
Jun 10, 2022
V_CELL1
V_CELL2
V_CELL3
V_CELL4
V_CELL5
V_CELL6
V_CELL7
V_CELL8
V_CELL9
V_CELL10
V_CELL11
V_CELL12
V_CELL13
V_CELL14
V_CELL15

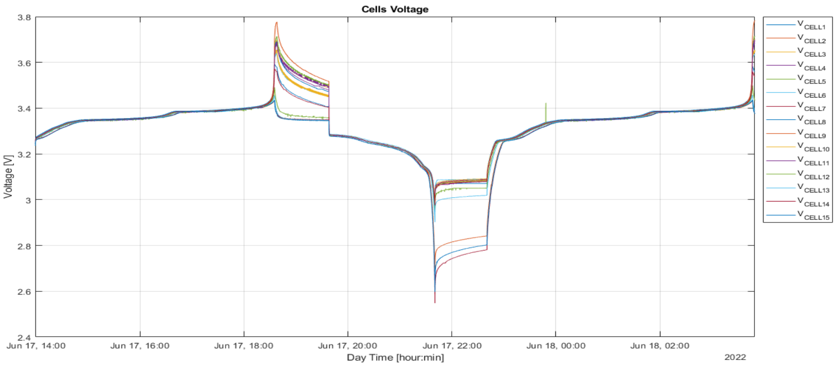

SOC & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
20
0
-20
-40
-60
-80
-100
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Day Time [hour:min]
Jun 10, 2022
SOC
Current

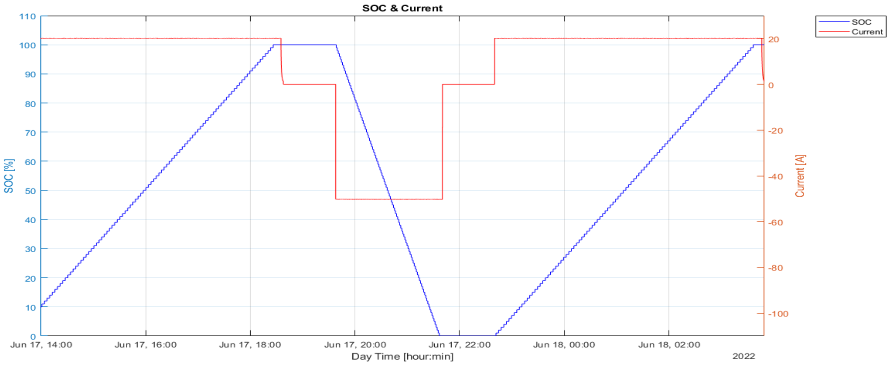

Temperatures
T [°C]
34
32
30
28
26
24
22
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Day Time [hour:min]
Jun 10, 2022
T_PCB
T_internal
T_01
T_02
T_03
T_04

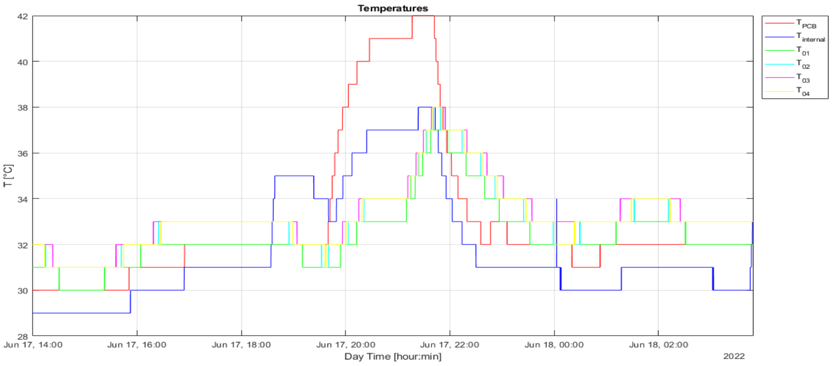


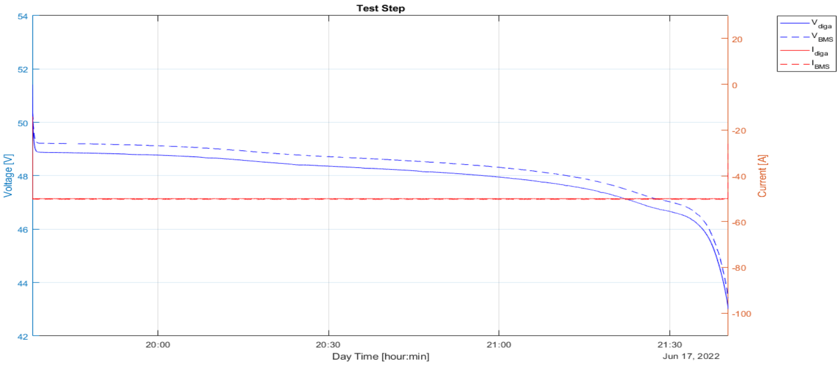
Discharge at 0,5C

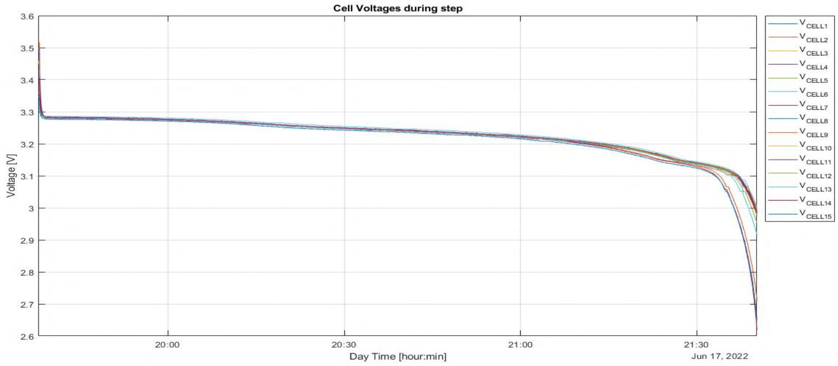


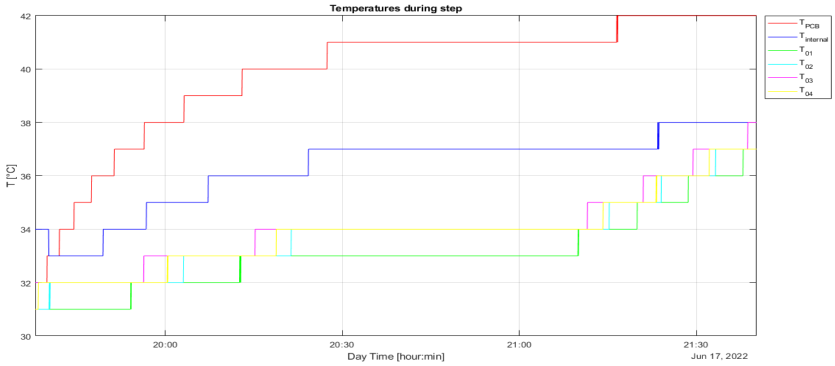



SOC & Current
SOC
Current
SOC [%]
Current [A]
110
100
90
80
70
60
50
40
30
20
10
0
20
0
-20
-40
-60
-80
-100
Jun 17, 14:00
Jun 17, 16:00
Jun 17, 18:00
Jun 17, 20:00
Jun 17, 22:00
Jun 18, 00:00
Jun 18, 02:00
Day Time [hour:min]
2022

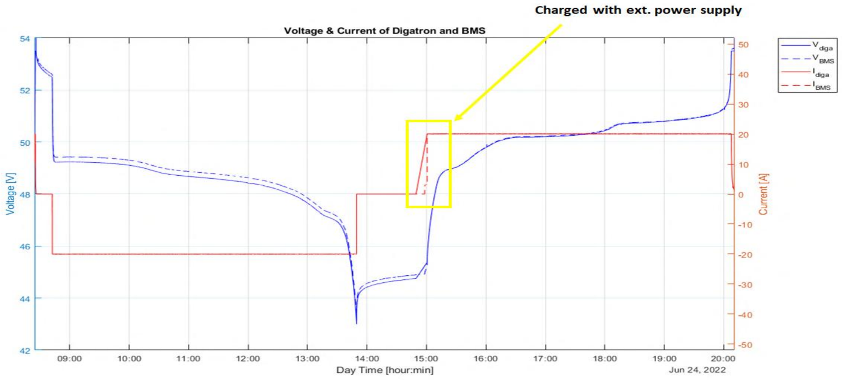

Temperatures
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}
T [°C]
42
40
38
36
34
32
30
28
Jun 17, 14:00
Jun 17, 16:00
Jun 17, 18:00
Jun 17, 20:00
Jun 17, 22:00
Jun 18, 00:00
Jun 18, 02:00
Day Time [hour:min]
2022

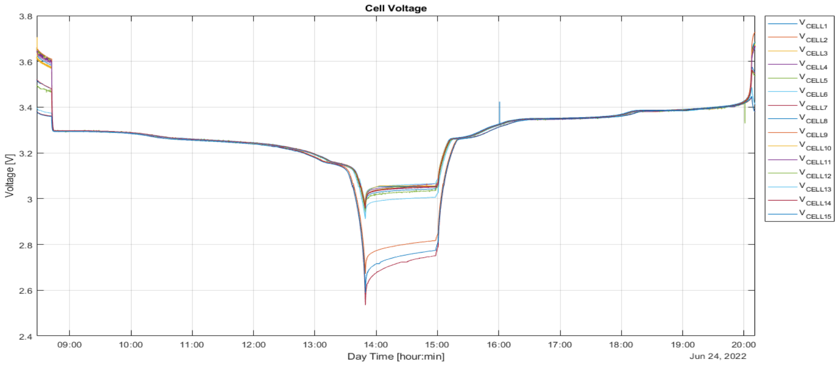

Test Step
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}
Voltage [V]
Current [A]
54
52
50
48
46
44
42
20
0
-20
-40
-60
-80
-100
20:00
20:30
21:00
21:30
Day Time [hour:min]
Jun 17, 2022

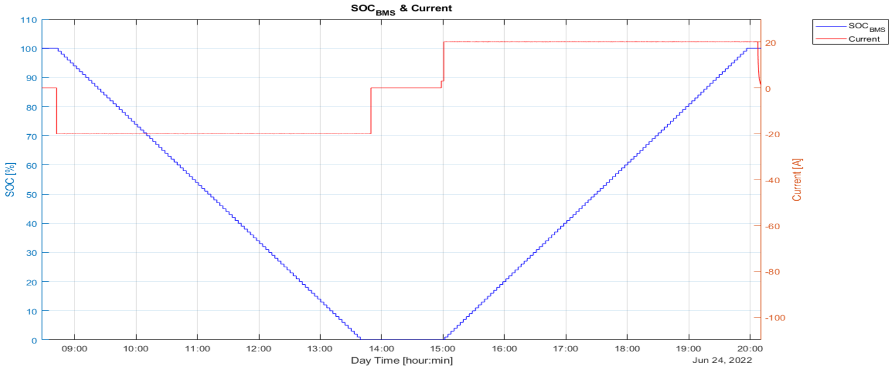


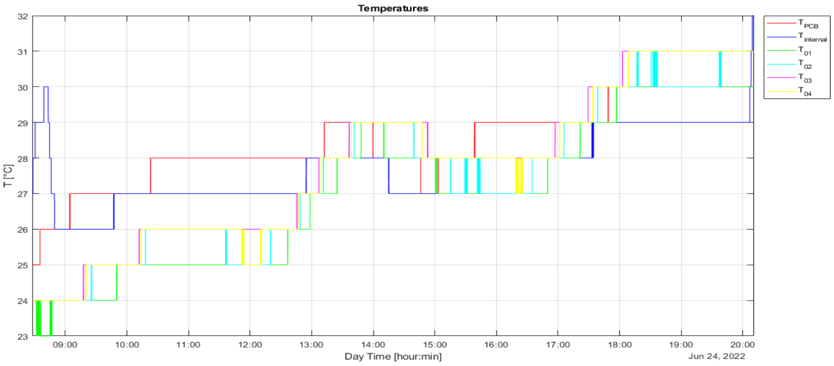


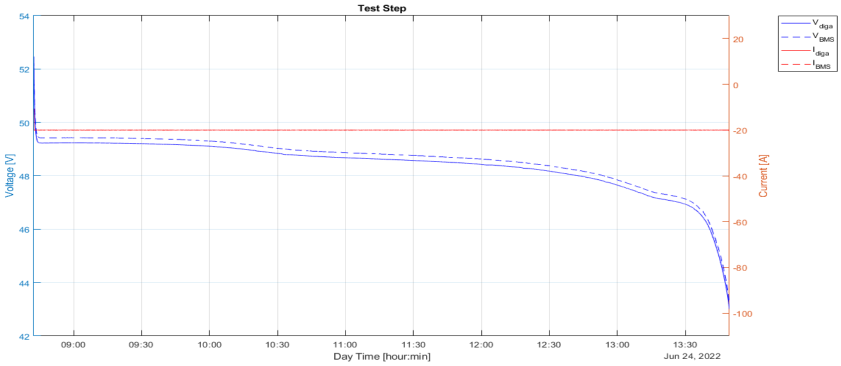
Discharge at 0,2C


Charged with ext. power supply

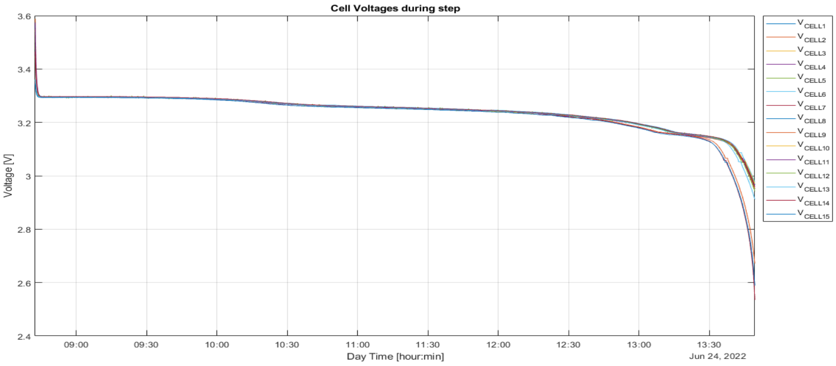

Cell Voltage
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Jun 24, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}


SOC_{BMS} & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
20
0
-20
-40
-60
-80
-100
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Jun 24, 2022
SOC_{BMS}
Current

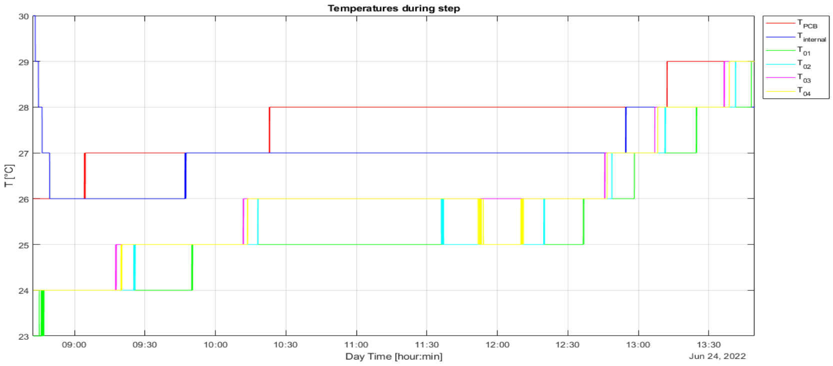

Temperatures
T [°C]
32
31
30
29
28
27
26
25
24
23
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Jun 24, 2022
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}



Test Step

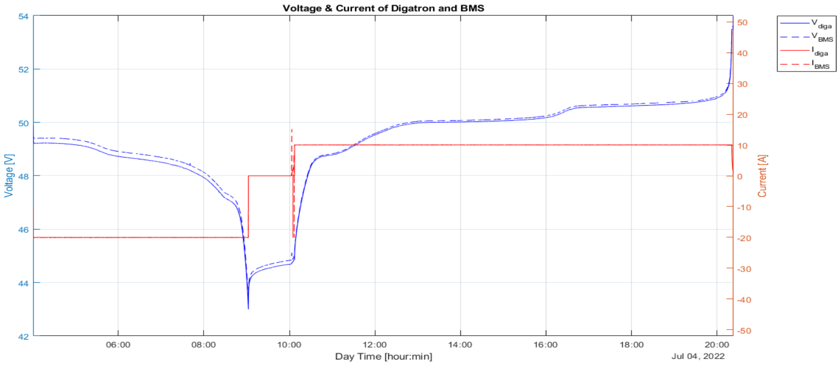


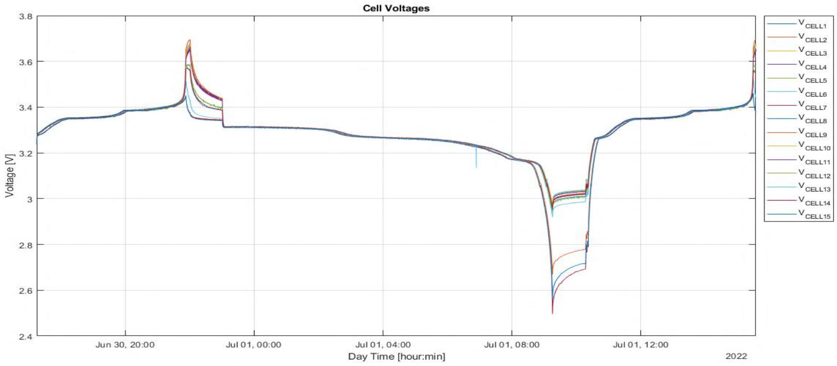
Cell Voltages during step

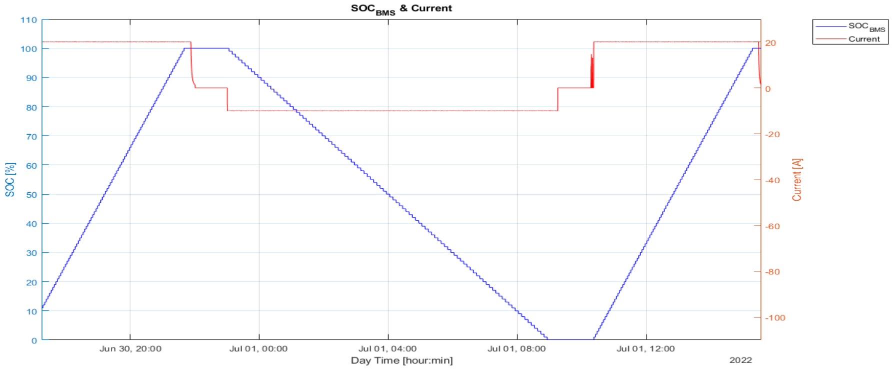


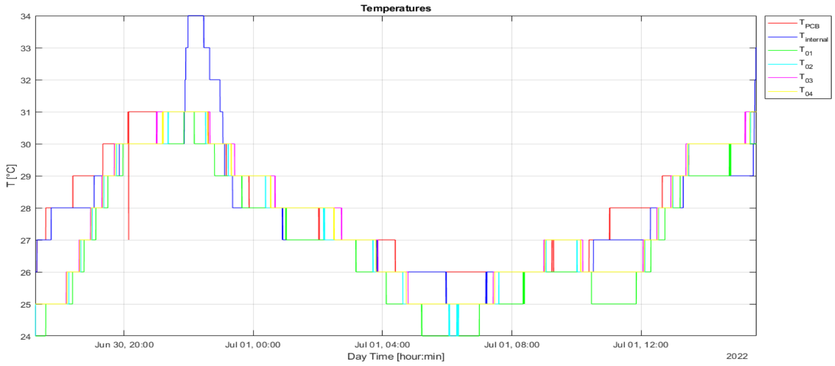
Temperatures during step

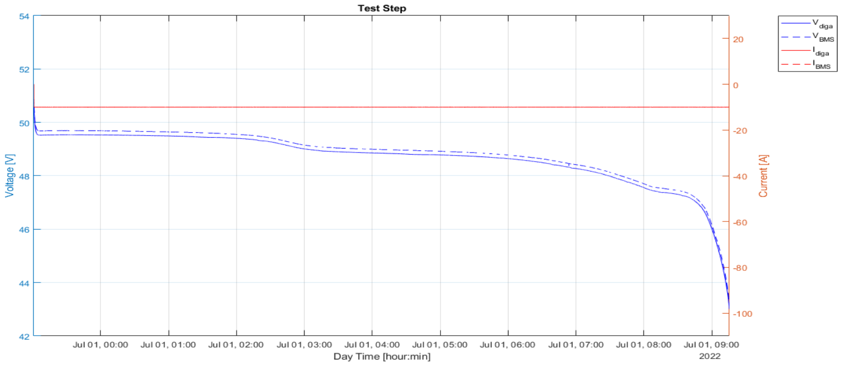
Discharge at 0,1C

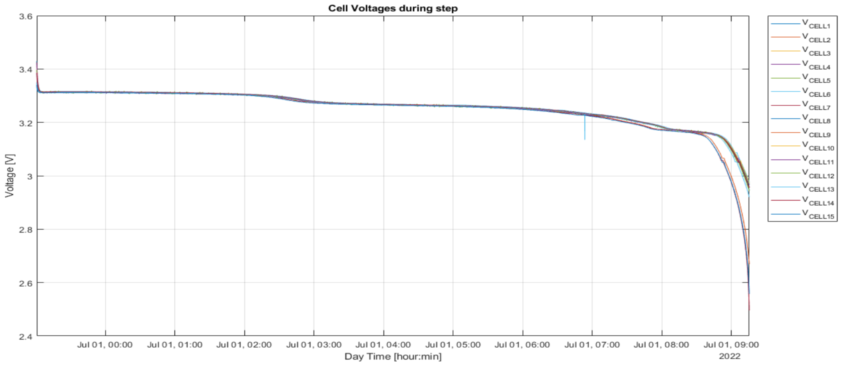


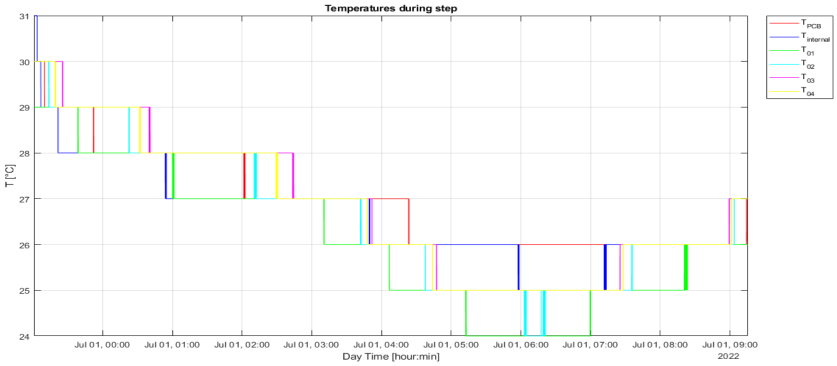


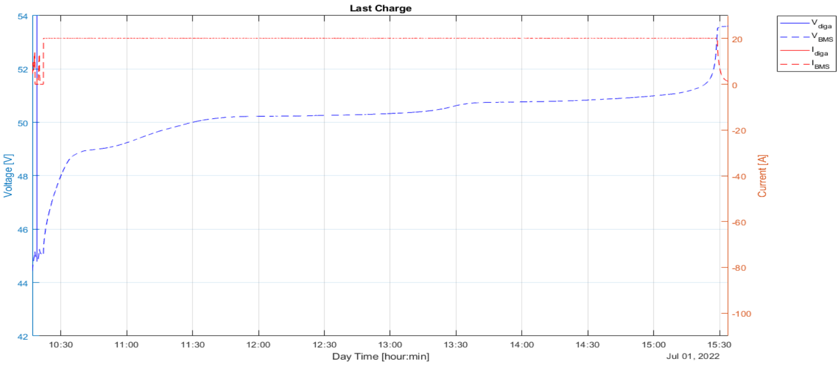



Temperatures
T [°C]
34
33
32
31
30
29
28
27
26
25
24
Jun 30, 20:00
Jul 01, 00:00
Jul 01, 04:00
Jul 01, 08:00
Jul 01, 12:00
2022
Day Time [hour:min]
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

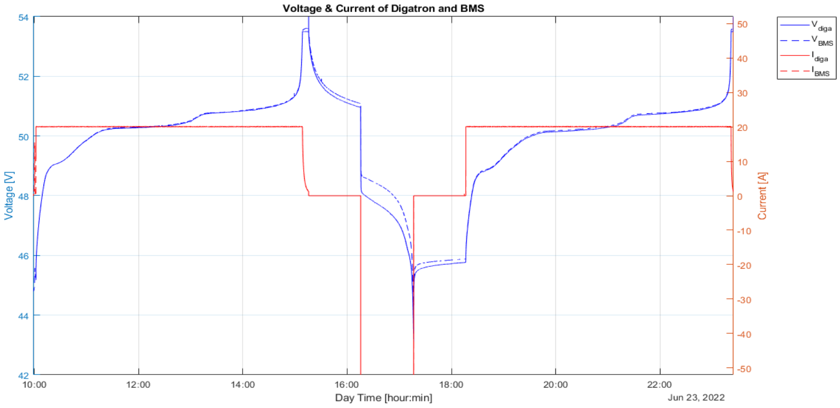

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
20
0
-20
-40
-60
-80
-100
Jul 01, 00:00
Jul 01, 01:00
Jul 01, 02:00
Jul 01, 03:00
Jul 01, 04:00
Jul 01, 05:00
Jul 01, 06:00
Jul 01, 07:00
Jul 01, 08:00
Jul 01, 09:00
2022
Day Time [hour:min]
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

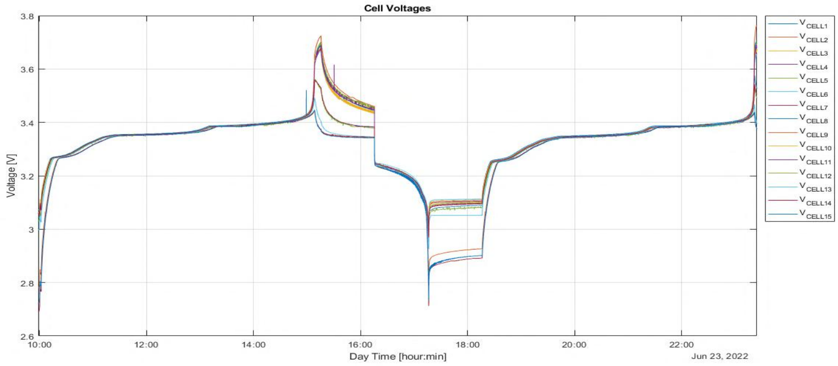

Cell Voltages during step
Voltage [V]
3.6
3.4
3.2
3
2.8
2.6
2.4
Jul 01, 00:00
Jul 01, 01:00
Jul 01, 02:00
Jul 01, 03:00
Jul 01, 04:00
Jul 01, 05:00
Jul 01, 06:00
Jul 01, 07:00
Jul 01, 08:00
Jul 01, 09:00
2022
Day Time [hour:min]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

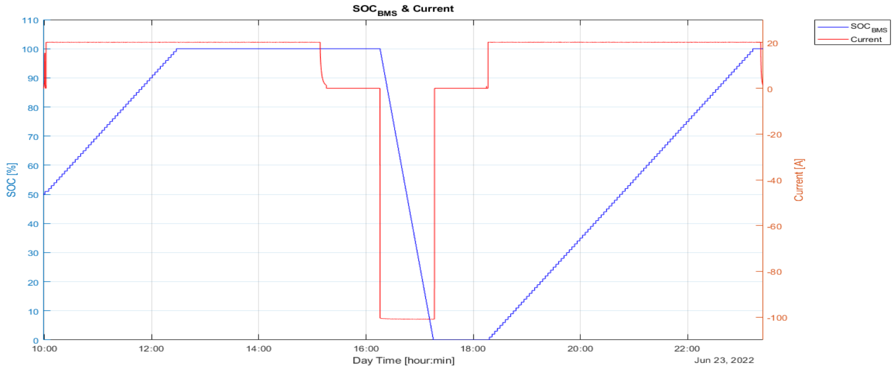


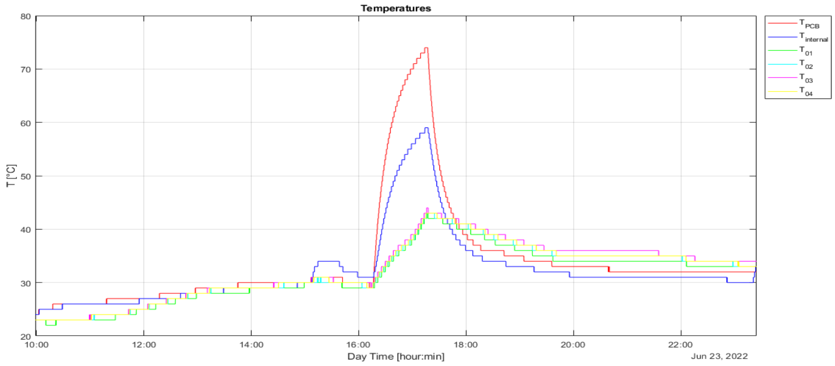


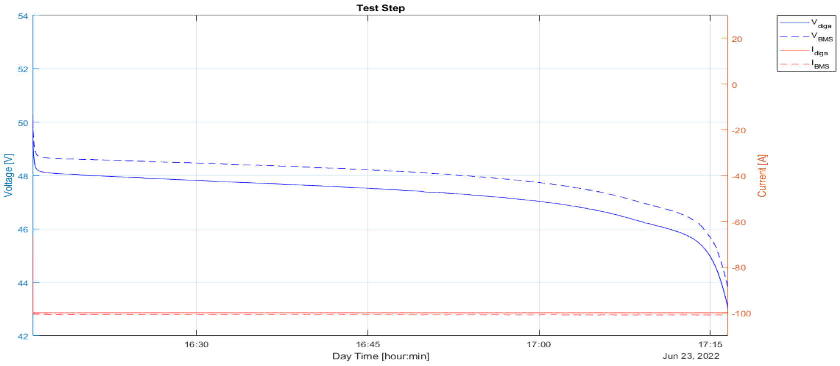
Discharge at 1C

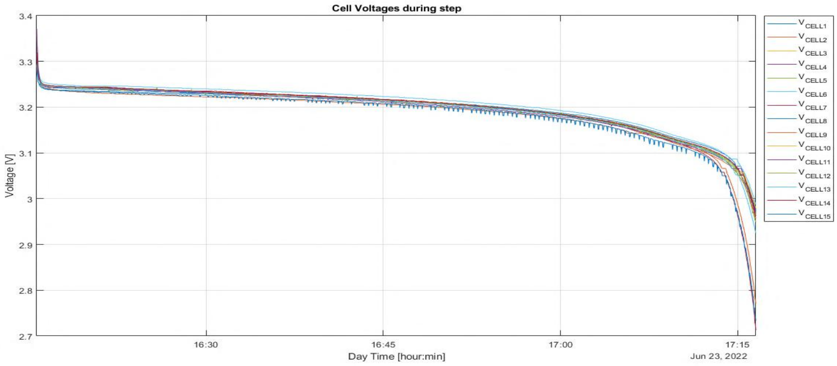


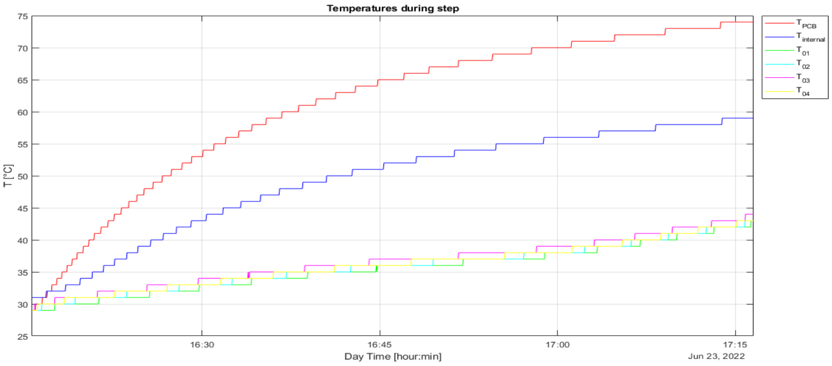

Cell Voltages
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Day Time [hour:min]
Jun 23, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}


SOC_{BMS} & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
20
0
-20
-40
-60
-80
-100
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Day Time [hour:min]
Jun 23, 2022
SOC_{BMS}
Current

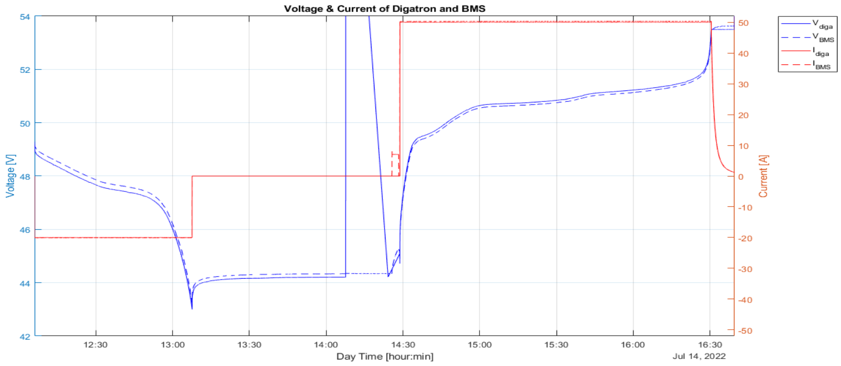

Temperatures
T [°C]
80
70
60
50
40
30
20
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Day Time [hour:min]
Jun 23, 2022
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

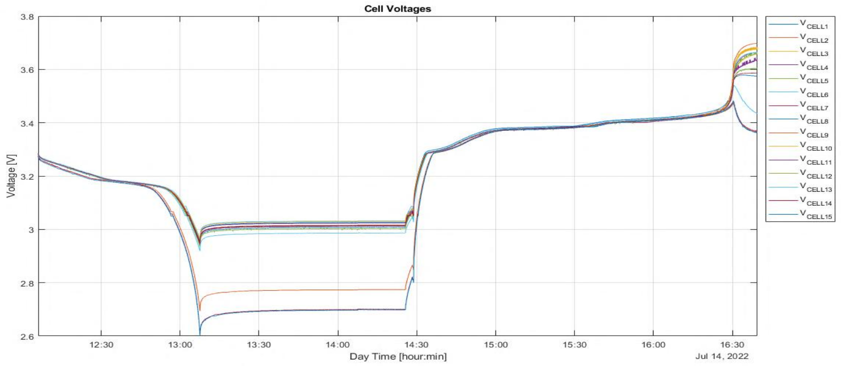

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
20
0
-20
-40
-60
-80
-100
16:30
16:45
17:00
17:15
Day Time [hour:min]
Jun 23, 2022
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

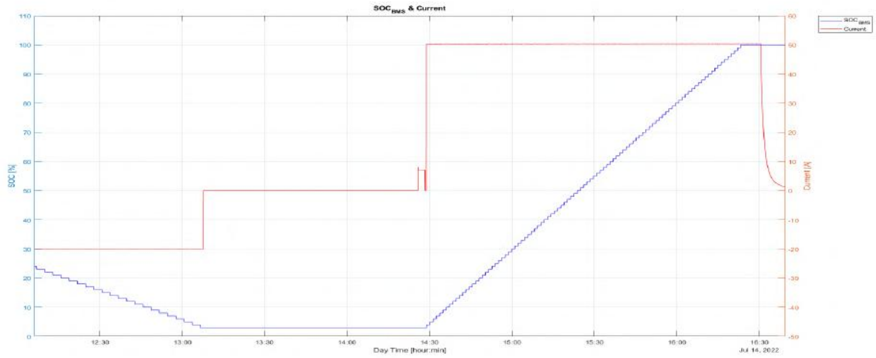

Cell Voltages during step
Voltage [V]
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
16:30
16:45
17:00
17:15
Day Time [hour:min]
Jun 23, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

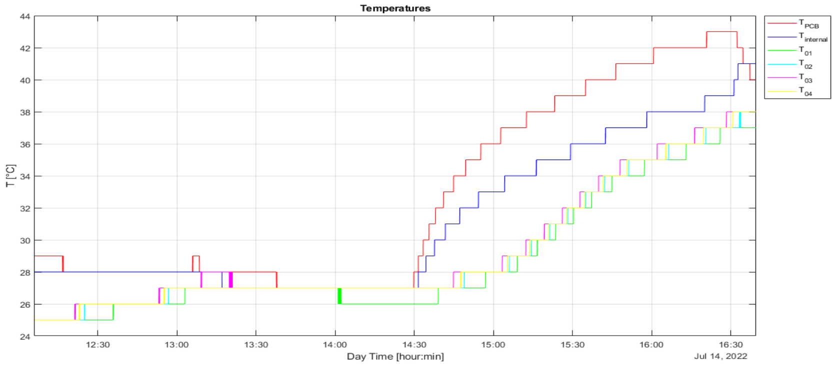

Temperatures during step
T [°C]
75
70
65
60
55
50
45
40
35
30
25
16:30
16:45
17:00
17:15
Day Time [hour:min]
Jun 23, 2022
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

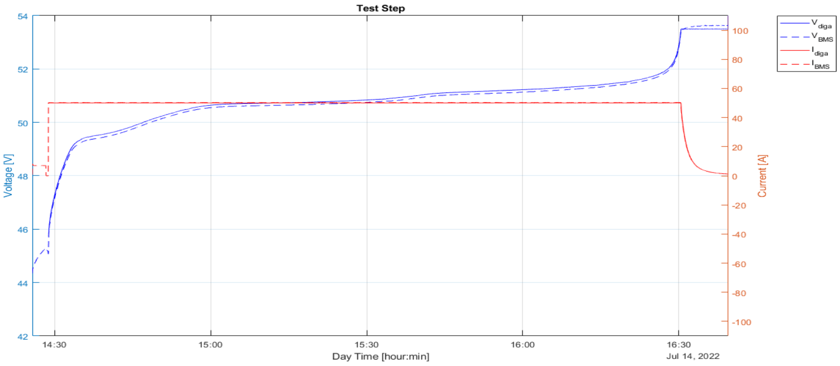
Charge at 0,5C

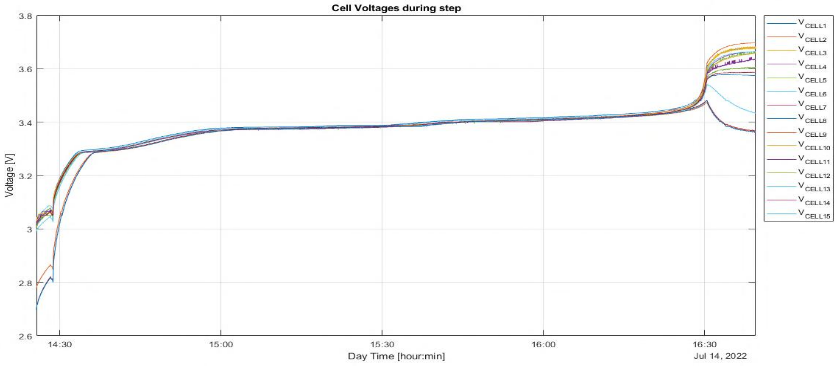


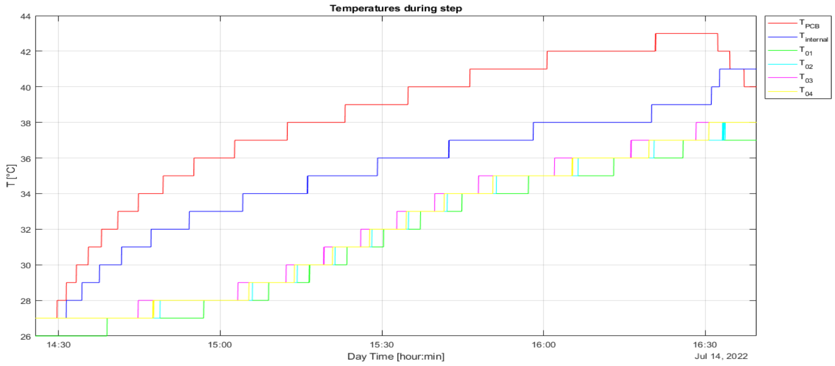




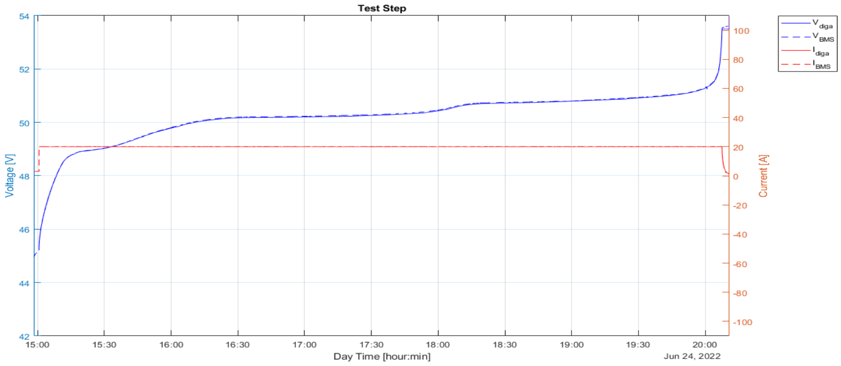

Temperatures
T [°C]
44
42
40
38
36
34
32
30
28
26
24
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
Day Time [hour:min]
Jul 14, 2022
T_PCB
T_internal
T_01
T_02
T_03
T_04

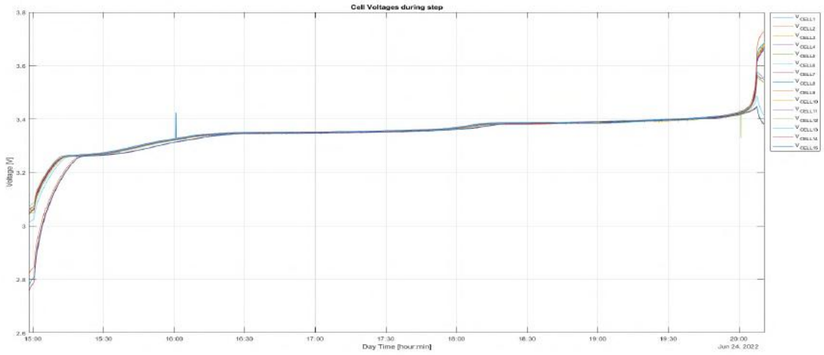

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
14:30
15:00
15:30
16:00
16:30
Day Time [hour:min]
Jul 14, 2022
V_diga
V_BMS
I_diga
I_BMS


Cell Voltages during step
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
14:30
15:00
15:30
16:00
16:30
Day Time [hour:min]
Jul 14, 2022
V_CELL1
V_CELL2
V_CELL3
V_CELL4
V_CELL5
V_CELL6
V_CELL7
V_CELL8
V_CELL9
V_CELL10
V_CELL11
V_CELL12
V_CELL13
V_CELL14
V_CELL15

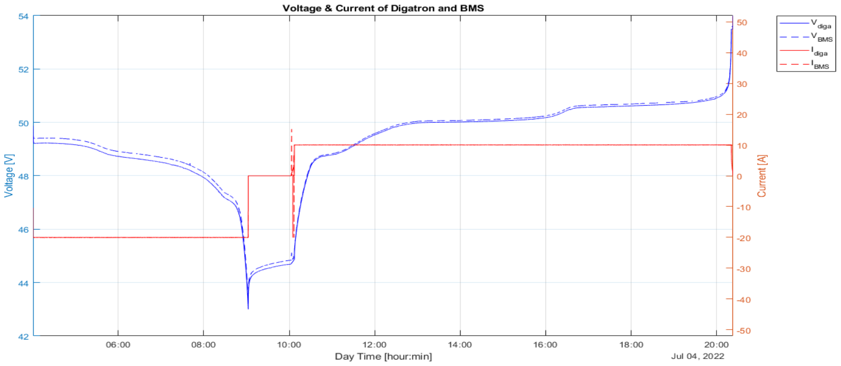


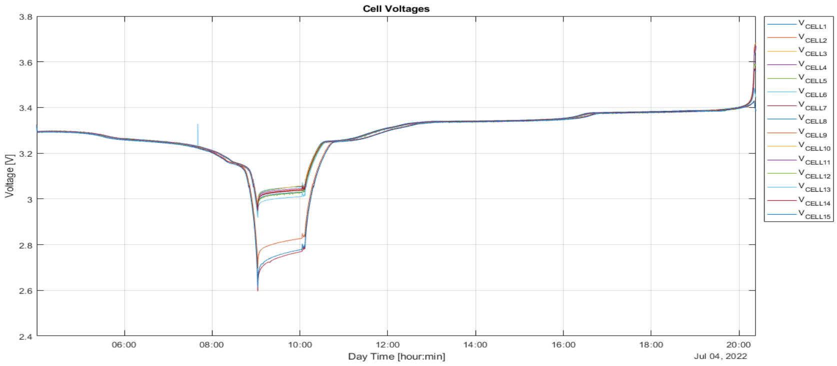
Charge at 0,2C

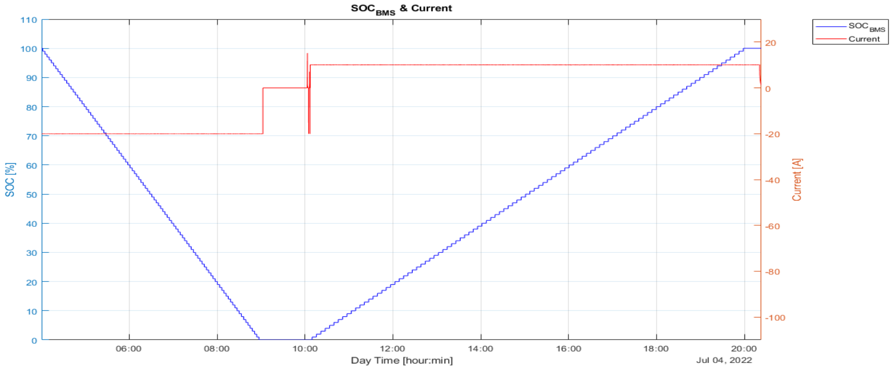


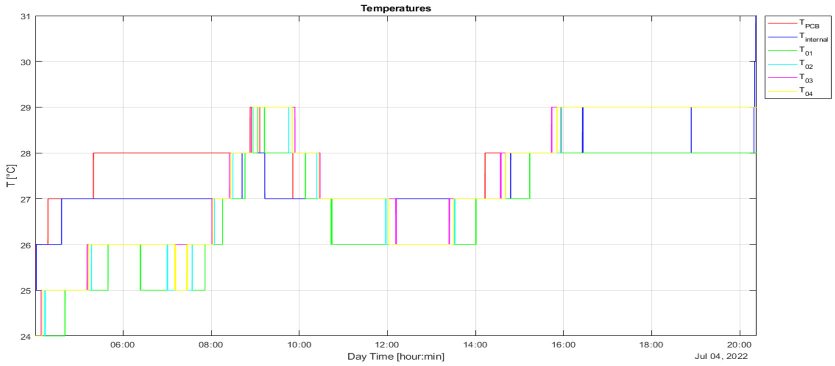


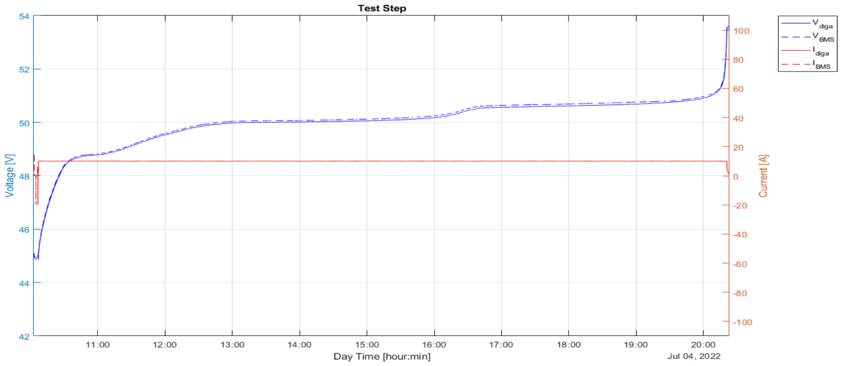
Charge at 0,1C

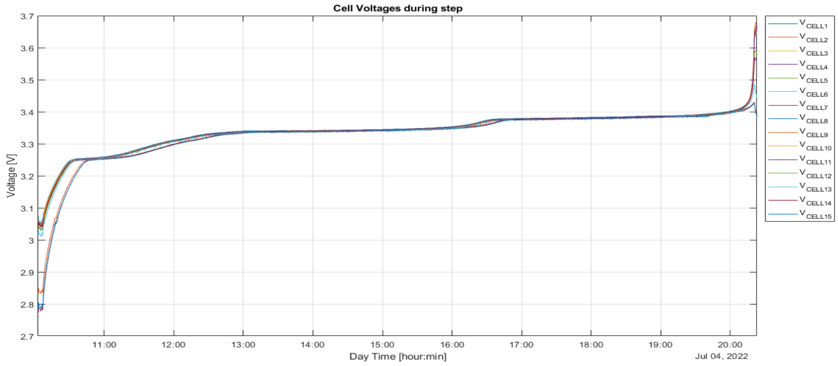


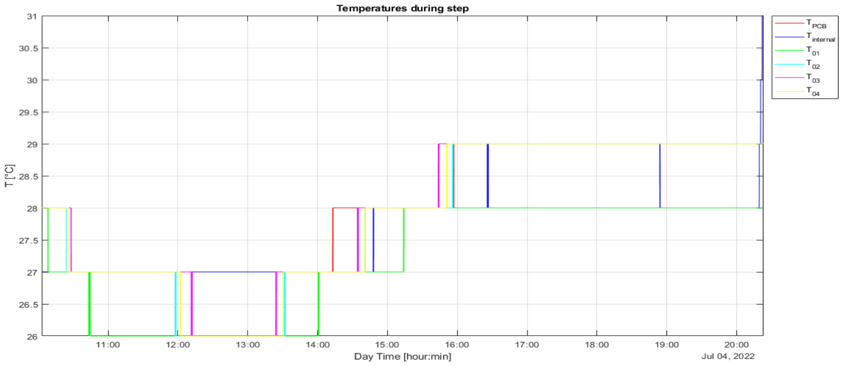




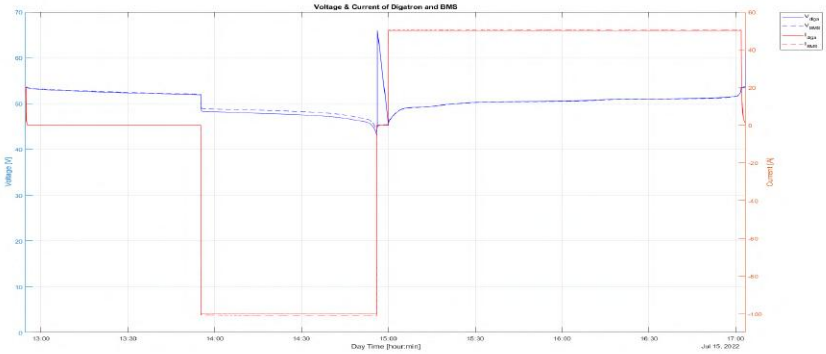

Temperatures
T [°C]
31
30
29
28
27
26
25
24
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
Day Time [hour:min]
Jul 04, 2022
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

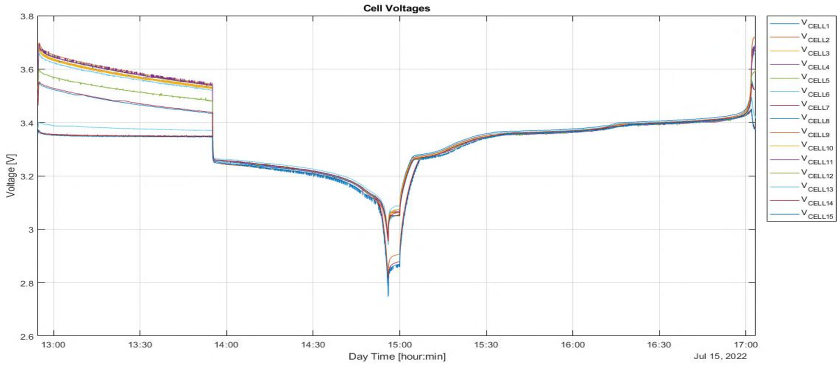

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Jul 04, 2022
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

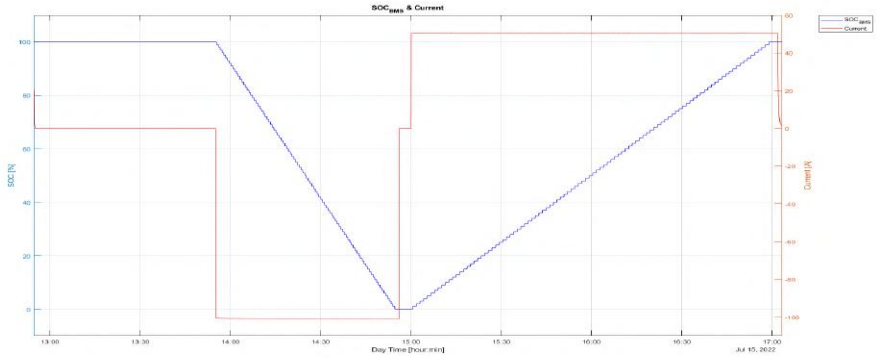

Cell Voltages during step
Voltage [V]
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Jul 04, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

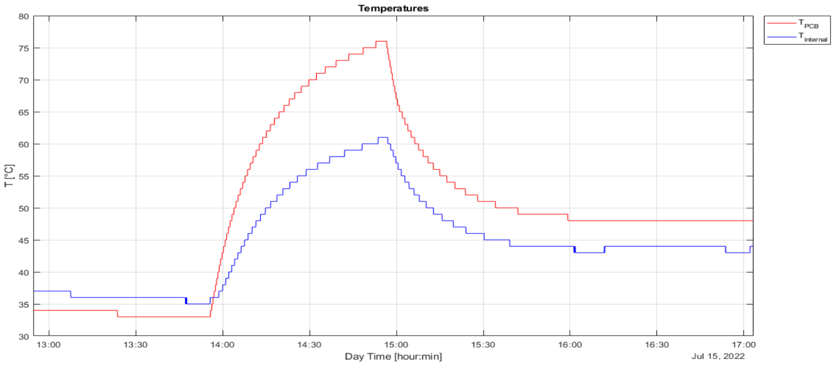


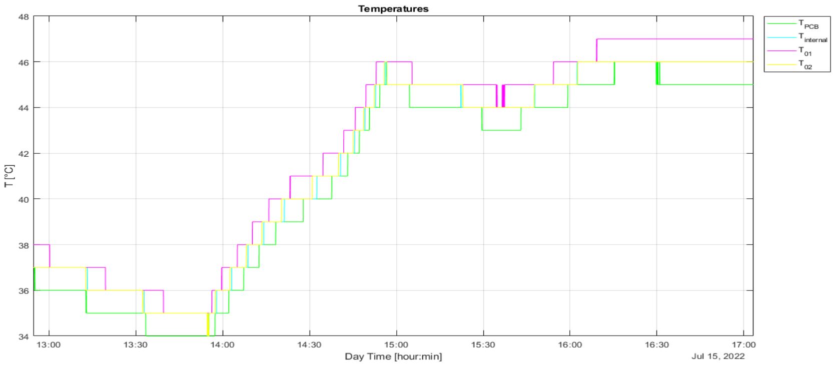
Maximum Discharge/Charge Current



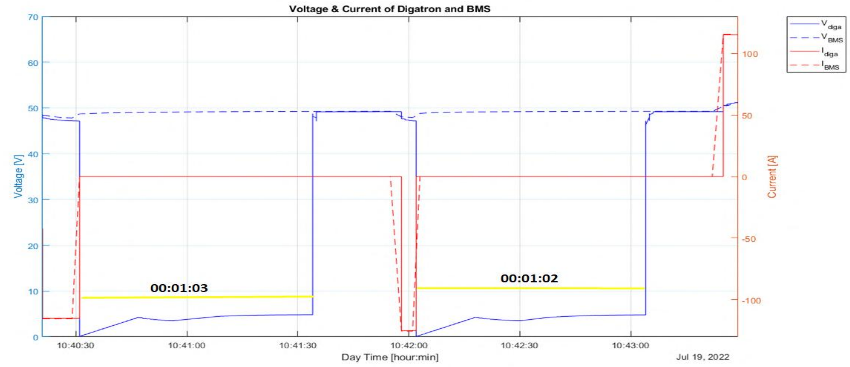


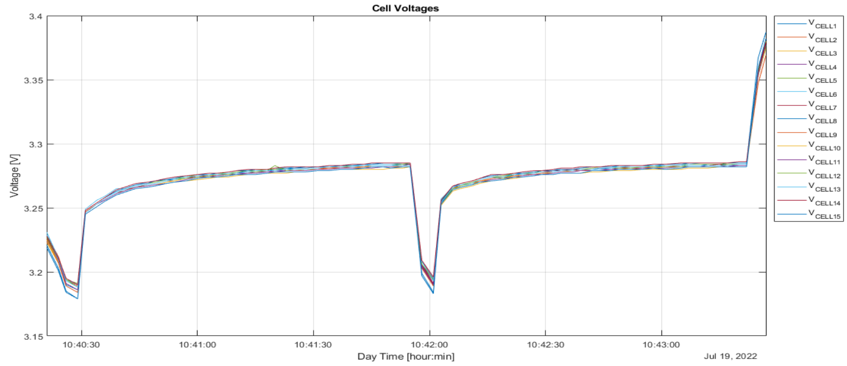

SOC$_{BMS}$ & Current
SOC$_{BMS}$
Current
SOC [%]
100
80
60
40
20
0
Current [A]
60
40
20
0
-20
-40
-60
-80
-100
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
Day Time [hour:min]
Jul 15, 2022


Temperatures
T$_{PCB}$
T$_{internal}$
T [°C]
80
75
70
65
60
55
50
45
40
35
30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
Day Time [hour:min]
Jul 15, 2022


Temperatures
T$_{PCB}$
T$_{internal}$
T$_{01}$
T$_{02}$
T [°C]
48
46
44
42
40
38
36
34
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
Day Time [hour:min]
Jul 15, 2022

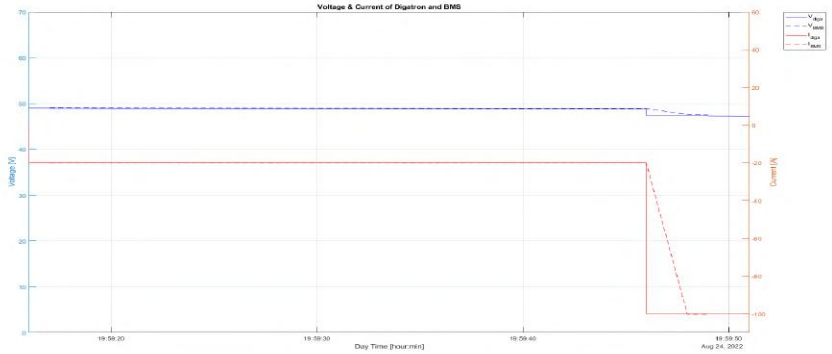
Overprotection Test



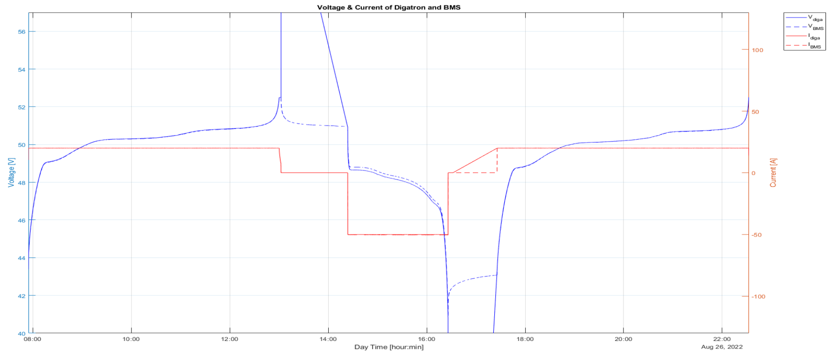


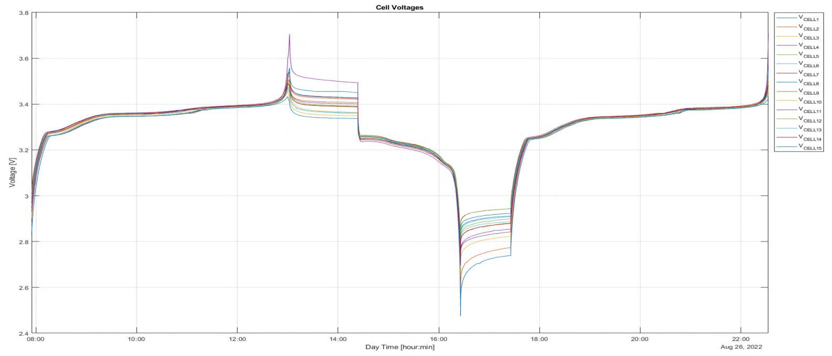
Battery Pack n.2

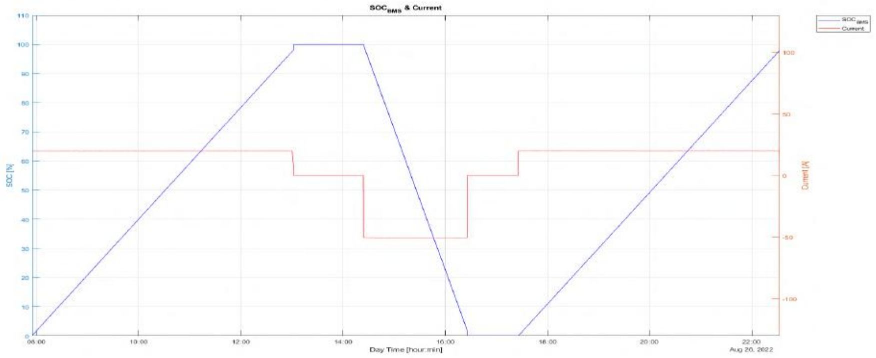
Internal Resistance

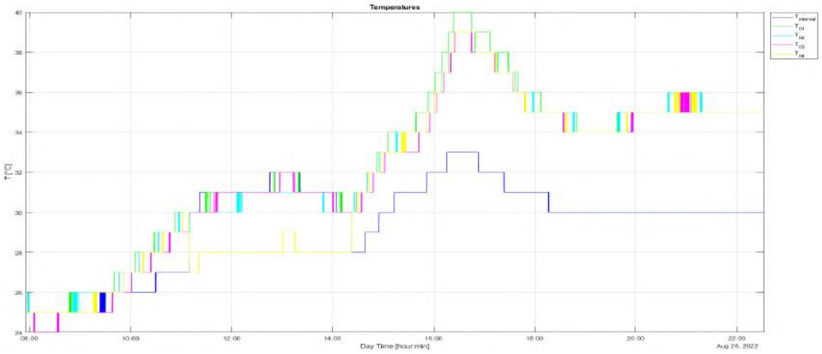


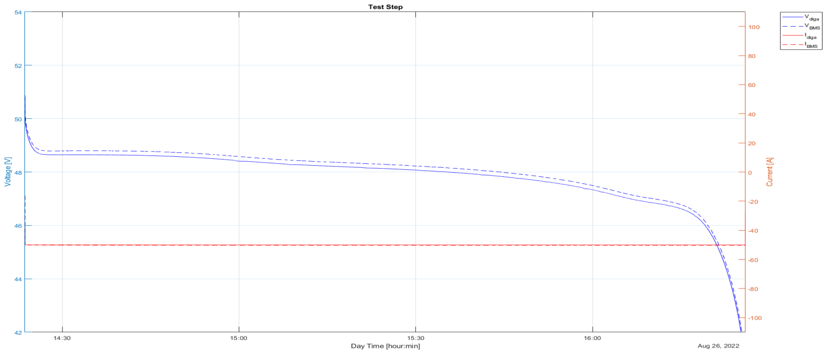
Discharge at 0,5C

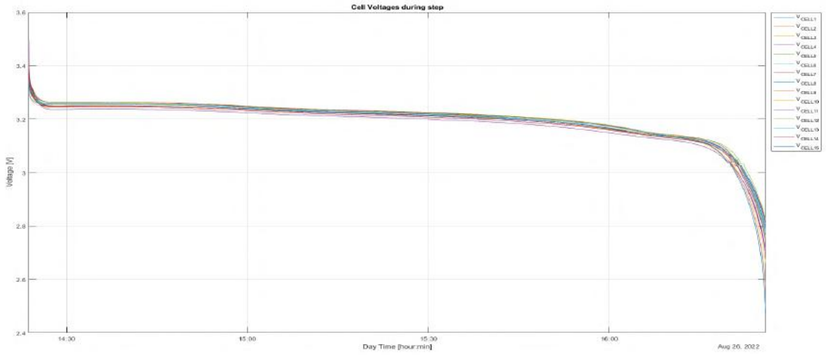


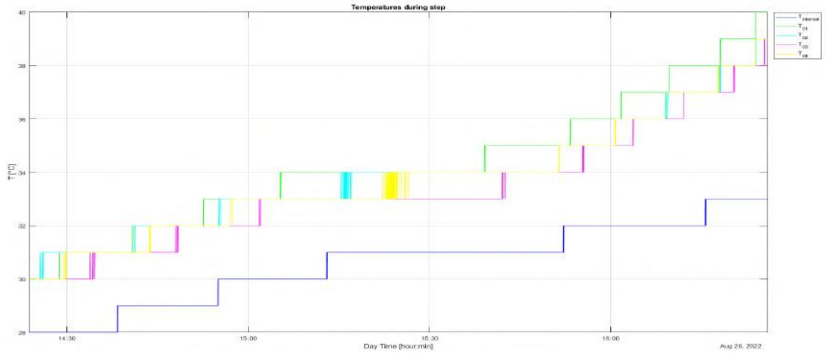



SOC$_{BMS}$ & Current
SOC$_{BMS}$
Current
SOC [%]
Current [A]
110
100
90
80
70
60
50
40
30
20
10
0
100
50
0
-50
-100
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Aug 26, 2022
Day Time [hour:min]

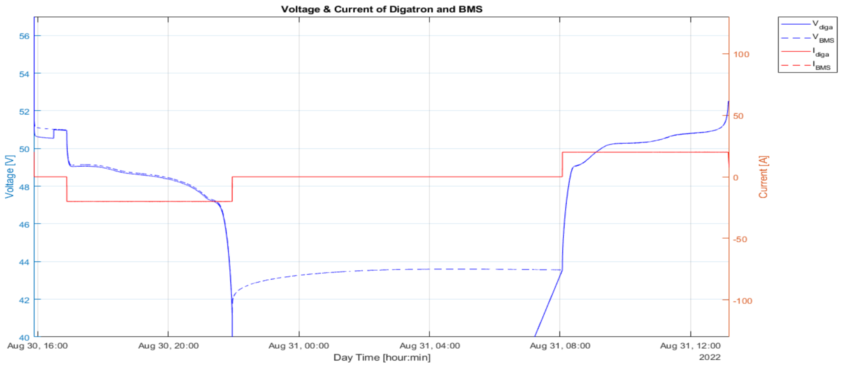

Temperatures
T$_{internal}$
T$_{01}$
T$_{02}$
T$_{03}$
T$_{04}$
T [°C]
40
38
36
34
32
30
28
26
24
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Aug 26, 2022
Day Time [hour:min]

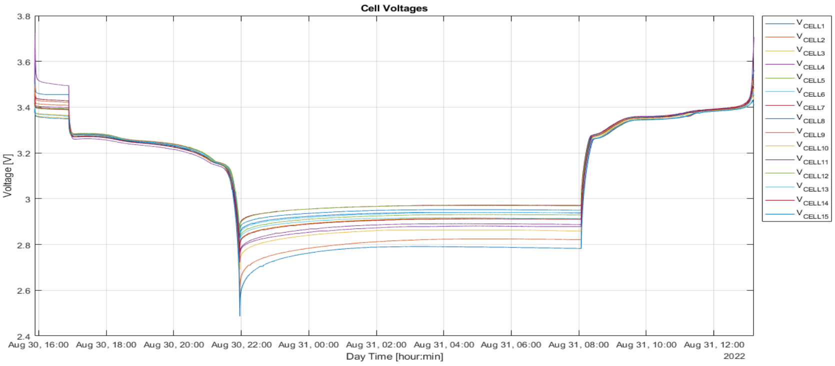

Test Step
V$_{diga}$
V$_{BMS}$
I$_{diga}$
I$_{BMS}$
Voltage [V]
Current [A]
54
52
50
48
46
44
42
100
80
60
40
20
0
-20
-40
-60
-80
-100
14:30
15:00
15:30
16:00
Aug 26, 2022
Day Time [hour:min]

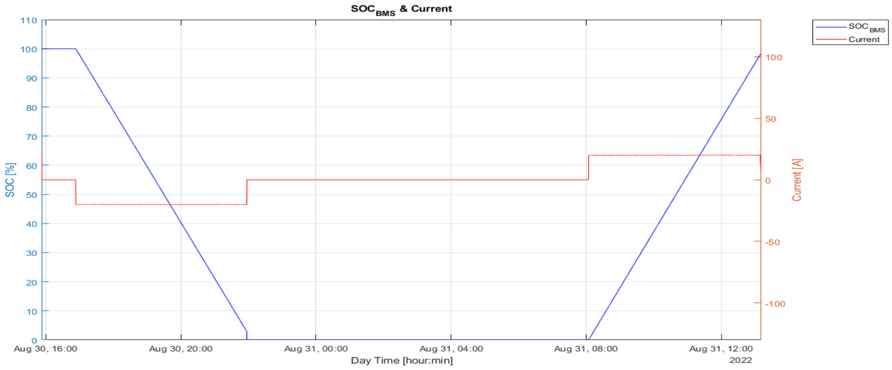


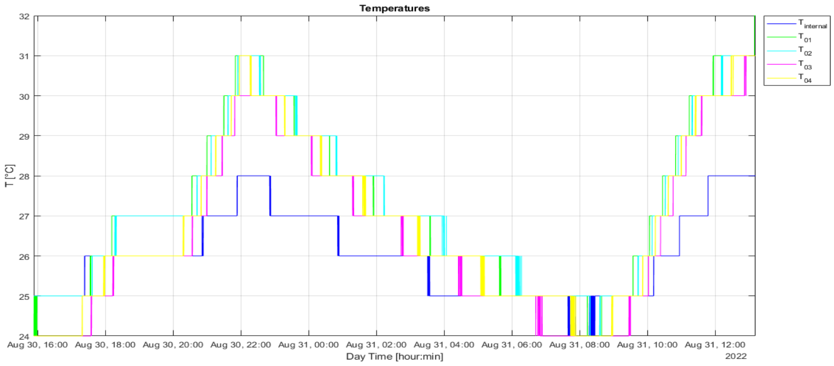


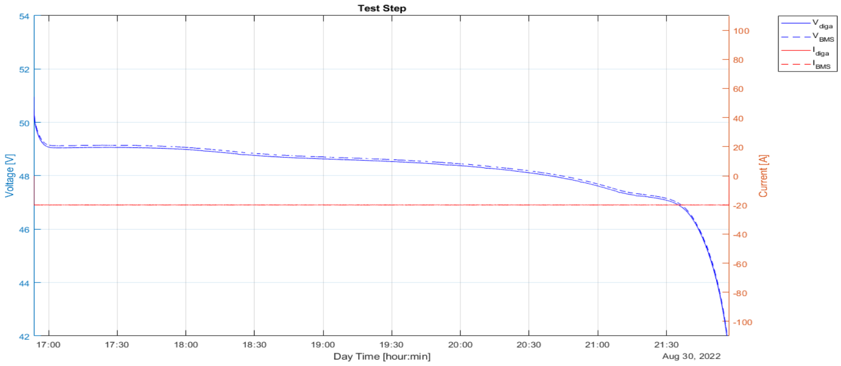
Discharge at 0,2C

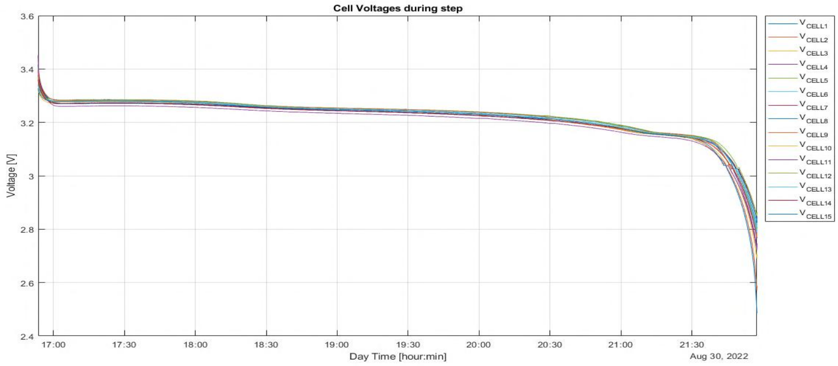


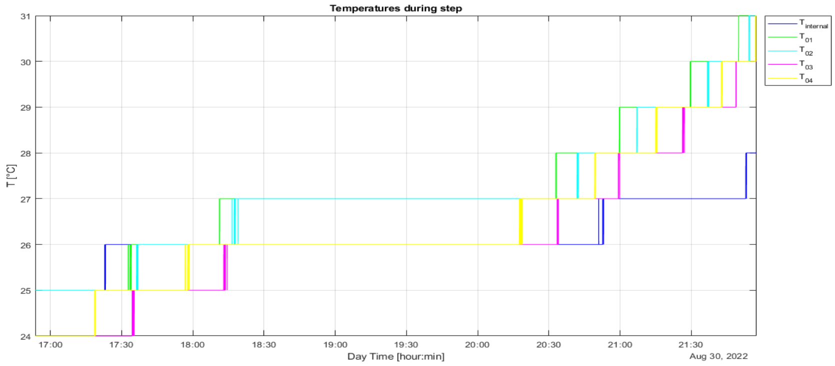

Cell Voltages
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
Aug 30, 16:00
Aug 30, 18:00
Aug 30, 20:00
Aug 30, 22:00
Aug 31, 00:00
Aug 31, 02:00
Aug 31, 04:00
Aug 31, 06:00
Aug 31, 08:00
Aug 31, 10:00
Aug 31, 12:00
2022
Day Time [hour:min]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

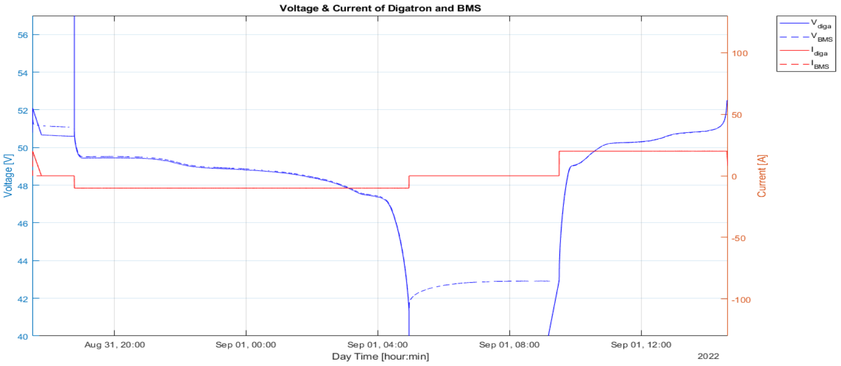

SOC_{BMS} & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
Aug 30, 16:00
Aug 30, 20:00
Aug 31, 00:00
Aug 31, 04:00
Aug 31, 08:00
Aug 31, 12:00
2022
Day Time [hour:min]
SOC_{BMS}
Current


Temperatures
T [°C]
32
31
30
29
28
27
26
25
24
Aug 30, 16:00
Aug 30, 18:00
Aug 30, 20:00
Aug 30, 22:00
Aug 31, 00:00
Aug 31, 02:00
Aug 31, 04:00
Aug 31, 06:00
Aug 31, 08:00
Aug 31, 10:00
Aug 31, 12:00
2022
Day Time [hour:min]
$T_{Internal}$
T_{01}
T_{02}
T_{03}
T_{04}

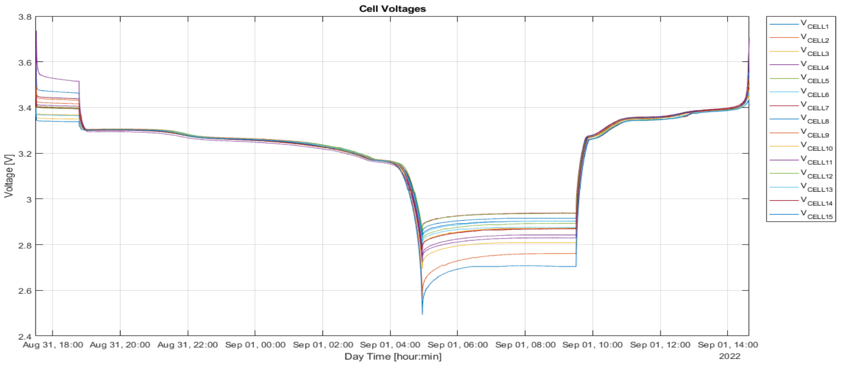

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
17:00
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
Aug 30, 2022
Day Time [hour:min]
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

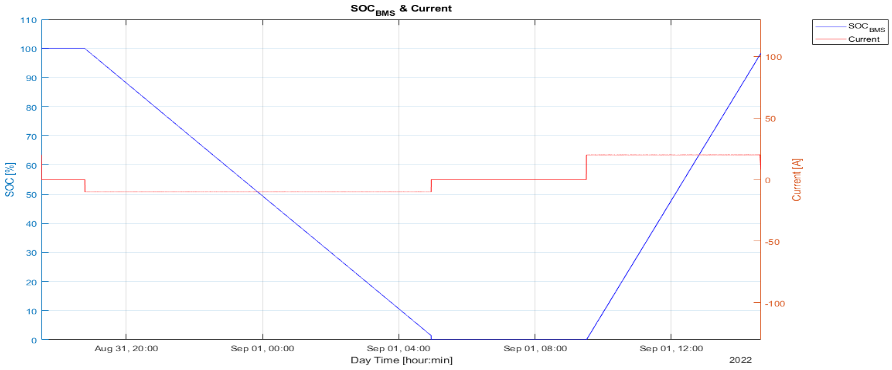

Cell Voltages during step
Voltage [V]
3.6
3.4
3.2
3
2.8
2.6
2.4
17:00
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
Aug 30, 2022
Day Time [hour:min]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

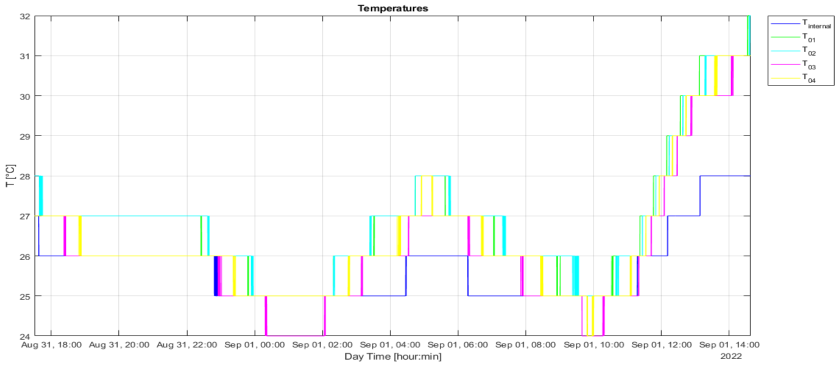

Temperatures during step
T [°C]
31
30
29
28
27
26
25
24
17:00
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
Aug 30, 2022
Day Time [hour:min]
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

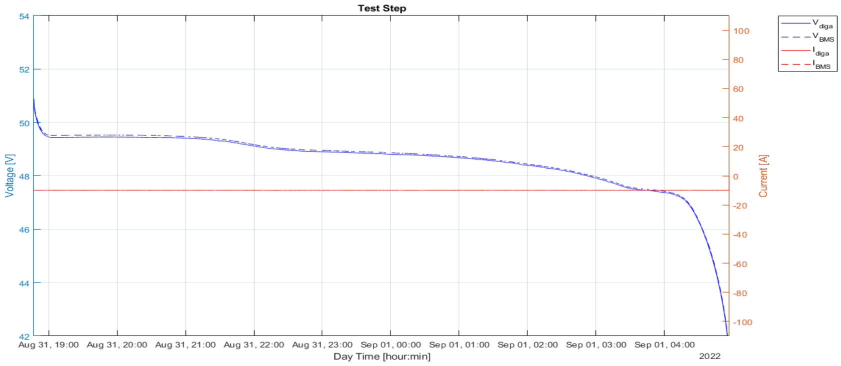


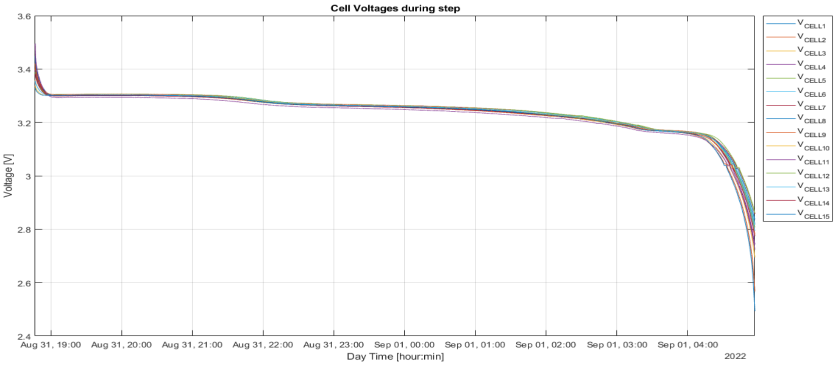
Discharge at 0,1C

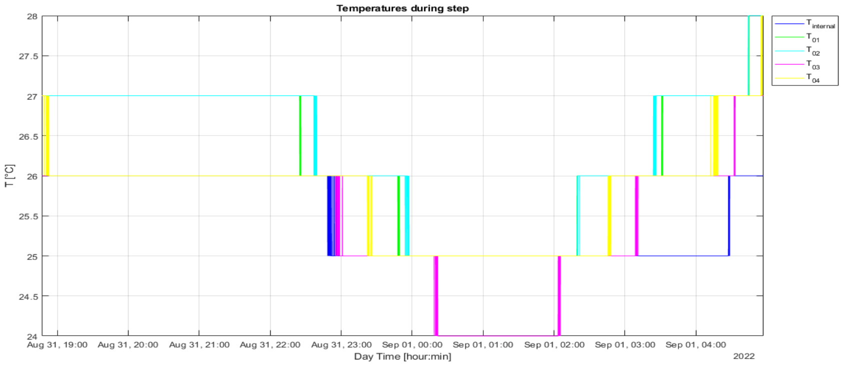




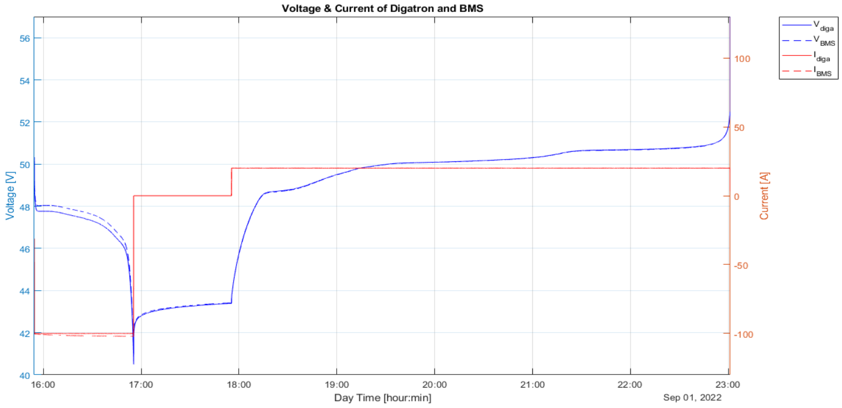

Temperatures
T [°C]
32
31
30
29
28
27
26
25
24
Aug 31, 18:00
Aug 31, 20:00
Aug 31, 22:00
Sep 01, 00:00
Sep 01, 02:00
Sep 01, 04:00
Sep 01, 06:00
Sep 01, 08:00
Sep 01, 10:00
Sep 01, 12:00
Sep 01, 14:00
2022
Day Time [hour:min]
T internal
T 01
T 02
T 03
T 04

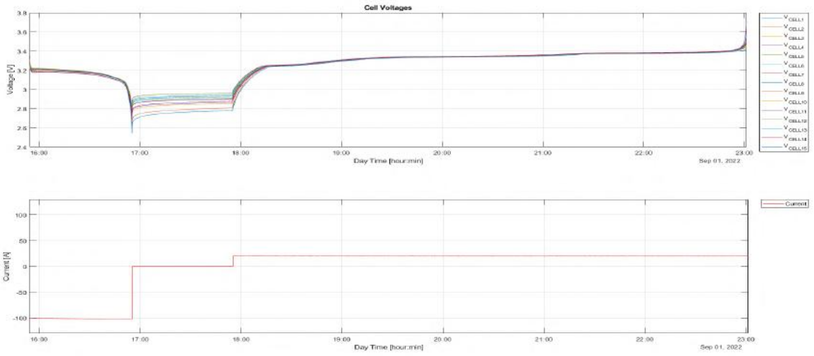

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Aug 31, 19:00
Aug 31, 20:00
Aug 31, 21:00
Aug 31, 22:00
Aug 31, 23:00
Sep 01, 00:00
Sep 01, 01:00
Sep 01, 02:00
Sep 01, 03:00
Sep 01, 04:00
2022
Day Time [hour:min]
V diga
V BMS
I diga
I BMS

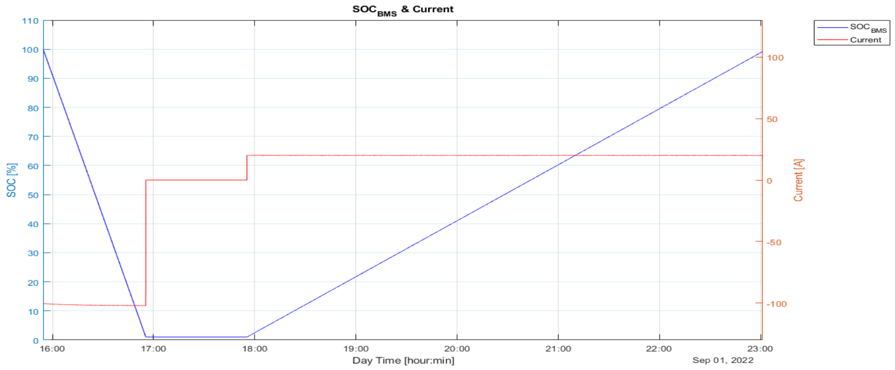

Cell Voltages during step
Voltage [V]
3.6
3.4
3.2
3
2.8
2.6
2.4
Aug 31, 19:00
Aug 31, 20:00
Aug 31, 21:00
Aug 31, 22:00
Aug 31, 23:00
Sep 01, 00:00
Sep 01, 01:00
Sep 01, 02:00
Sep 01, 03:00
Sep 01, 04:00
2022
Day Time [hour:min]
V CELL1
V CELL2
V CELL3
V CELL4
V CELL5
V CELL6
V CELL7
V CELL8
V CELL9
V CELL10
V CELL11
V CELL12
V CELL13
V CELL14
V CELL15

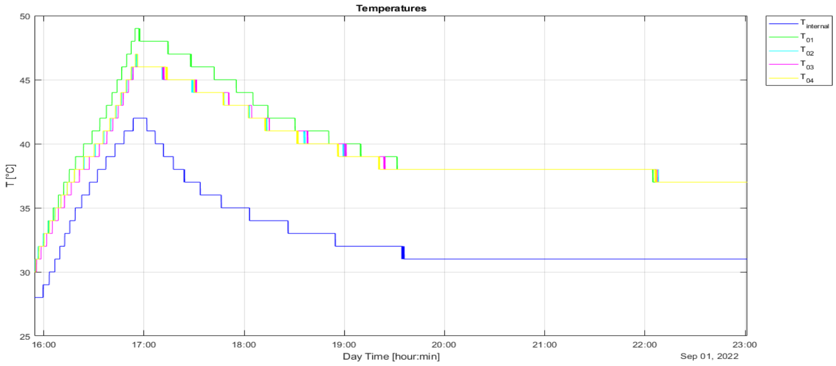


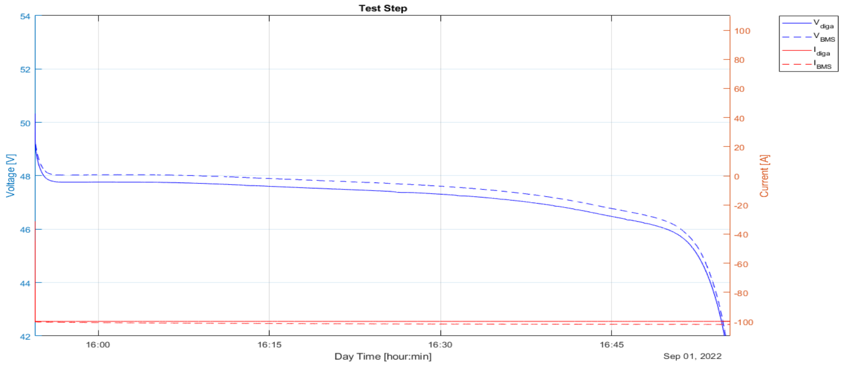
Discharge at 1C

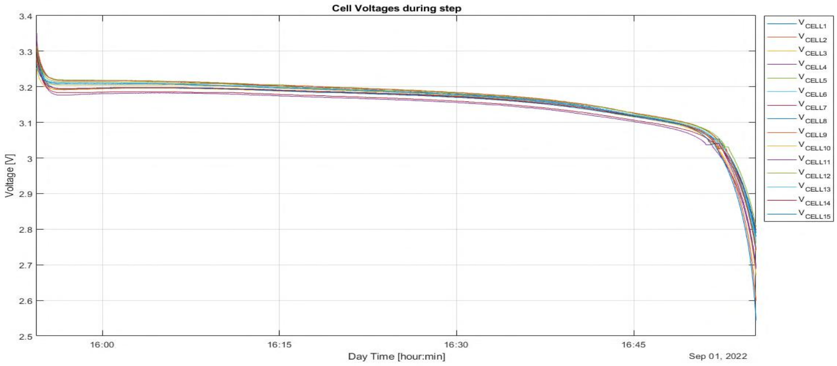


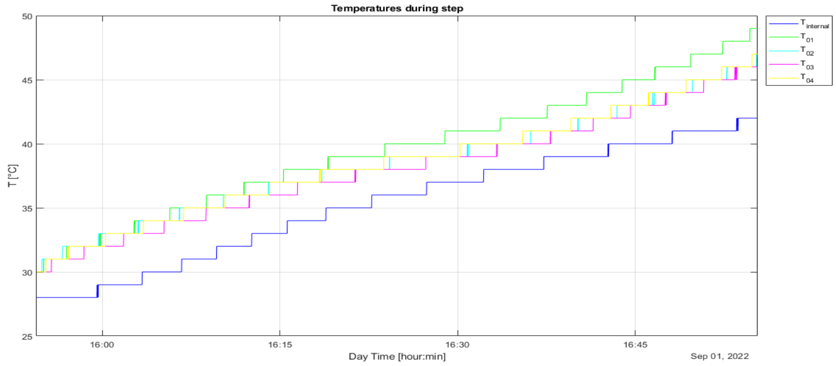



SOC_{BMS} & Current
SOC [%]
0
10
20
30
40
50
60
70
80
90
100
110
Current [A]
-100
-50
0
50
100
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Day Time [hour:min]
Sep 01, 2022
SOC_{BMS}
Current

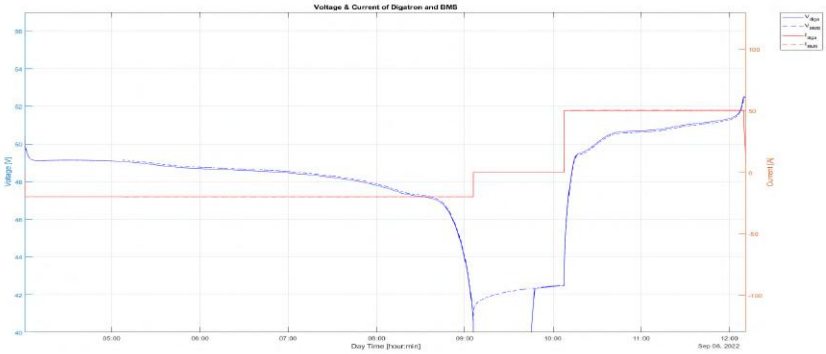

Temperatures
T [°C]
25
30
35
40
45
50
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Day Time [hour:min]
Sep 01, 2022
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

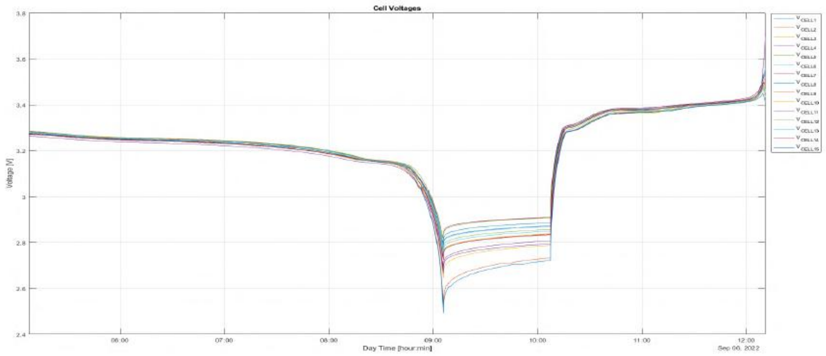

Test Step
Voltage [V]
42
44
46
48
50
52
54
Current [A]
-100
-80
-60
-40
-20
0
20
40
60
80
100
16:00
16:15
16:30
16:45
Day Time [hour:min]
Sep 01, 2022
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

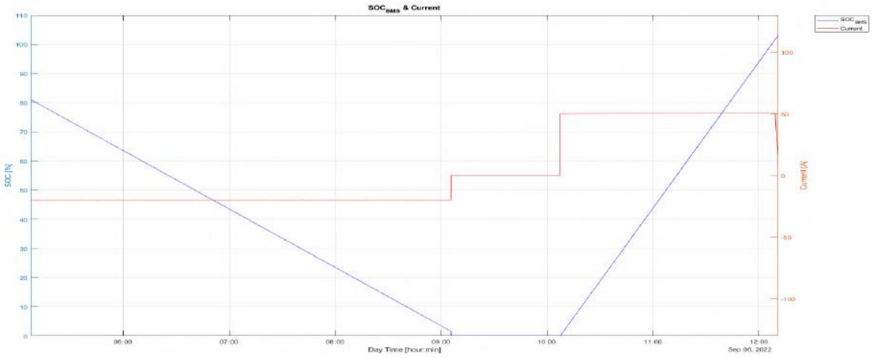


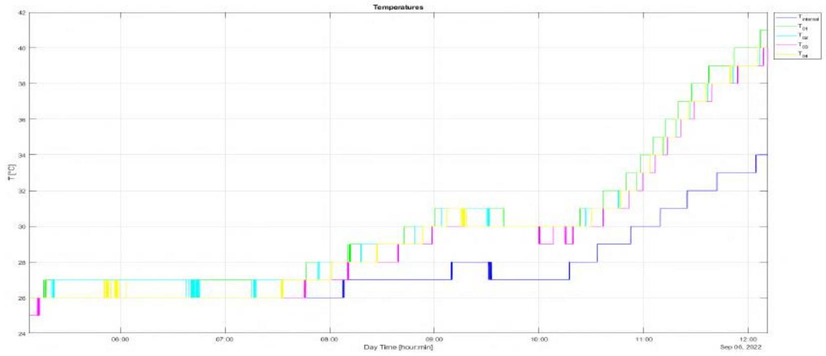


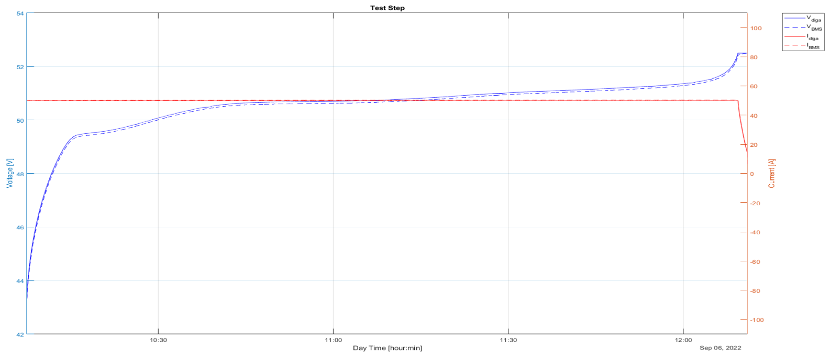
Charge at 0,5C

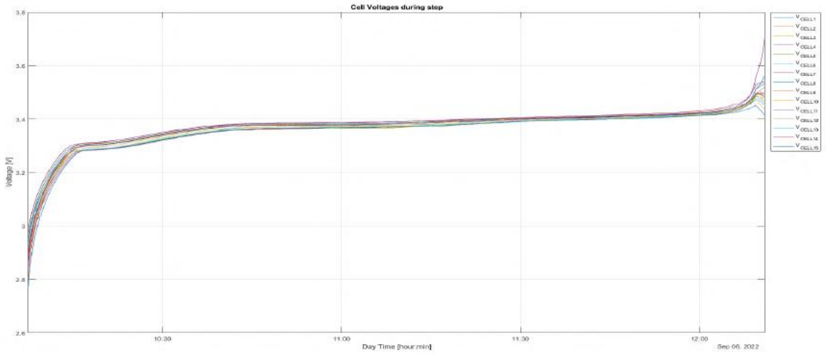


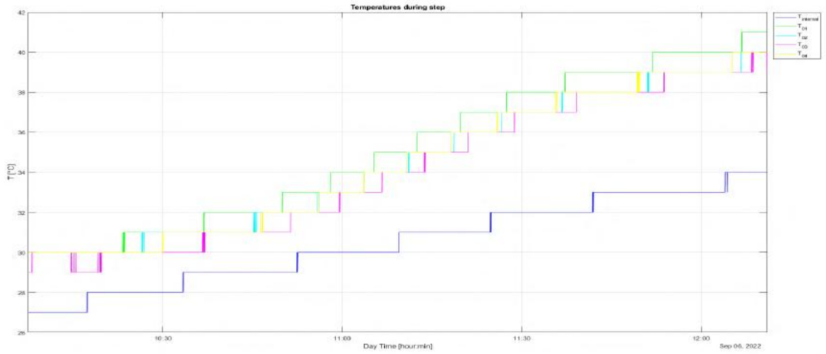

Cell Voltages
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
06:00
07:00
08:00
09:00
10:00
11:00
12:00
Sep 06, 2022
Day Time [hour:min]


SOC_{BMS} & Current
SOC_{BMS}
Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
06:00
07:00
08:00
09:00
10:00
11:00
12:00
Sep 06, 2022
Day Time [hour:min]

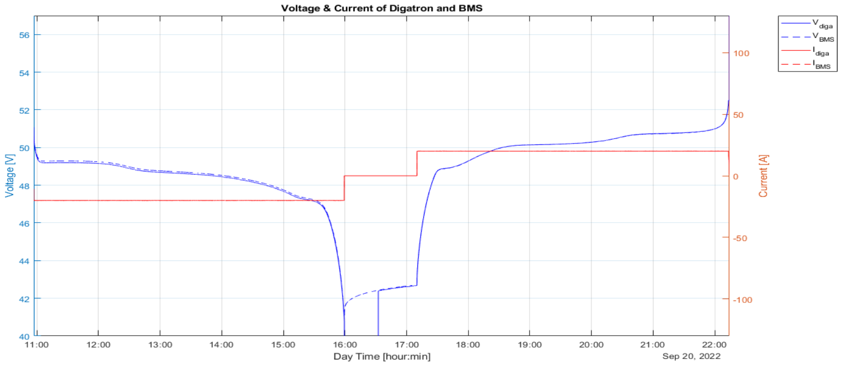

Temperatures
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}
T [°C]
42
40
38
36
34
32
30
28
26
24
06:00
07:00
08:00
09:00
10:00
11:00
12:00
Sep 06, 2022
Day Time [hour:min]

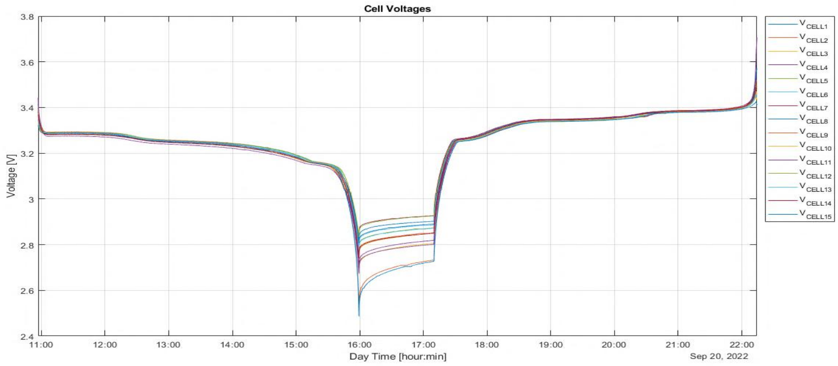

Test Step
54
52
50
48
46
44
42
Voltage [V]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Current [A]
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}
10:30
11:00
11:30
12:00
Sep 06, 2022
Day Time [hour:min]

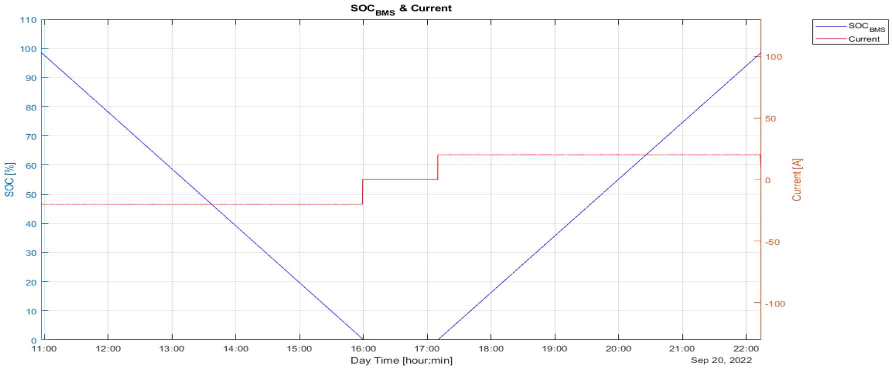

Cell Voltages during step
3.8
3.6
3.4
3.2
3
2.8
2.6
Voltage [V]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}
10:30
11:00
11:30
12:00
Sep 06, 2022
Day Time [hour:min]

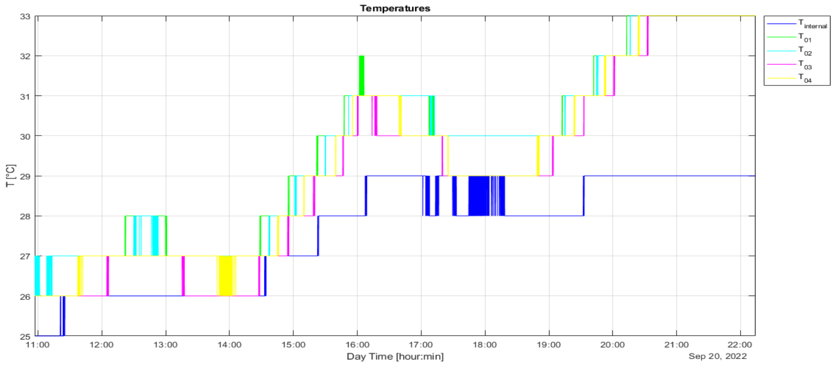

Temperatures during step
42
40
38
36
34
32
30
28
26
T [°C]
$T_{internal}$
T_{C1}
T_{C2}
T_{C3}
T_{C4}
10:30
11:00
11:30
12:00
Sep 06, 2022
Day Time [hour:min]

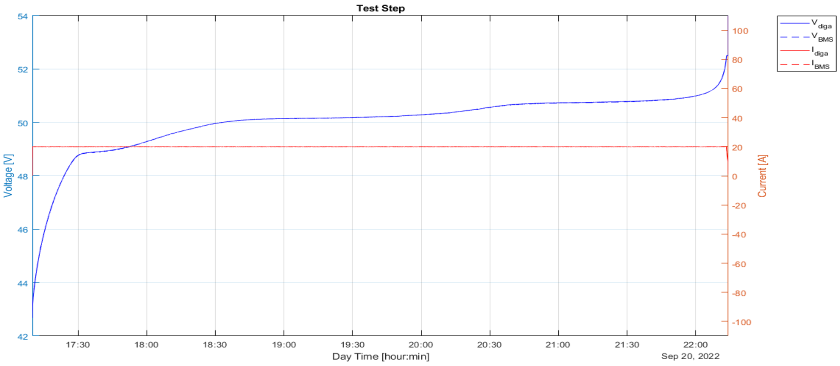
Charge at 0,2C

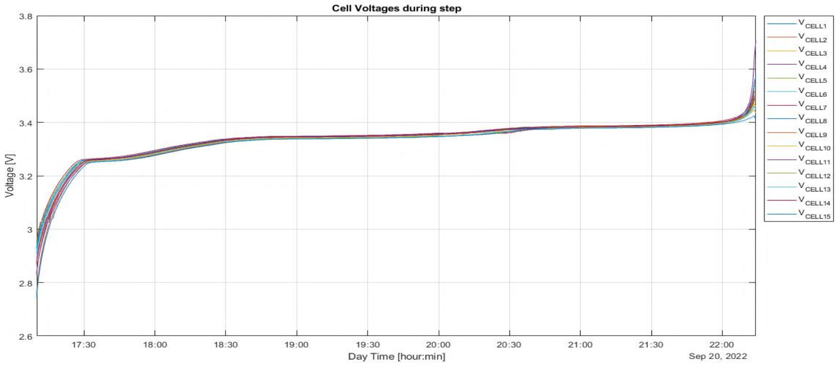


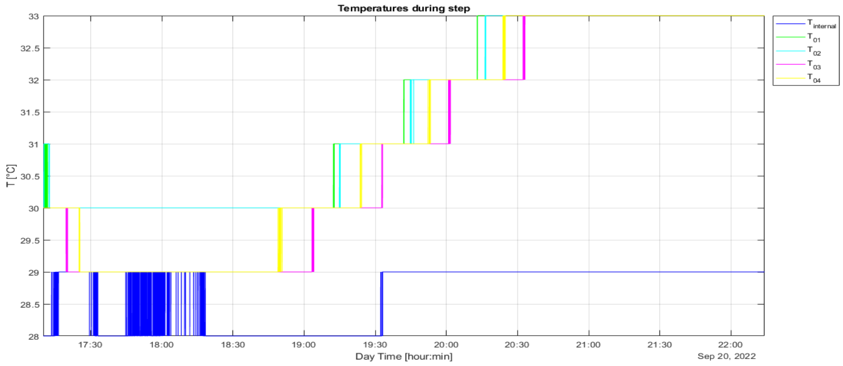




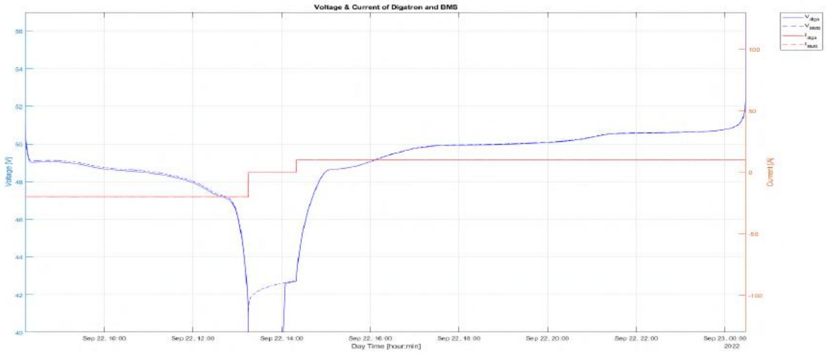

Temperatures
33
32
31
30
29
28
27
26
25
T [°C]
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
Day Time [hour:min]
Sep 20, 2022
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

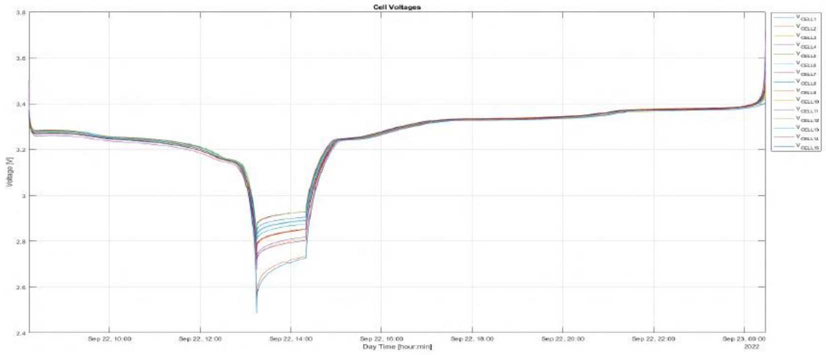

Test Step
54
52
50
48
46
44
42
Voltage [V]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Current [A]
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
22:00
Day Time [hour:min]
Sep 20, 2022
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

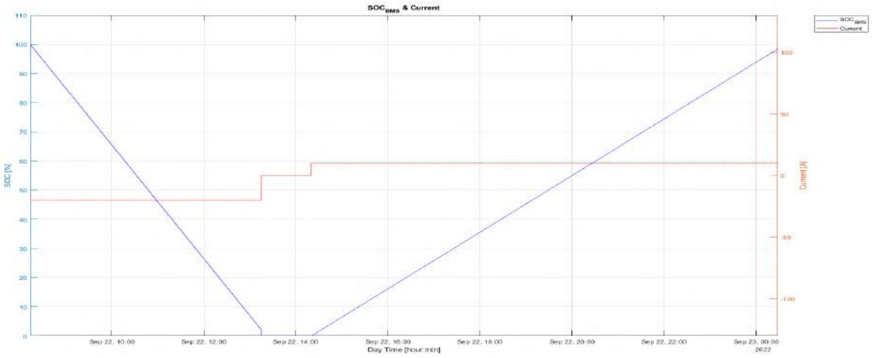

Cell Voltages during step
3.8
3.6
3.4
3.2
3
2.8
2.6
Voltage [V]
17:30
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
22:00
Day Time [hour:min]
Sep 20, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

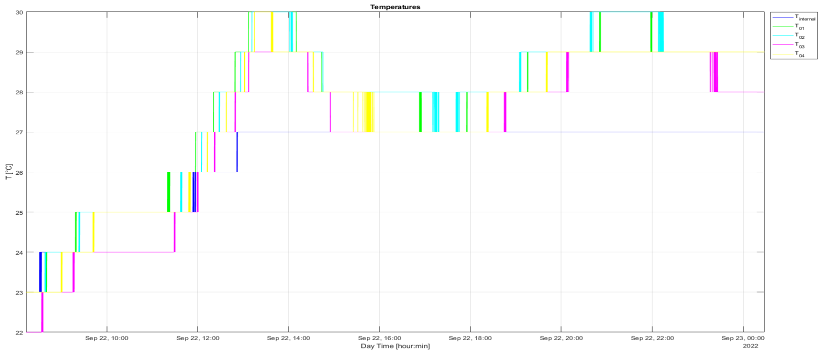


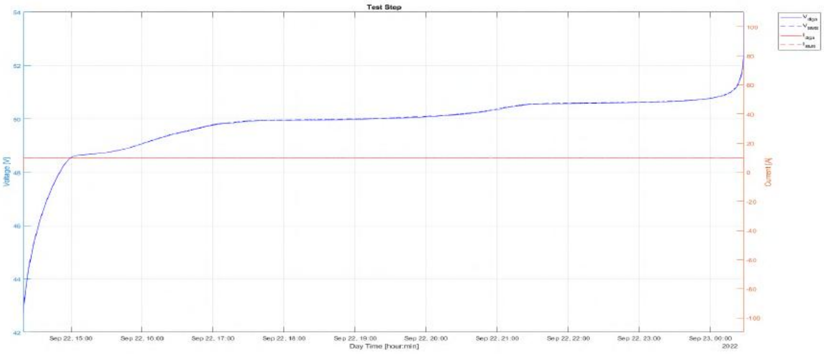
Charge at 0,1C

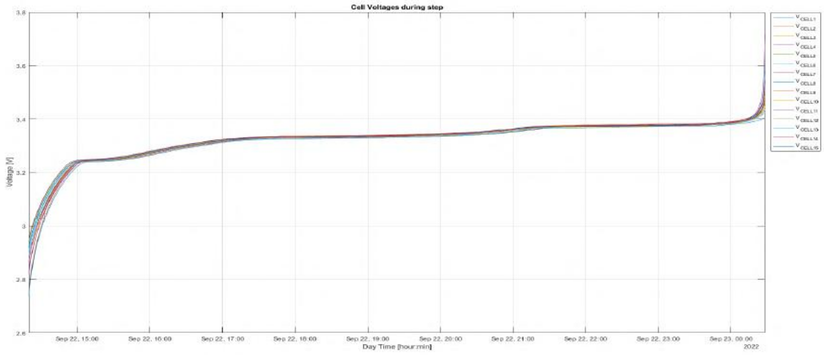


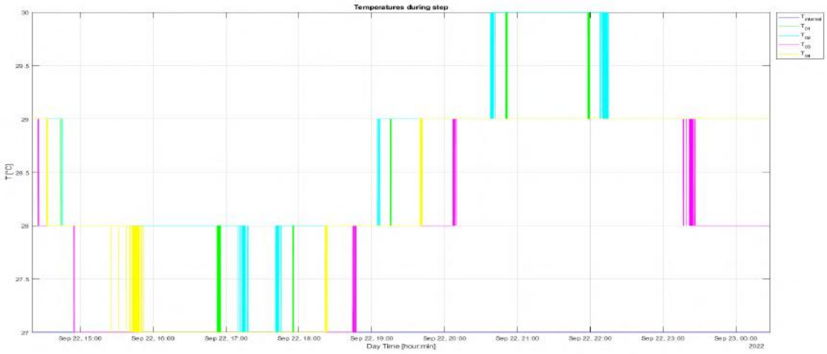



SOC$_{BMS}$ & Current
SOC$_{BMS}$
Current
SOC [%]
Current [A]
110
100
90
80
70
60
50
40
30
20
10
0
100
50
0
-50
-100
Sep 22, 10:00
Sep 22, 12:00
Sep 22, 14:00
Sep 22, 16:00
Sep 22, 18:00
Sep 22, 20:00
Sep 22, 22:00
Sep 23, 00:00
2022
Day Time [hour:min]

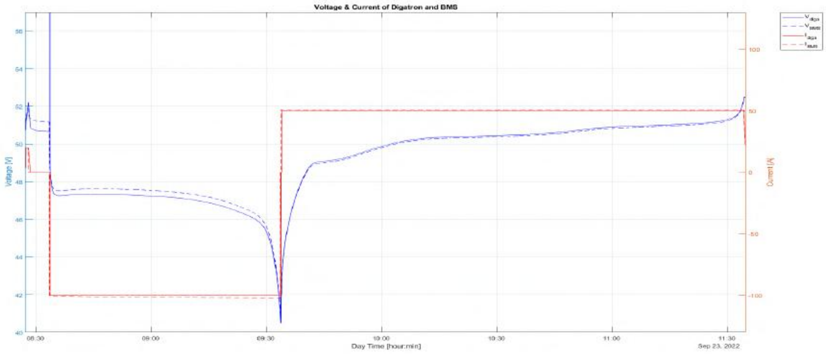

Temperatures
T$_{internal}$
T$_{01}$
T$_{02}$
T$_{03}$
T$_{04}$
T [°C]
30
29
28
27
26
25
24
23
22
Sep 22, 10:00
Sep 22, 12:00
Sep 22, 14:00
Sep 22, 16:00
Sep 22, 18:00
Sep 22, 20:00
Sep 22, 22:00
Sep 23, 00:00
2022
Day Time [hour:min]

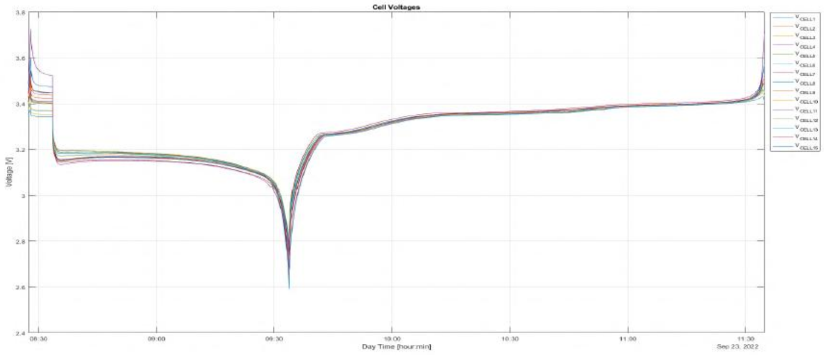

Test Step
V$_{diga}$
V$_{BMS}$
I$_{diga}$
I$_{multi}$
Voltage [V]
Current [A]
54
52
50
48
46
44
42
100
80
60
40
20
0
-20
-40
-60
-80
-100
Sep 22, 15:00
Sep 22, 16:00
Sep 22, 17:00
Sep 22, 18:00
Sep 22, 19:00
Sep 22, 20:00
Sep 22, 21:00
Sep 22, 22:00
Sep 22, 23:00
Sep 23, 00:00
2022
Day Time [hour:min]

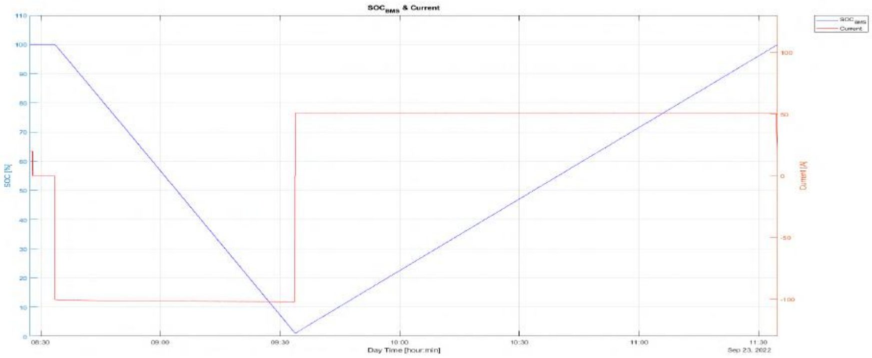


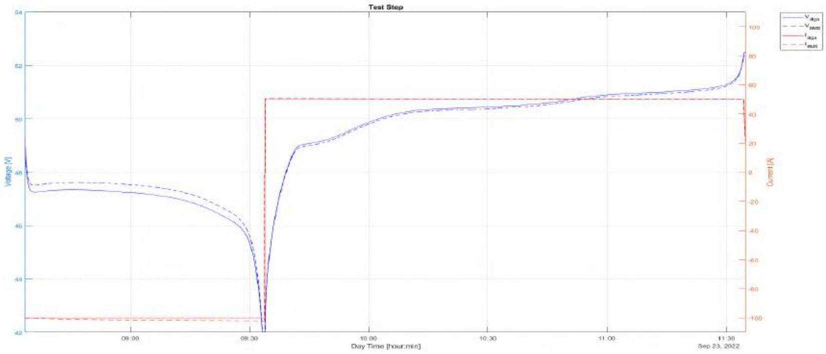


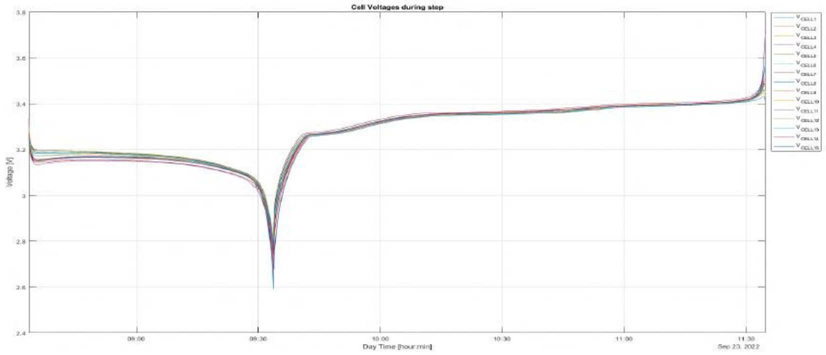
Maximum charge/discharge Current

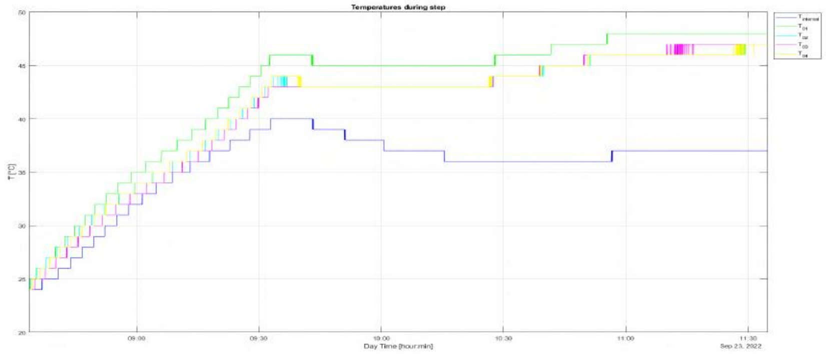



Cell Voltages
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
08:30
09:00
09:30
10:00
10:30
11:00
11:30
Sep 23, 2022
Day Time [hour:min]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

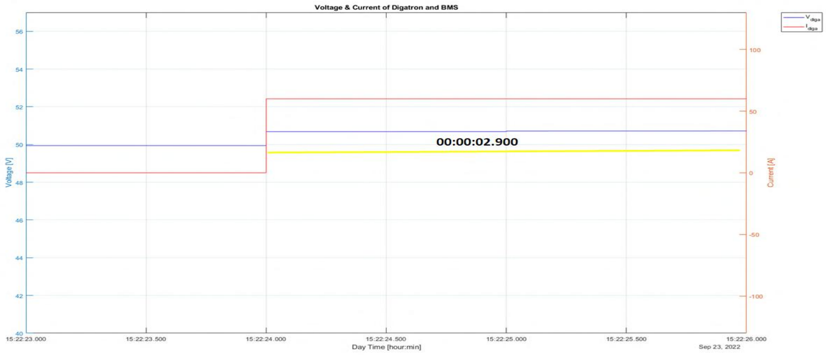

SOC_{BMS} & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
08:30
09:00
09:30
10:00
10:30
11:00
11:30
Sep 23, 2022
Day Time [hour:min]
SOC_{BMS}
Current

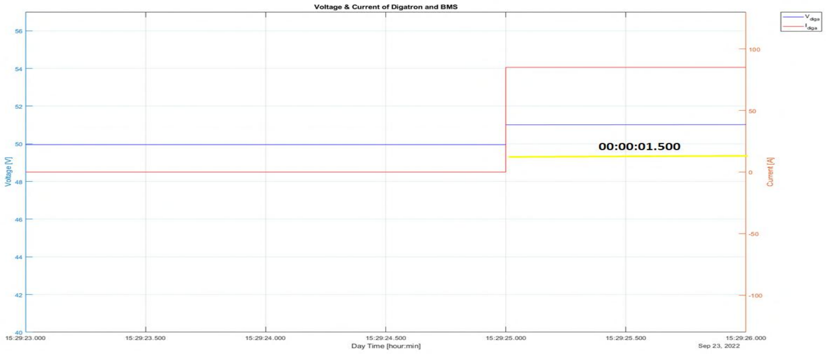

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
09:00
09:30
10:00
10:30
11:00
11:30
Sep 23, 2022
Day Time [hour:min]
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}

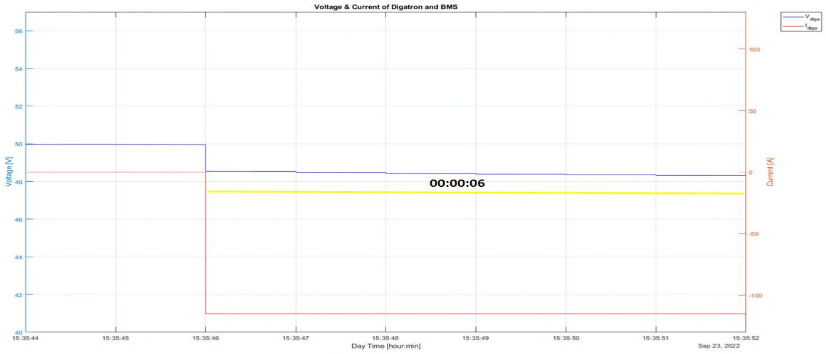


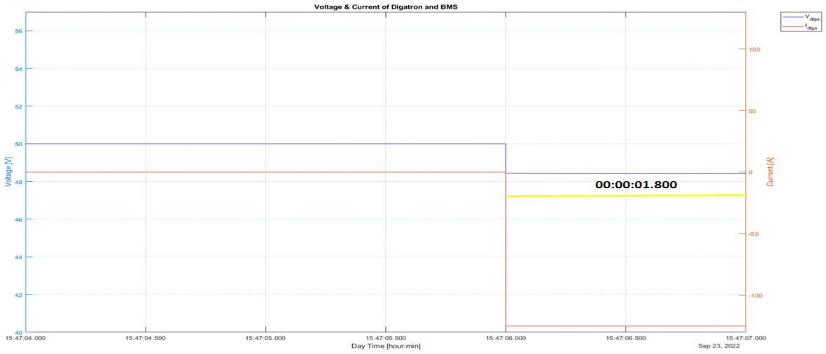


Overprotection Test



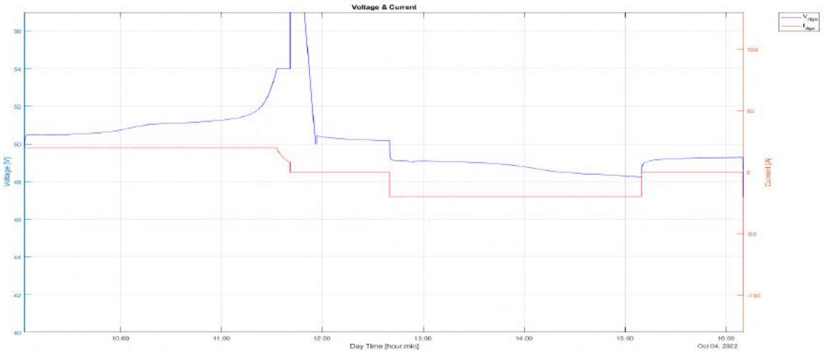

Voltage & Current of Digatron and BMS
V_{diga}
I_{diga}
56
54
52
50
48
46
44
42
40
Voltage [V]
100
50
0
-50
-100
Current [A]
00:00:01.500
15:29:23.000
15:29:23.500
15:29:24.000
15:29:24.500
15:29:25.000
15:29:25.500
15:29:26.000
Day Time [hour:min]
Sep 23, 2022


Voltage & Current of Digatron and BMS
V_{diga}
I_{diga}
56
54
52
50
48
46
44
42
40
Voltage [V]
100
50
0
-50
-100
Current [A]
00:00:06
15:35:44
15:35:45
15:35:46
15:35:47
15:35:48
15:35:49
15:35:50
15:35:51
15:35:52
Day Time [hour:min]
Sep 23, 2022

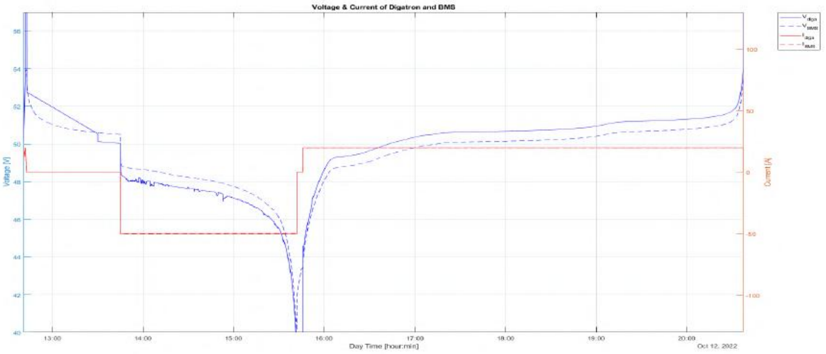

Voltage & Current of Digatron and BMS
V_{diga}
I_{diga}
56
54
52
50
48
46
44
42
40
Voltage [V]
100
50
0
-50
-100
Current [A]
00:00:01.800
15:47:04.000
15:47:04.500
15:47:05.000
15:47:05.500
15:47:06.000
15:47:06.500
15:47:07.000
Day Time [hour:min]
Sep 23, 2022

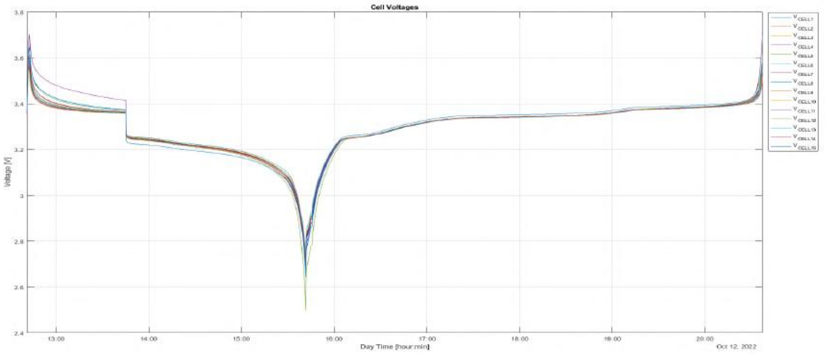
Battery Pack n.3

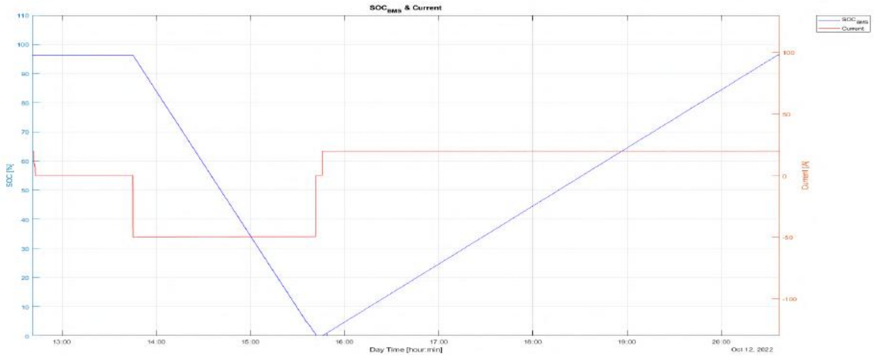
Internal Resistance

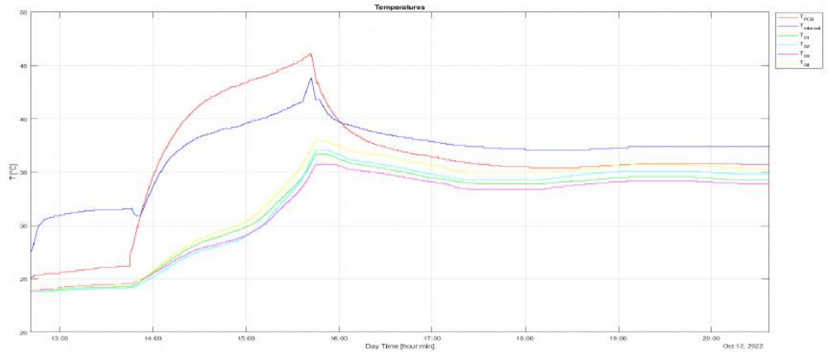


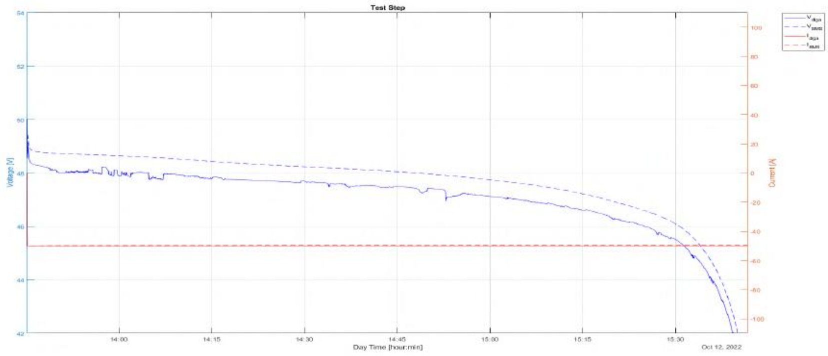
Discharge at 0,5C

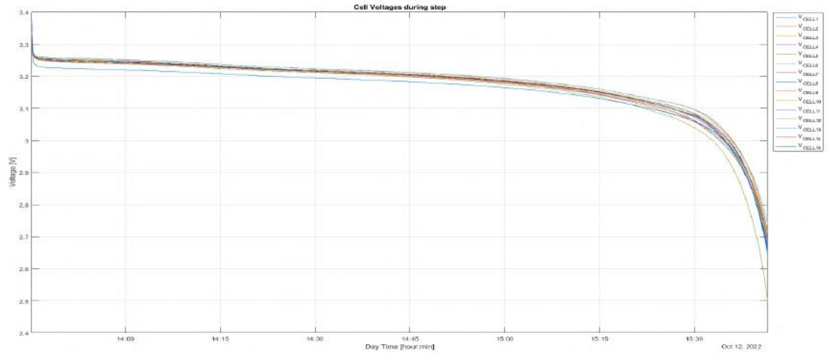


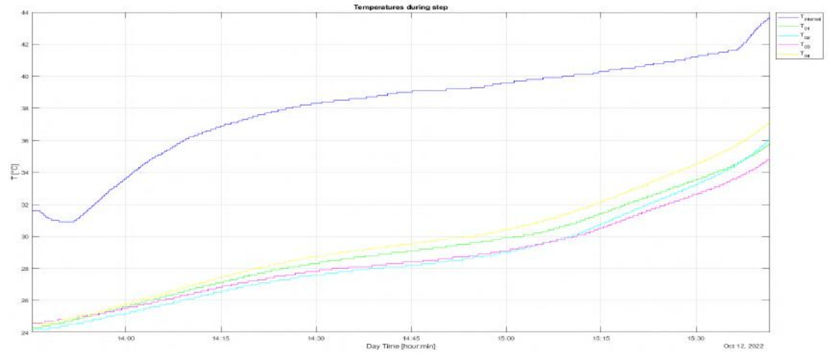



SOC_{BMS} & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Oct 12, 2022
SOC_{BMS}
Current

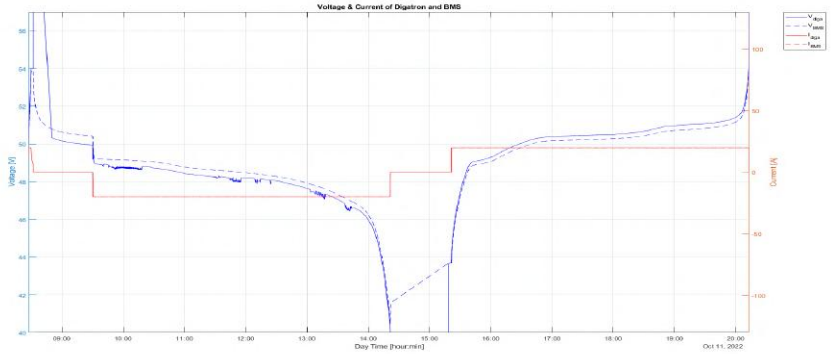

Temperatures
T [°C]
50
45
40
35
30
25
20
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Oct 12, 2022
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

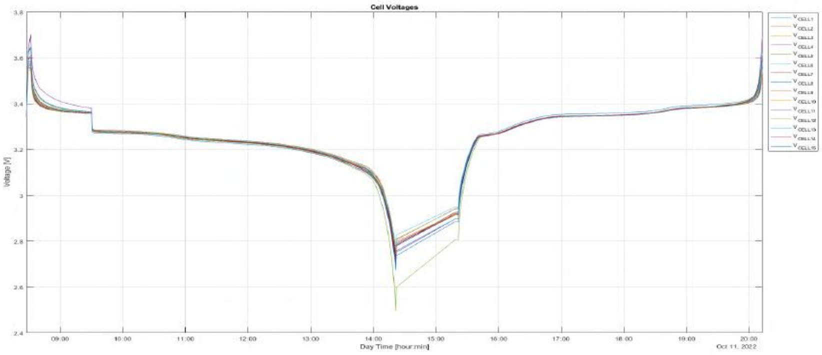

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
14:00
14:15
14:30
14:45
15:00
15:15
15:30
Day Time [hour:min]
Oct 12, 2022
V_{digia}
V_{BMS}
I_{digia}
I_{BMS}

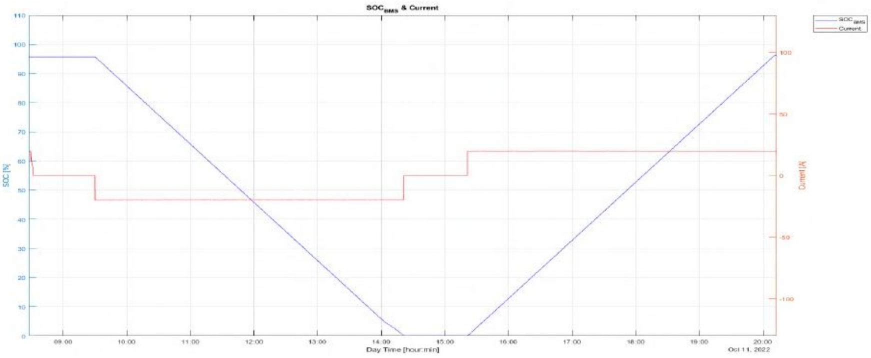


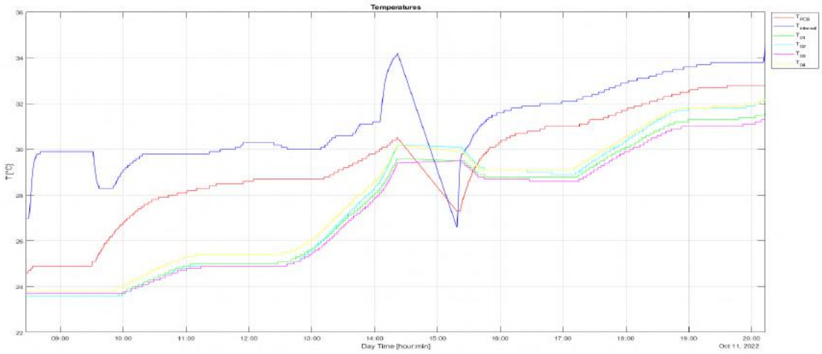


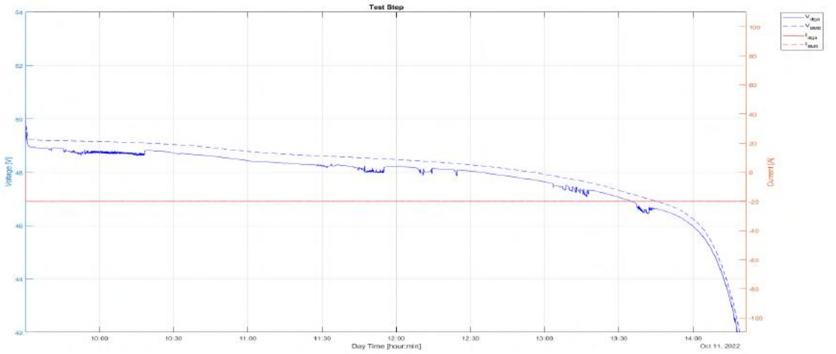
Discharge at 0,2C

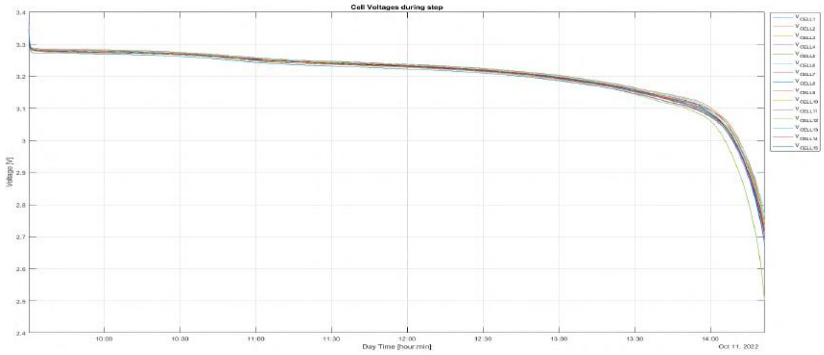


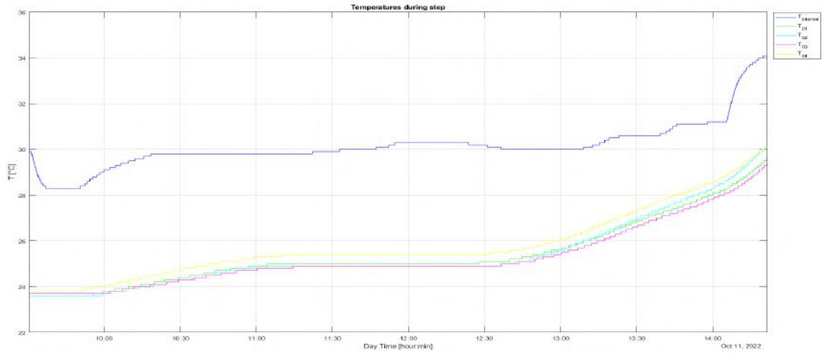

Cell Voltages
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
Voltage [V]
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Oct 11, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}


SOC_{BMS} & Current
110
100
90
80
70
60
50
40
30
20
10
0
SOC [%]
100
50
0
-50
-100
Current [A]
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Oct 11, 2022
SOC_{BMS}
Current

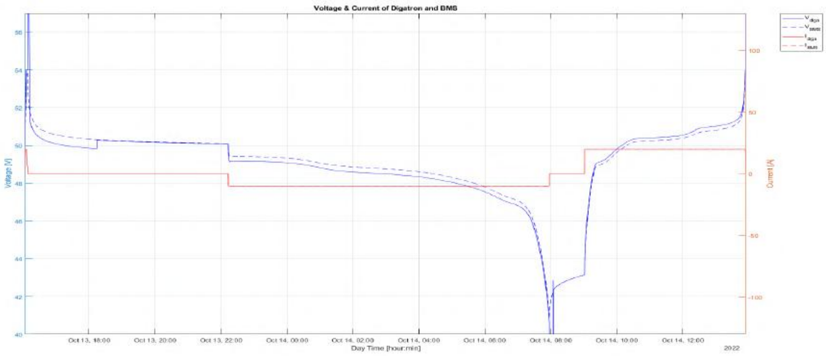

Temperatures
36
34
32
30
28
26
24
22
T[°C]
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Day Time [hour:min]
Oct 11, 2022
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

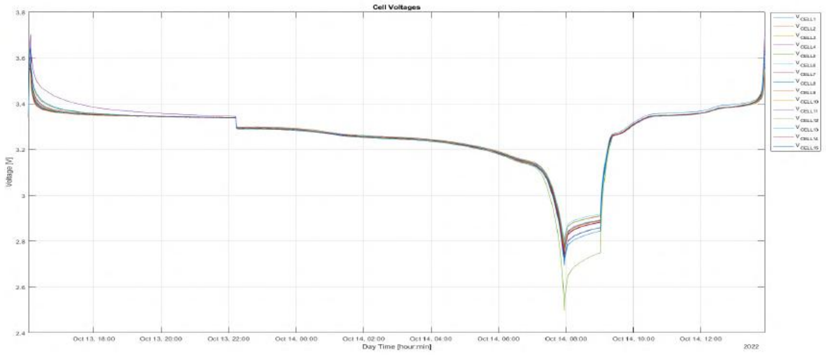

Test Step
Voltage [V]
Current [A]
54
52
50
48
46
44
42
100
80
60
40
20
0
-20
-40
-60
-80
-100
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
Oct 11, 2022
Day Time [hour:min]
V_dga
V_bms
I_dga
I_bms

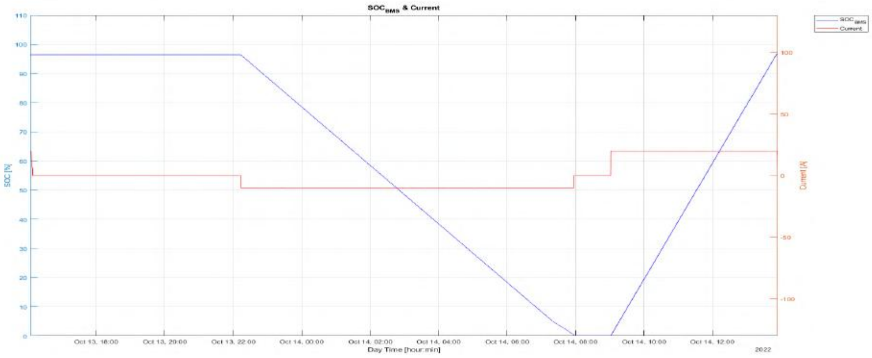

Cell Voltages during step
Voltage [V]
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
Oct 11, 2022
Day Time [hour:min]
V_CELL1
V_CELL2
V_CELL3
V_CELL4
V_CELL5
V_CELL6
V_CELL7
V_CELL8
V_CELL9
V_CELL10
V_CELL11
V_CELL12
V_CELL13
V_CELL14
V_CELL15

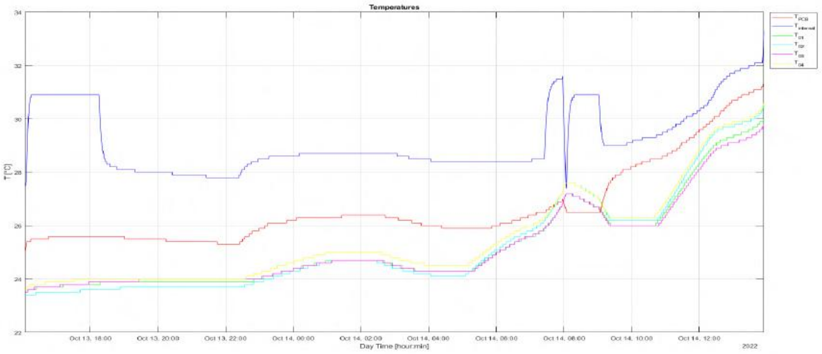

Temperatures during step
T [°C]
36
34
32
30
28
26
24
22
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
Oct 11, 2022
Day Time [hour:min]
T_internal
T_01
T_02
T_03
T_04

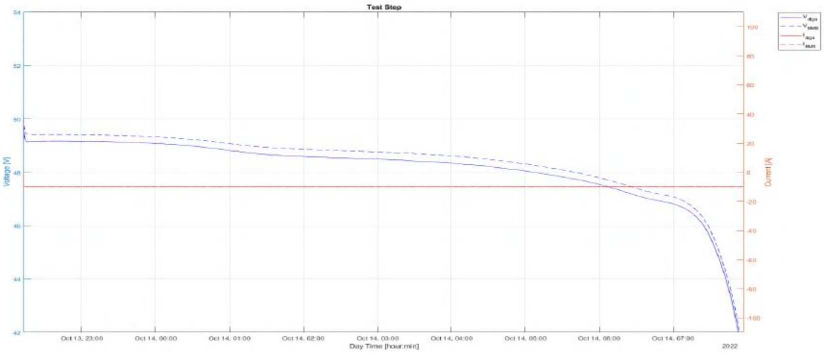
Discharge at 0,1C

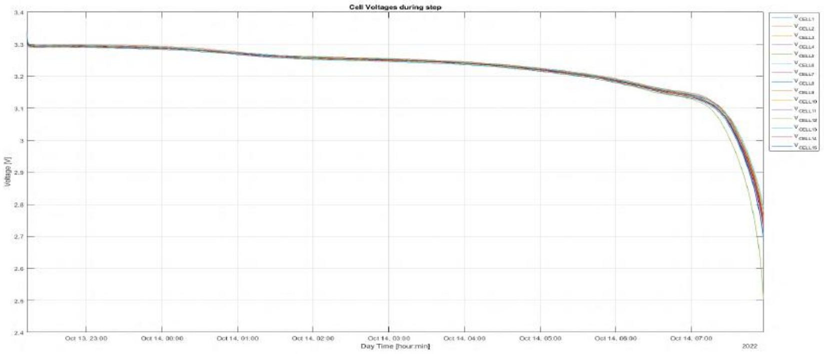


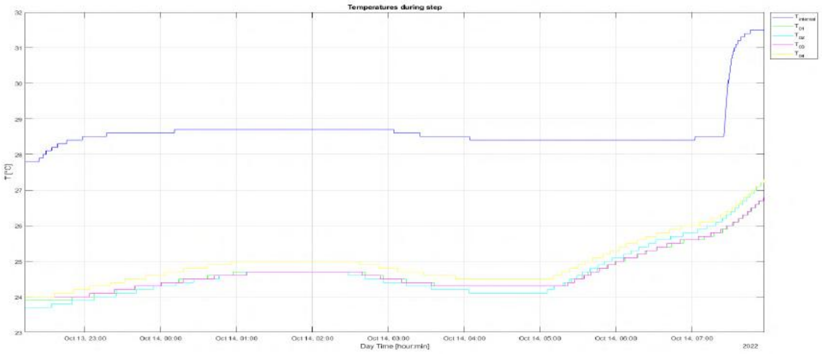




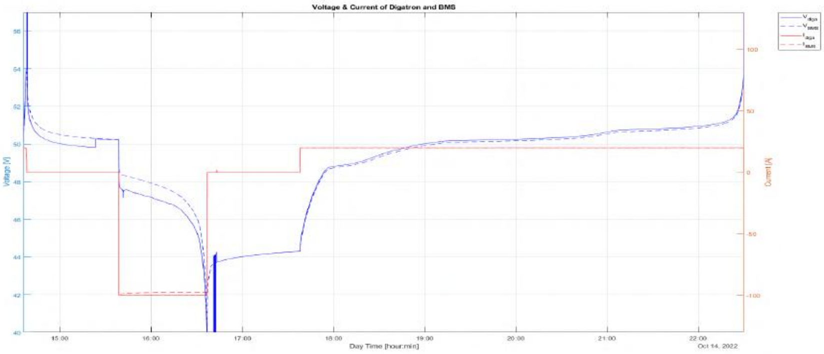

Temperatures
T [°C]
34
32
30
28
26
24
22
Oct 13, 18:00
Oct 13, 20:00
Oct 13, 22:00
Oct 14, 00:00
Oct 14, 02:00
Oct 14, 04:00
Oct 14, 06:00
Oct 14, 08:00
Oct 14, 10:00
Oct 14, 12:00
2022
Day Time [hour:min]
T_PCB
T_internal
T_01
T_02
T_03
T_04

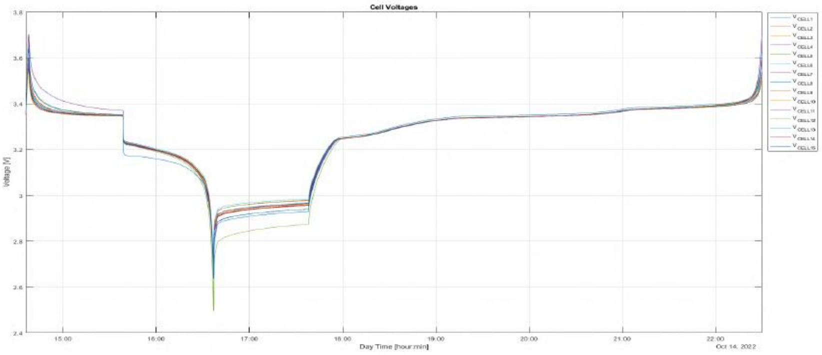

Test Step
Voltage [V]
54
52
50
48
46
44
42
Current [A]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Oct 13, 23:00
Oct 14, 00:00
Oct 14, 01:00
Oct 14, 02:00
Oct 14, 03:00
Oct 14, 04:00
Oct 14, 05:00
Oct 14, 06:00
Oct 14, 07:00
2022
Day Time [hour:min]
V_daq
V_BMS
I_daq
I_BMS

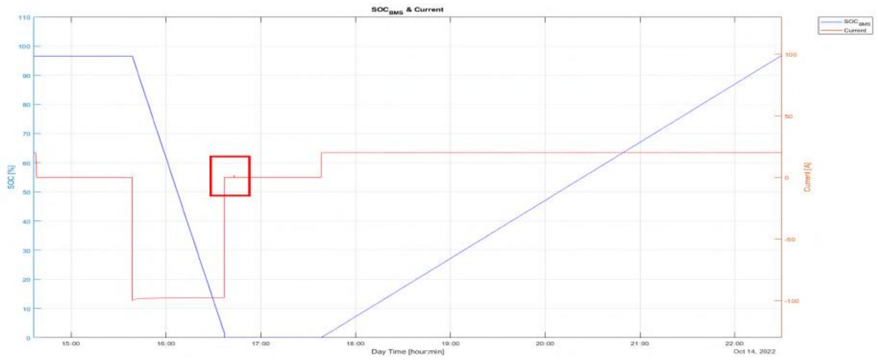

Cell Voltages during step
Voltage [V]
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
Oct 13, 23:00
Oct 14, 00:00
Oct 14, 01:00
Oct 14, 02:00
Oct 14, 03:00
Oct 14, 04:00
Oct 14, 05:00
Oct 14, 06:00
Oct 14, 07:00
2022
Day Time [hour:min]
V_CELL1
V_CELL2
V_CELL3
V_CELL4
V_CELL5
V_CELL6
V_CELL7
V_CELL8
V_CELL9
V_CELL10
V_CELL11
V_CELL12
V_CELL13
V_CELL14
V_CELL15

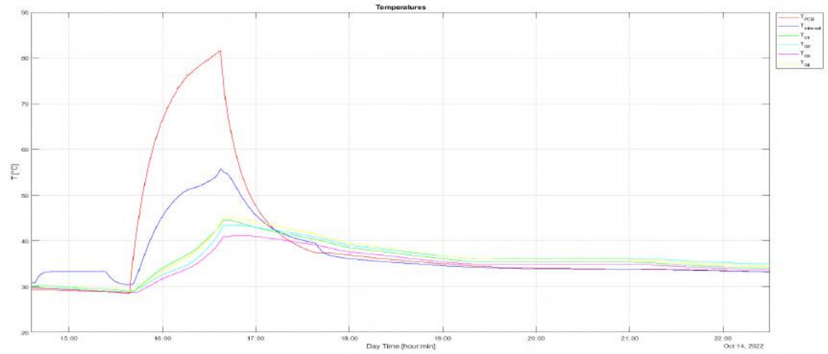


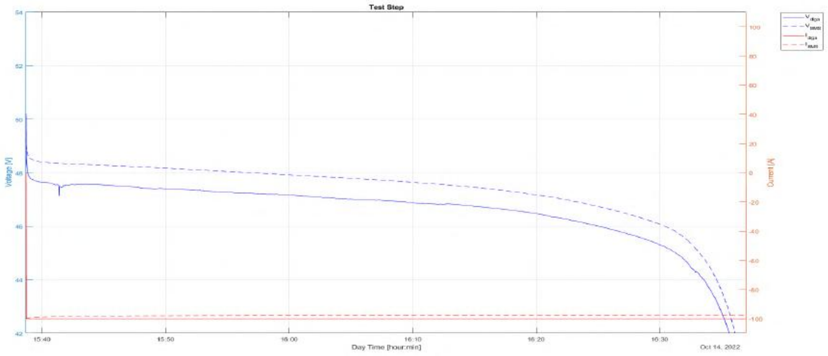
Discharge at 1C

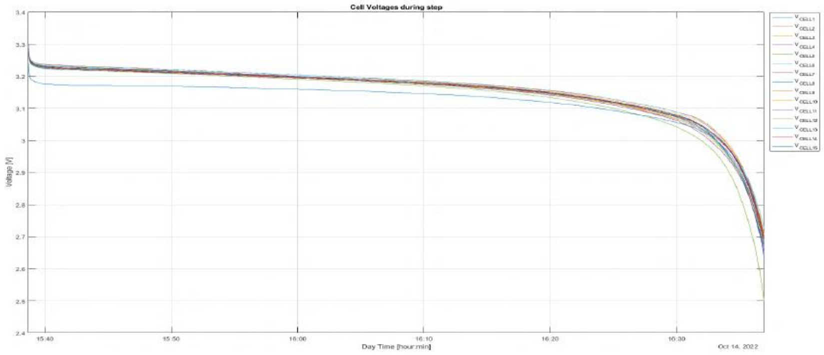


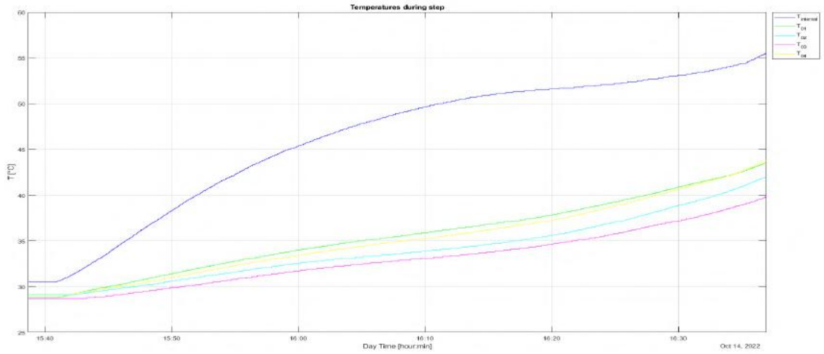



SOC_{BMS} & Current
SOC_{BMS}
Current
SOC [%]
Current [A]
110
100
90
80
70
60
50
40
30
20
10
0
100
50
0
-50
-100
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
Day Time [hour:min]
Oct 14, 2022

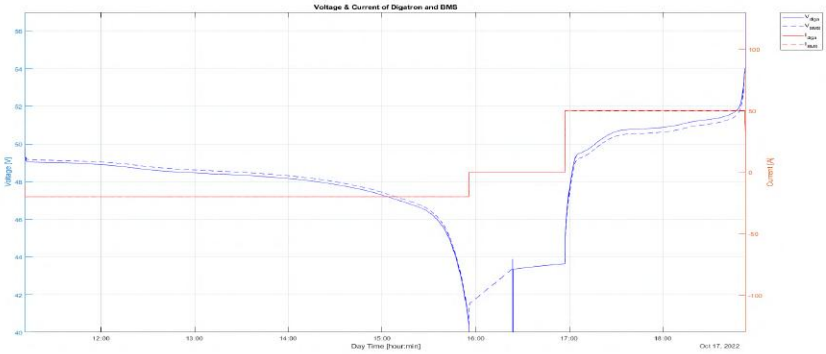

Temperatures
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}
T [°C]
90
80
70
60
50
40
30
20
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
Day Time [hour:min]
Oct 14, 2022

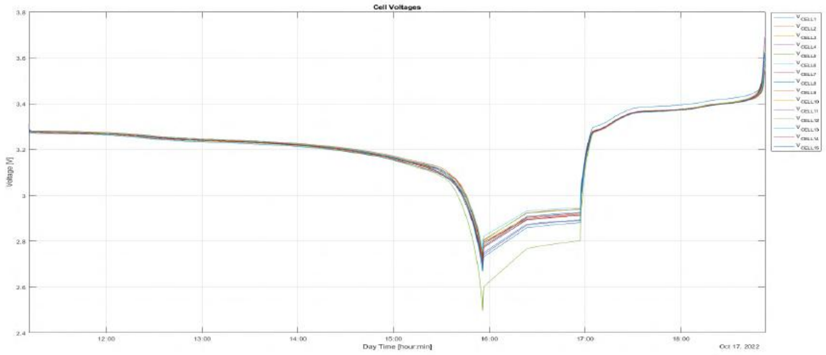

Test Step
V_{BMS}
I_{BMS}
Voltage [V]
Current [A]
54
52
50
48
46
44
42
100
80
60
40
20
0
-20
-40
-60
-80
-100
15:40
15:50
16:00
16:10
16:20
16:30
Day Time [hour:min]
Oct 14, 2022

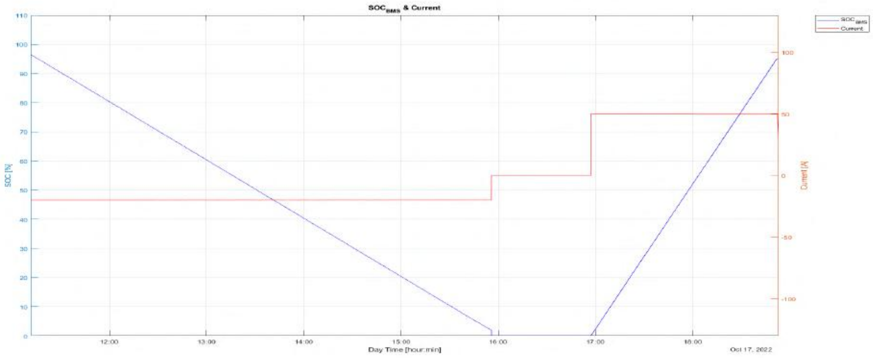


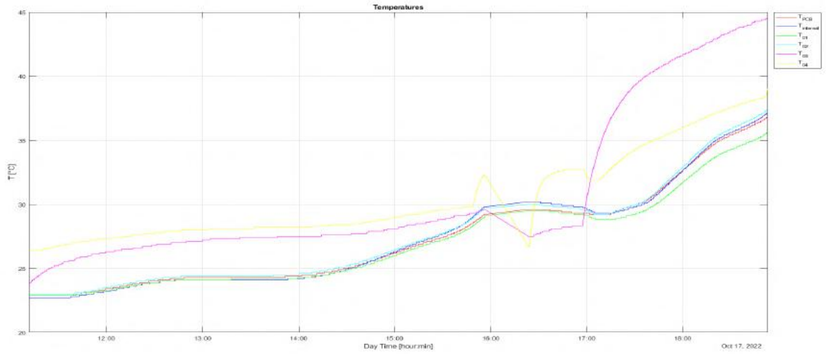


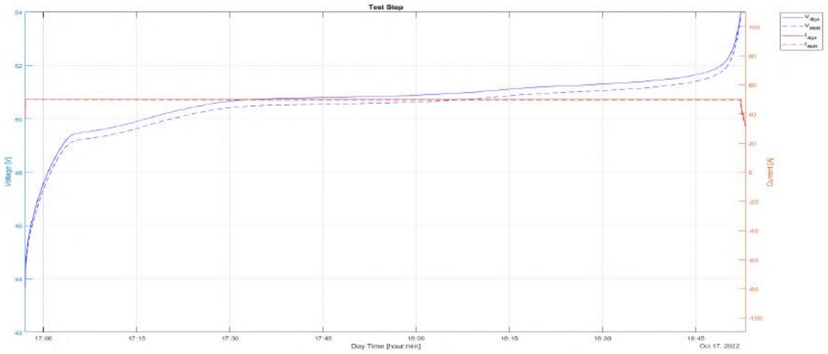
Charge at 0.5C

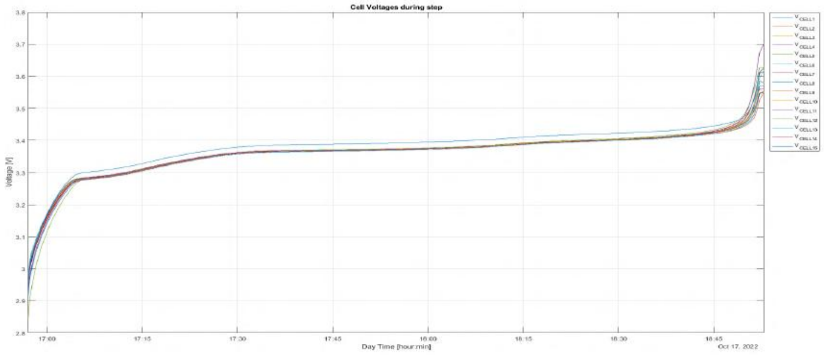


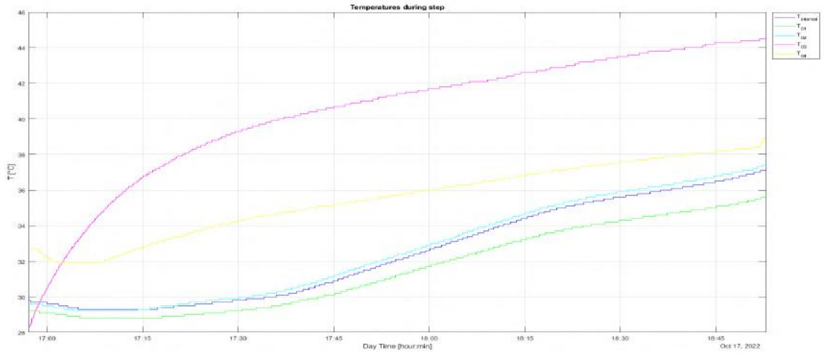

Cell Voltages
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Oct 17, 2022
Day Time [hour:min]
V CELL1
V CELL2
V CELL3
V CELL4
V CELL5
V CELL6
V CELL7
V CELL8
V CELL9
V CELL10
V CELL11
V CELL12
V CELL13
V CELL14
V CELL15


SOC BMS & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Oct 17, 2022
Day Time [hour:min]
SOC BMS
Current

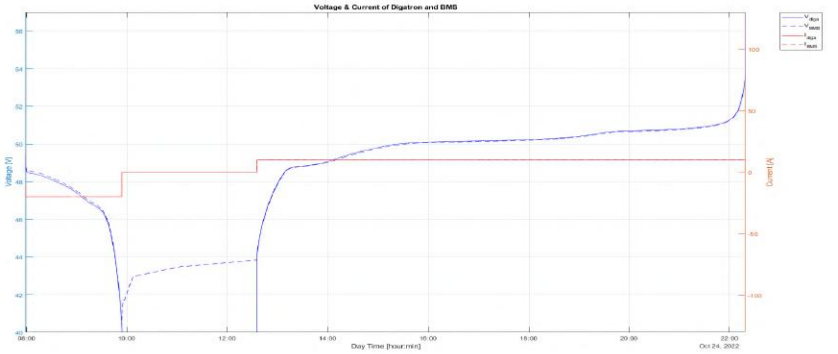

Temperatures
T [°C]
45
40
35
30
25
20
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Oct 17, 2022
Day Time [hour:min]
T PCB
T internal
T 01
T 02
T 03
T 04

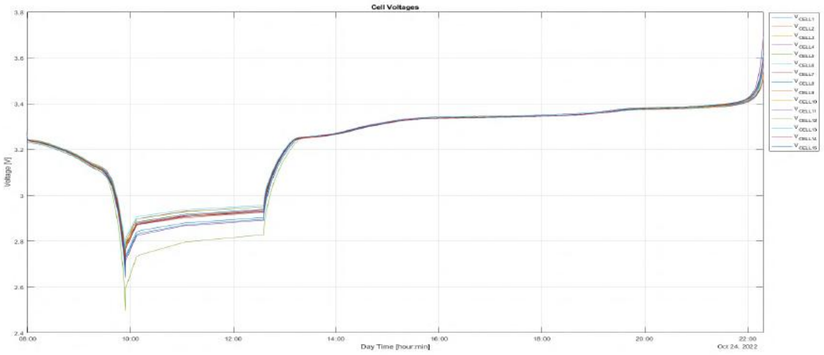


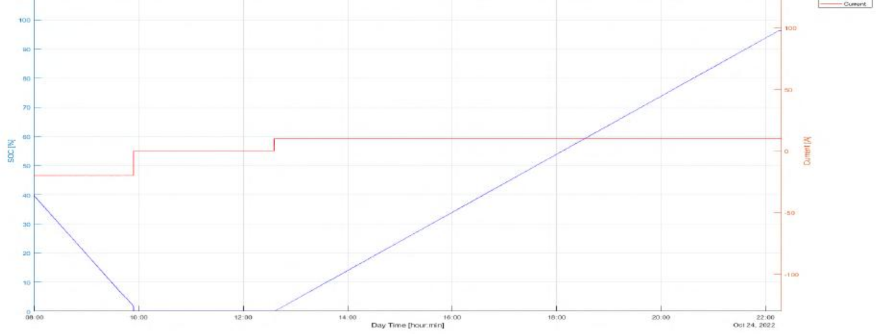


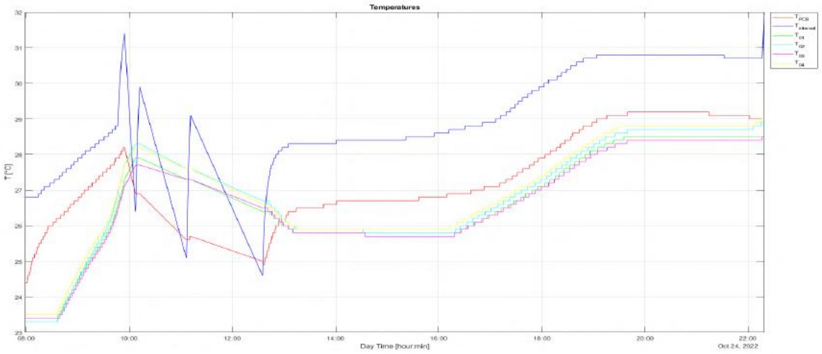


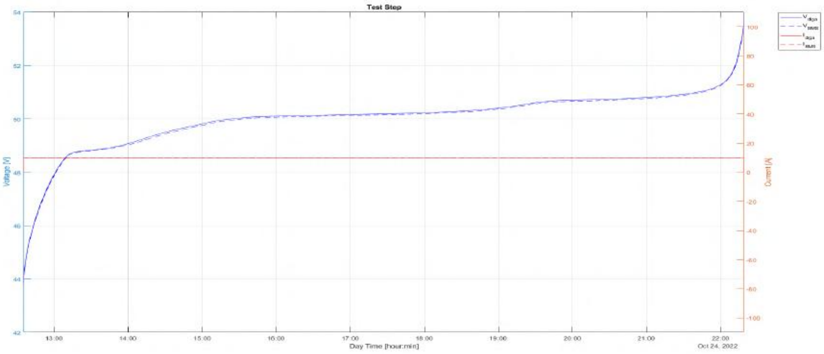
Charge at 0.1C

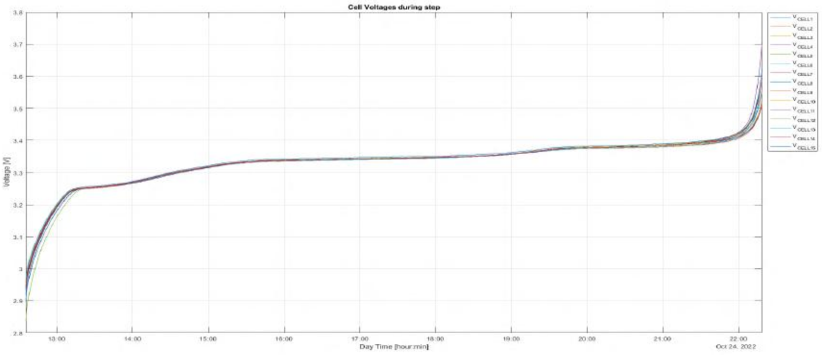

Voltage & Current of Digatron and BMS
V_{diga}
V_{BMS}
I_{diga}
I_{BMS}
Voltage [V]
56
54
52
50
48
46
44
42
40
Current [A]
100
50
0
-50
-100
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Oct 24, 2022
Day Time [hour:min]

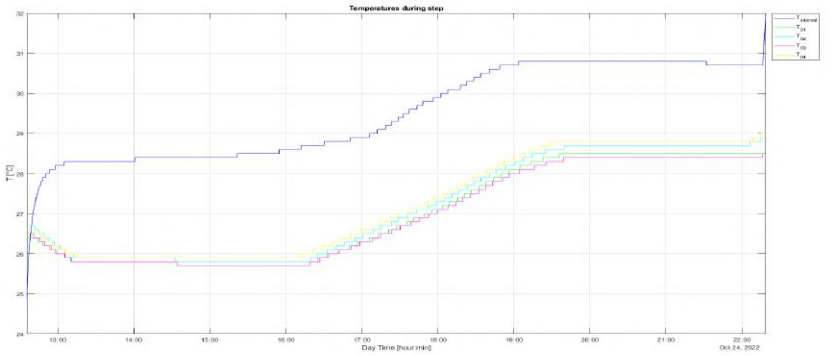

Cell Voltages
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Oct 24, 2022
Day Time [hour:min]


SOC_{BMS} & Current
SOC_{BMS}
Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Oct 24, 2022
Day Time [hour:min]

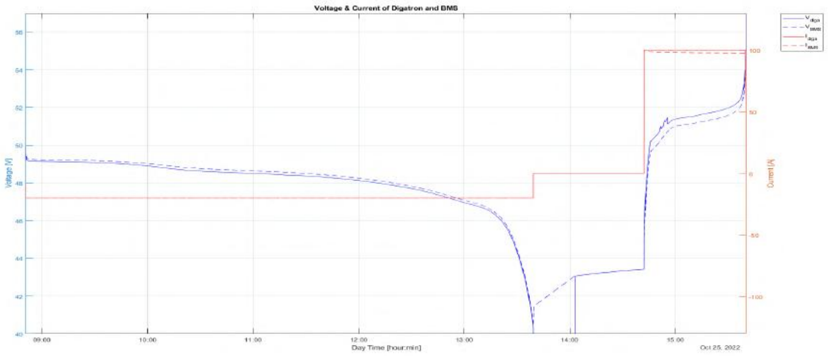

Temperatures
32
31
30
29
28
27
26
25
24
23
T [°C]
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Oct 24, 2022
Day Time [hour:min]
T_{PCB}
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}

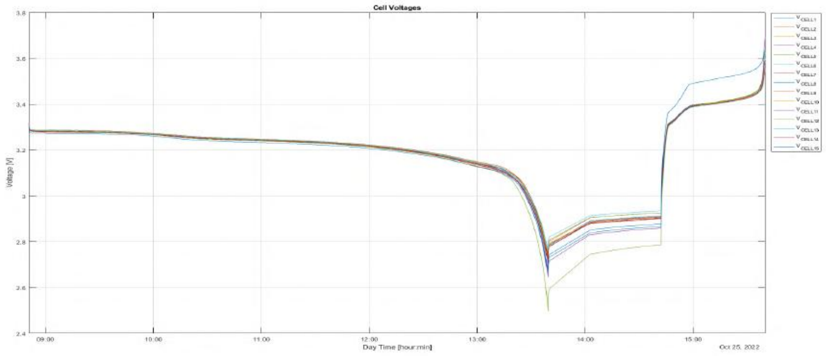

Test Step
54
52
50
48
46
44
42
Voltage [V]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Current [A]
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
Oct 24, 2022
Day Time [hour:min]
V_{dga}
V_{BMS}
I_{dga}
I_{BMS}

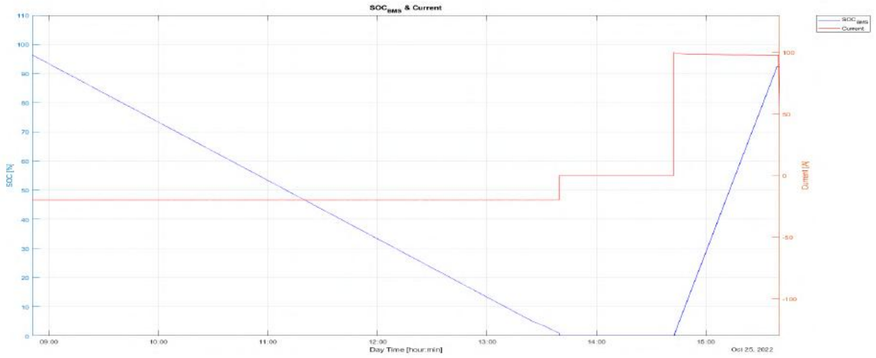

Cell Voltages during step
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
Voltage [V]
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
Oct 24, 2022
Day Time [hour:min]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}

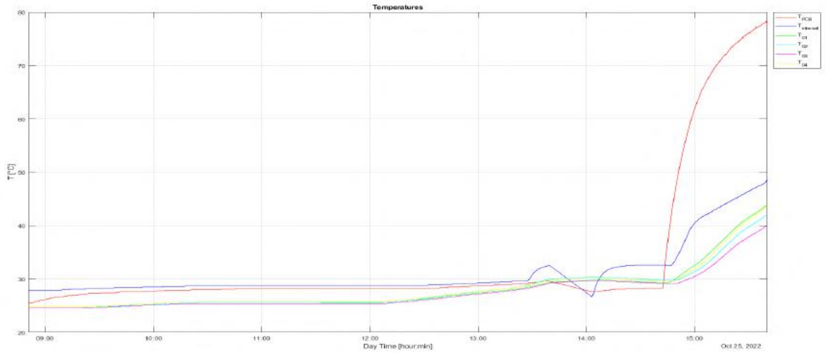


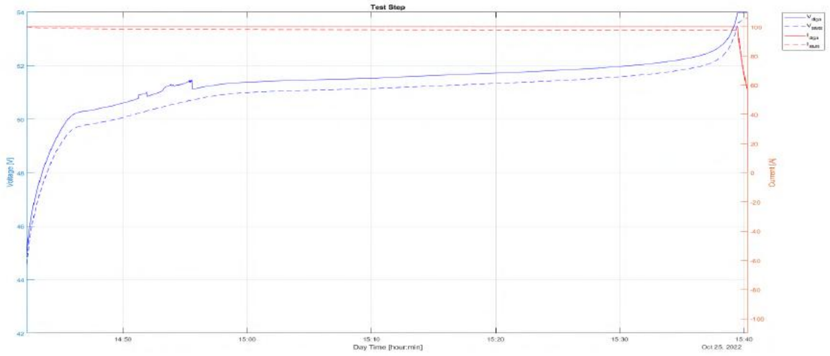
Maximum Charge

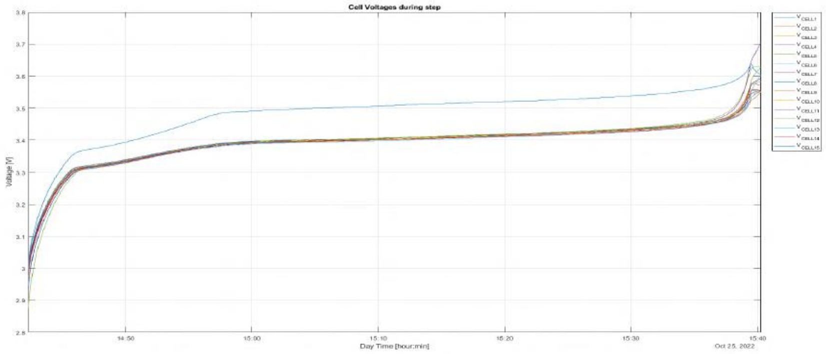


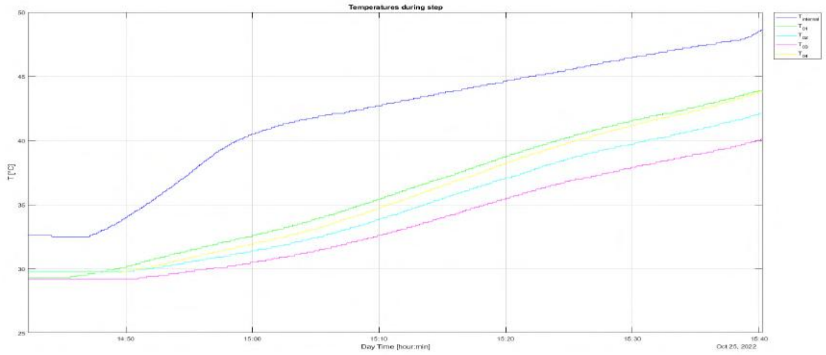



SOC_BMS & Current
SOC_BMS
Current
110
100
90
80
70
60
50
40
30
20
10
0
SOC [%]
100
50
0
-50
-100
Current [A]
09:00
10:00
11:00
12:00
13:00
14:00
15:00
Day Time [hour:min]
Oct 25, 2022

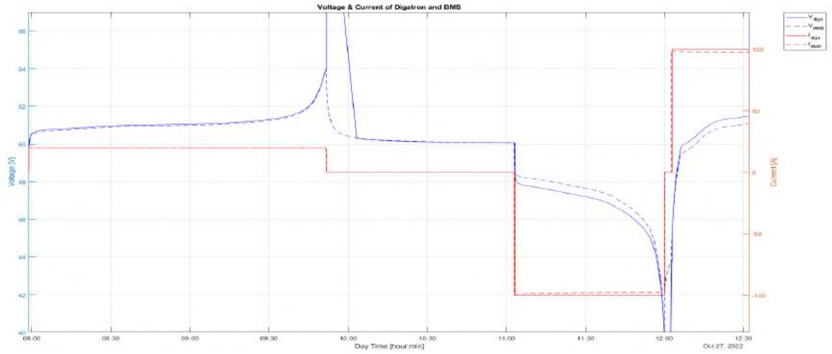

Temperatures
T_PCB
T_internal
T_c1
T_c2
T_c3
T_c4
80
70
60
50
40
30
20
T [°C]
09:00
10:00
11:00
12:00
13:00
14:00
15:00
Day Time [hour:min]
Oct 25, 2022

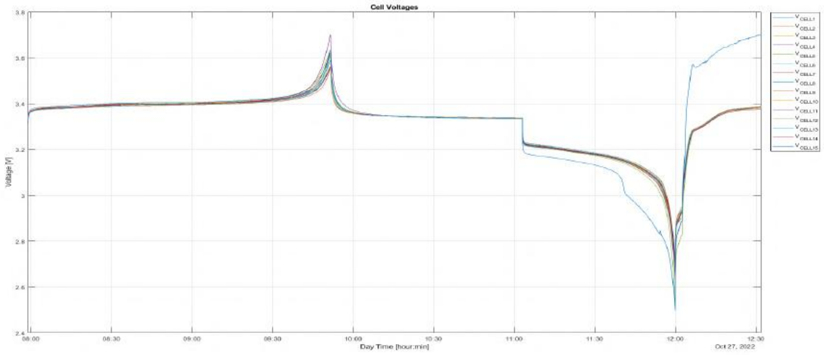

Test Step
V_dga
V_BMS
I_dga
I_BMS
54
52
50
48
46
44
42
Voltage [V]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Current [A]
14:50
15:00
15:10
15:20
15:30
15:40
Day Time [hour:min]
Oct 25, 2022

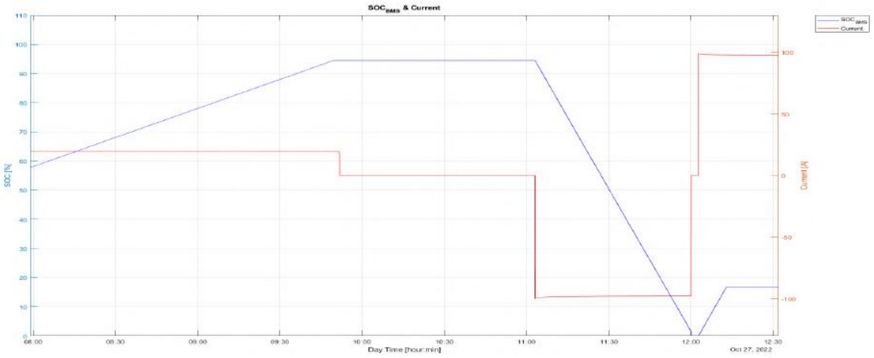


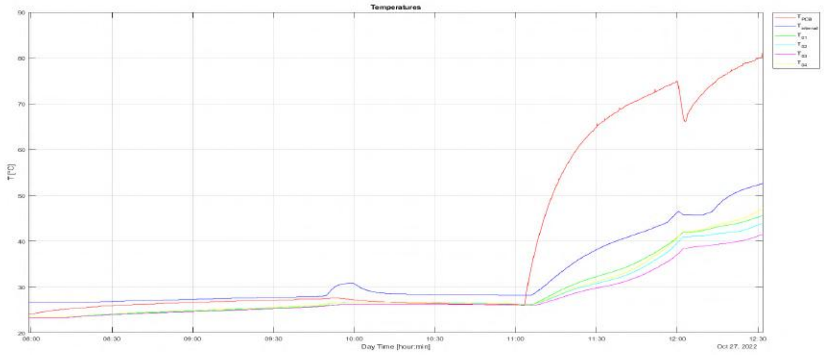


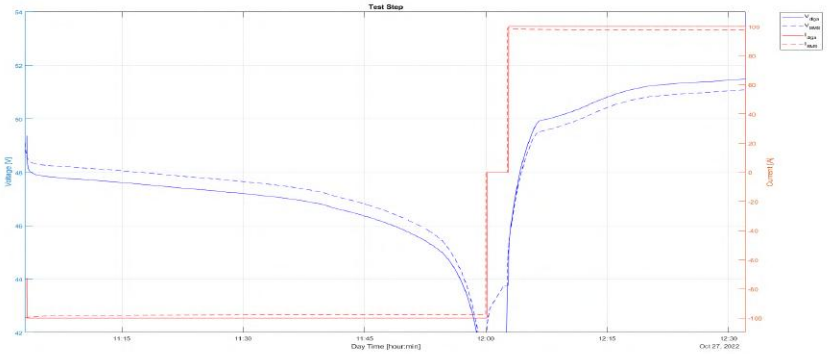
Maximum Discharge and Charge

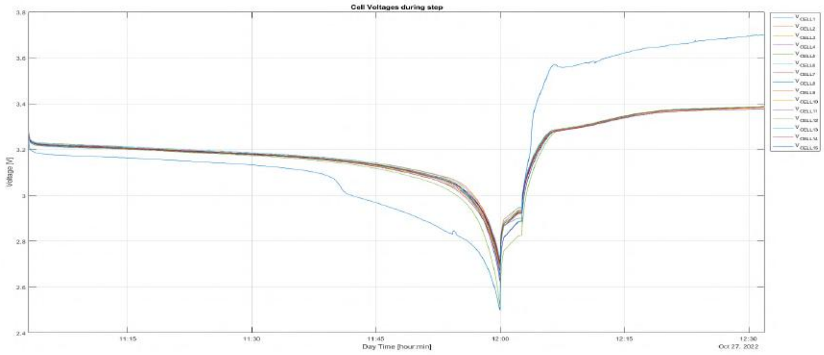


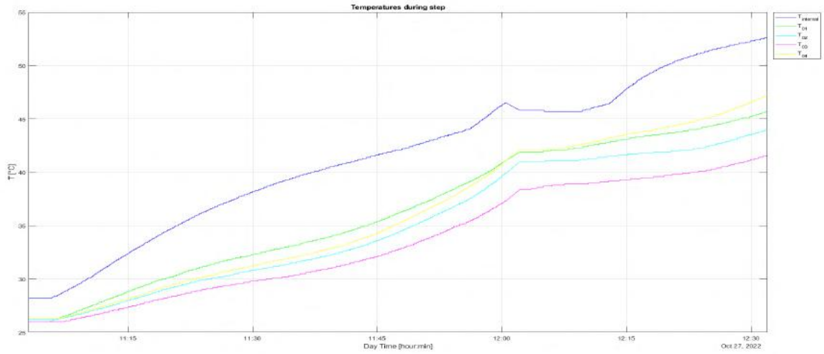

Cell Voltages
Voltage [V]
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
Day Time [hour:min]
Oct 27, 2022
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}


SOC_{BMS} & Current
SOC [%]
110
100
90
80
70
60
50
40
30
20
10
0
Current [A]
100
50
0
-50
-100
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
Day Time [hour:min]
Oct 27, 2022
SOC_{BMS}
Current

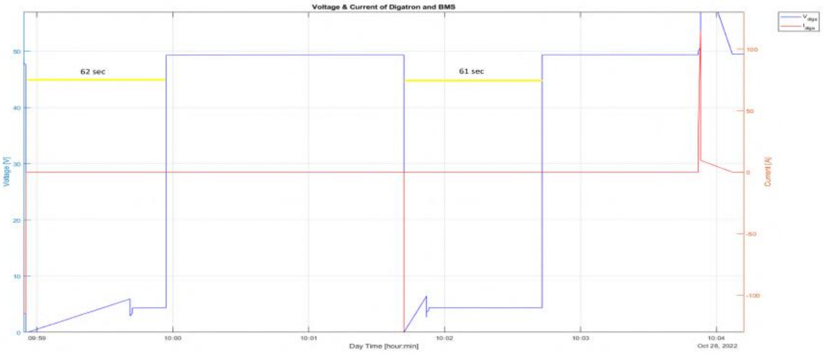

Temperatures
T [°C]
90
80
70
60
50
40
30
20
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
Day Time [hour:min]
Oct 27, 2022
T_{PCB}
$T_{internal}$
T_{S1}
T_{S2}
T_{S3}
T_{S4}


Test Step
54
52
50
48
46
44
42
Voltage [V]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Current [A]
V_{diga}
V_{bms}
I_{diga}
I_{bms}
11:15
11:30
11:45
12:00
12:15
12:30
Oct 27, 2022
Day Time [hour:min]


Cell Voltages during step
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
Voltage [V]
V_{CELL1}
V_{CELL2}
V_{CELL3}
V_{CELL4}
V_{CELL5}
V_{CELL6}
V_{CELL7}
V_{CELL8}
V_{CELL9}
V_{CELL10}
V_{CELL11}
V_{CELL12}
V_{CELL13}
V_{CELL14}
V_{CELL15}
11:15
11:30
11:45
12:00
12:15
12:30
Oct 27, 2022
Day Time [hour:min]


Temperatures during step
55
50
45
40
35
30
25
T [°C]
$T_{internal}$
T_{01}
T_{02}
T_{03}
T_{04}
11:15
11:30
11:45
12:00
12:15
12:30
Oct 27, 2022
Day Time [hour:min]

Overload Test



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List of Tables

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