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Development of a management system for the active control of the main battery parameters

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Abstract

During the last years, the world of electrical vehicle (EV) had a huge growth due the continuous research for less polluting solutions, replacing the common thermal engines. Thanks to the high-properties of lithium-ion batteries most of EVs employ this solution as principal source. This led the car manufactures to have to develop reliable control system capable to achieve the optimal management of the battery ensuring that only correct operations are carried out and keeping the main factors within the safe zones, avoiding dangerous situations which could drastically reduce its life cycle and operational capability. Indeed, the batteries are very sensitive to various events such as over-charging, over-discharging, voltage drop and high (low) temperature, so these parameters must always be kept under control to ensure no vehicle's malfunctions while it works.

The goal of the thesis a battery management system (BMS) has been developed, able to monitor the main input of a lithium-ion battery and act in case one these reached values out the allowed range. The battery system considered is made up of nine modules in parallel each one consisting of twenty cells in series while the key parameters analysed are voltage, temperature, current and state of charge (SOC).

The over-charging (over-discharging) matter could arise whenever the accumulated charge exceeds the granted value causing possible electrolytic decomposition and short-circuit, leading to a complete failure. The second parameter is closely related to the previous one, causing problem such degradation and overheating, damaging the battery sometimes irreversibly. High (low) temperature can deeply affect the efficiency of chemical reactions inside the battery causing a fast degradation and possible explosion as well as capacity problems that could be much lower than a fresh battery. Last but not least, issues could occur with the presence of errors in the SOC balance between the different modules, leading to unexpected and unwanted low performances in terms of power, failing to deliver the required couple or speed as well as unpredicted distance really viable compared to the excepted one.

To create the whole system model in the thesis two programmes has been involved: Simscape and Matlab. Two main parts have been created, the BMS itself, where all the control and correction phases take place and the battery pack system. Firstly, an equivalent circuit model (ECM) with two RC branches has been introduced to simulate the behaviour of a single cell where look-up tables has been implemented to carry out the relation between the SOC and the circuit parameters. Then the full battery pack has been developed in the Simscape environment as described in the beginning. The battery is monitored by the BMS through the implementation of current sensors inside each module and a voltage sensor, placed at the two poles (+) (-) of the battery. Instead, the implementation of a possible input manipulation is obtained with the use of dedicated switches, activated whenever is required, i.e., fault detection of one or more parameters. Finally, a balancing system has been designed to control the state of charge levels inside the modules, more specifically during the charging phase, through the use of a passive model made of parallel resistors, to avoid any possibility of unbalancing at its end. Several tests have been conducted on the model to verify its functionality, starting from easier single error cases up to simulations involving the presence of multiple simultaneous errors, to test the reliability of the BMS in increasingly critical situations

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Chapter 1

Introduction

The aim of this thesis is to obtain an optimal manage of the Li-ion battery while working, by controlling its main parameters. To accomplish this goal a first step must be done, analysing the electrical and chemical general properties of the battery understanding how these characteristics can be modelled to recreate with a good approximation the real system. The second step is to create a proper BMS which interacts with the defined battery model obtaining an entire system that works in good manner.
Performances of the batteries are strongly related to their working point in terms of state of charge and temperature, because these two characteristics can lead to possible issues and so it is crucial that the designed BMS can guarantee an optimal usage within safety conditions.
To develop a battery pack model made by different cells in series and/or parallel, it is first necessary to get the model for a single cell. To represent the electro-chemical characteristics of the cell an electrical circuit is required and among the different models found in the literature the equivalent circuit model (ECM) with two RC branches has been chosen since it is a good compromise in terms of complexity and accuracy. Other models such as electrochemical one is often more accurate, but it demands a great amount of computing power, not available in real-time system applications.
Once the ECM is defined, the battery pack system has been developed and several analyses has been done on it to check how the BMS would behave facing various possible problems, also testing the proper operation of the passive balancing system during the charging phase to control the SOC levels. Further explanation and results in the next chapters.

In the recent years, to limit the increasingly dangerous amount of emissions of toxic agents into the atmosphere, harmful to man and the earth, legal restrictions have been applied to the automotive world as underlined by the agreement in the European Parliament to stop the sale of internal combustion engine (ICE) vehicles from 2035 [1]. This decision gave a big boost to research in the electrical field, as evidenced by the extensive use of electric vans in the work environment as amazon [2] and by the rise of Tesla, with the demand for increasingly high mileage capacity.
A brief summary of the main features of the lithium-Ion battery will be exposed in the following subchapters.

1.1 Battery Chemistry

A battery is made up of one or more electrochemical cells, arranged to achieve required voltage and/or current values. Inside them the energy released from chemical reaction is converted into electrical energy. The conversion process is obtained through electrochemical reactions where the anode loses one ore more electrons while the cathode gains them, respectively called oxidation and reduction [3].

$$A \rightarrow A^{n+} + ne^- \qquad \textit{oxidation}$$
$$A + ne^- \rightarrow A^{n-} \qquad \textit{reduction}$$

These reactions generate a current flow from the anode towards the cathode, which are connected but physically separated, due to the potential difference between the two electrodes that are immersed in electrolyte solutions. To maintain a continuously flow of electrons a salt bridge is needed, made of membrane or a porous plug, keeping the electrical neutrality within the circuit leading inert ions moving from one reservoir to the other [4].

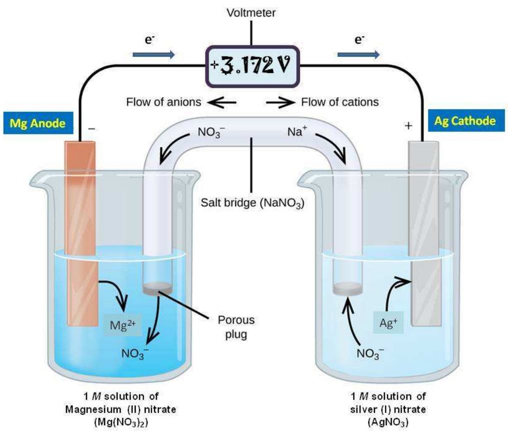


Figure 1: Example of electrochemical cell

Moreover in case of lithium-Ion batteries the reaction is bi-directional or reversible, meaning that it can be discharged and recharged. These properties are well known in the field of electrical vehicles where the regenerative breaking is widely used in every major brand, i.e., Toyota and it is highly sponsored within the tv advertisements.

1.2 Battery Properties

As a result of the great impact in the automotive world by electric vehicles (EVs), hybrid-electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) attention has been focused more on what are the main properties provided by the different batteries, such as durability, safety, reliability, power density (W/L) and specific power (W/kg) [5].
The specific power is an indicator of the battery's capability to develop large demands for short period, i.e., an acceleration is necessary or in case of uphill road, while specific energy is required for long distances at lower-mid power demand, i.e., high mileage capacity [6] (Figure 4). The latter is an important point in the sale of electric vehicles due to the fact that customer demanding always bigger autonomy.

It is easy to understand that the two properties are chosen through a trade-off based on the type of use of the vehicle, i.e., city car or sportive car.

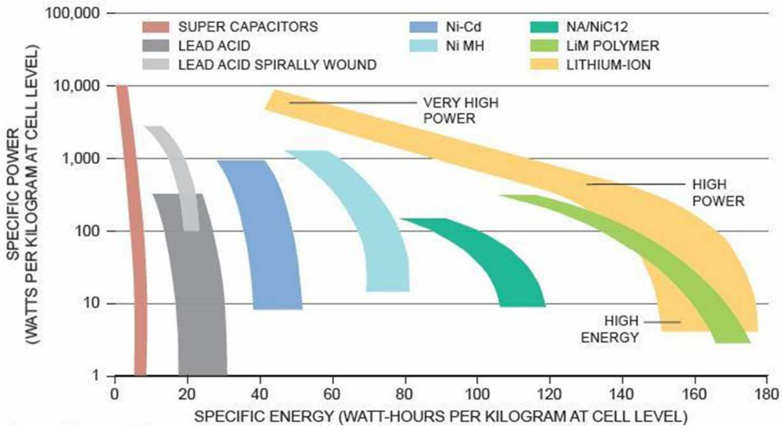


Figure 2: Specific Power vs Specific Energy

A brief overview on the most common batteries characteristics (Table 1) is given:

Lead-acid is very common due to its high power, safety, reliable and low cost. However, its specific energy is quite low and short cycle life.

Nickel-metal hydride offers reasonable specific energy and specific power capabilities. It has a much longer life cycle than lead-acid batteries and have been widely used in HEVs. However, it has high cost, high self-discharge and heat generation problem.

Ultracapacitors can provide quick release of power during acceleration and help recover braking energy, as shown by their extensive use in ‘Formula 1’ where they have a crucial role to achieve victory. They may also be useful as secondary energy-storage devices in electric-drive vehicles.

Lithium-Ion has high specific energy and density, high specific power. Moreover, it has a good power-to-weight ratio and no/low memory effect. However, its cost is high compared to the lead-acid batteries [7][8].

Energy Storage Type	**Lead-acid battery**	**Ni-based battery**	**Li-based battery**
Specific Power (W/kg)	50-180	50-1000	250-400
Specific Energy (Wh/kg)	30-50	30-70	90-190
Life (Years)	3-15	15-20	~15
Cycle	500-4500	100-40000	500-18000
Efficiency (%)	70-90	50-90	80-95
Cost ($/kWh)	50-200	150-2400	100-2000

Table 1. Characteristic comparisons of the primary types of batteries used in EVs (source: Diana Lemian and Florin Bode, Battery-Supercapacitor Energy Storage Systems for Electrical Vehicles: A Review)

1.3 Lithium-Ion Chemistry

This subchapter will introduce what are the main common chemistry lithium batteries [9]:

- **LCO**: Lithium Cobalt Oxide ($LiCoO_2$) consist of a cobalt oxide cathode and graphite carbon anode. It has high specific energy but limited specific power. Moreover, it is expensive and has short life span and low thermal stability (Figure 9). It is used for laptops and mobile phones.

- **LMO:** Lithium Manganese Oxide ($LiMn_2O_4$), a substitute of LCO, has lithium manganese oxide as cathode. It is cheaper, has lower internal resistance allowing fast charging and high-current discharging, higher thermal stability and it is safety (Figure 9). However, the cycle and life span are still limited. No longer common nowadays, just for special applications.

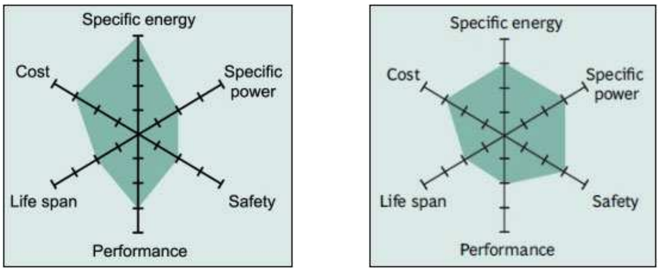


Figure 3: LCO (left) and LMO properties (right)

- **NMC:** Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_4$) is one of the most successful systems where the cathode is a combination of Nickel, Manganese and Cobalt. It provides high capacity and high power with a low cost (Figure 10). It employed for power tools, electric powertrains, automotive and energy storage system (EES).

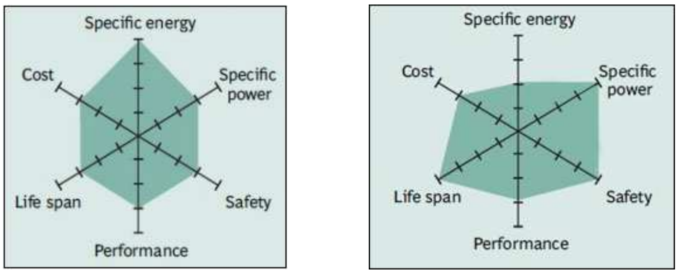


Figure 4: NMC (left) and LFP properties (right)

- **LFP:** Lithium Iron Phosphate ($LiFePO_4$) has phosphate as cathode, offering a high current rating. long cycle life and thermal stability. Anyway, has a low capacity and higher self-discharge which could cause unbalancing inside the battery with aging (Figure 10).

- **NCA:** Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$) has similarities with NMC offering high specific energy and specific power, and long-life span while safety and cost are not as advantageous (Figure 11). Mainly used by Panasonic and Tesla.

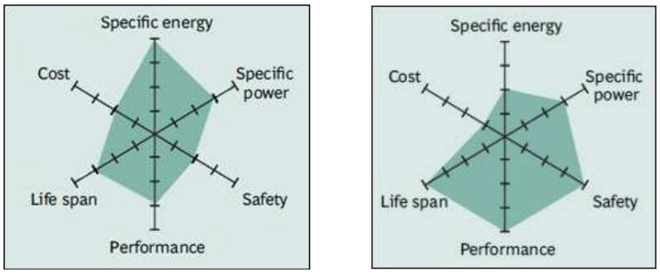


Figure 5: NCA (left) and LTO properties (right)

- **LTO:** Lithium Titanate (Li_2TiO_3) has lithium titanate anodes. It can be fast charged, it is safe, has long life and provide discharge current up to 10C but it is expensive (Figure 11). Employed in electric powertrains.

1.4 Lithium-Ion battery working overview

Lithium ions (Li^+) can be intercalated or 'absorbed' by both the electrodes in a lithium cell due to the materials the latter are made of. This means that the li-ions can be stored inside the host material structure without bringing any instability. In lithium-ion charged battery lithium ions are linked to an electron in the anode structure and when a discharging phase is involved the lithium ions are released, thus being absorbed by the cathode releasing the electrons previously linked with them, which are responsible for the electric current flow generation in presence of an external wire.
On the opposite, when the battery is full discharge all its lithium ions are intercalated inside the cathode structure and during its charging phase an oxidation occurs at the cathode, losing some of its negatively charged electrons leading to the dissolution of an equal number of lithium ions to get a charge balance, travelling to the anode where they are intercalated within the graphite.
However, several degradations could occur during cycling or storage, i.e., lithium metal plating causing capacity losses or structural degradation of cathode materials resulting in 'electrode saturation' [10][11].

Chapter 2

Battery Definition

The aim of this chapter is to briefly define the main characteristics of the single cell (Samsung) and the definition of an equivalent model among all the possible models available in the literature. The selected one must keep the model results as close to reality as possible, but without excessive complexity.
The full battery pack system considered in this thesis is made of nine modules in parallel each on containing twenty cells in series.

2.1 Samsung-Cell Data

The cell considered as source power is Samsung INR21700-50E (Figure 12), a lithium-ion rechargeable employed in the purpose of obtaining and testing the BMS in its various aspects, i.e., fault testing and SOC balancing.

Figure 6 Samsung INR21700-50E

Table 2 shows the main characteristics of the Samsung Cell, useful and necessary for defining the constraints to which the BMS must refer when monitoring and controlling the battery pack.

Geometry		Cylindrical	-
Maximum Voltage		4.2	V
Nominal Voltage		3.6	V
Nominal Capacity		4.9	Ah
Maximum Continuous Discharge Current		9.8	A
Maximum Non Continuous Discharge Current		14.7	A
Recharge Maximum Current		4.9	A
Discharge Cut-Off Voltage		2.5	V
Discharge Temperature (Operative Range)		[-20; 60]	°C
Charge Cut-Off Voltage		4.2	V
Charge Temperature (Operative Range)		[0; 45]	°C
Cell Weight (max)		69	g
Cell Dimensions	Height (max)	70.8	mm
	Diameter (max)	20.25	mm

Tabella 2. Samsung INR21700-50E characteristics

2.2 Electrical Model

Equivalent circuit models (ECM) (Figure 13) are widely used in many applications due to its fast execution time, low-mid complexity and relatively high accuracy, characteristics that make it particularly suitable for real-time system. Contrary to ECM, electrochemical models provide more accurate results but they even more complex, demanding a great amount computational effort and making them not suitable for real-time applications [12].

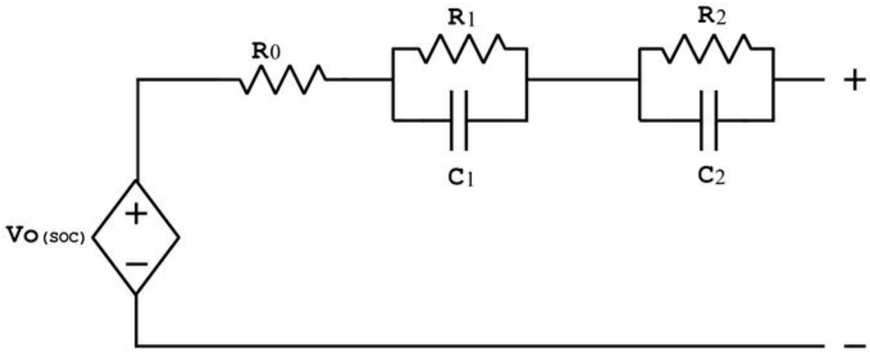


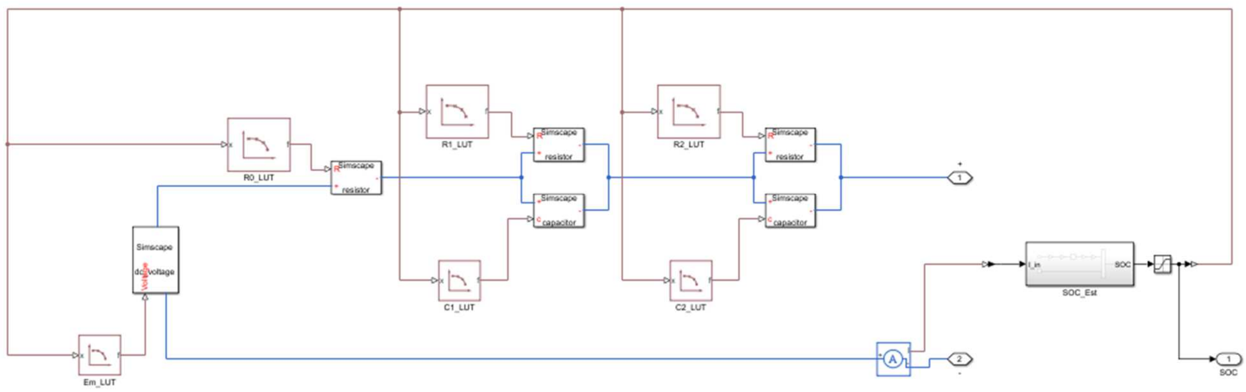
Figure 7: Second-Order Equivalent Circuit Model (ECM)

Then, each cell of our battery is modelled in the Simulink environment using a second-order electric circuit model.
Thevenin's Open Circuit Voltage (V_{OCV}) is represented by the ideal voltage source *Vo* while the resistor *R0* represents the voltage battery drop when the load is connected and the current is provided to the system. Lastly the two *RC* branches represent with a good approximation dynamic phenomena as charging and discharging. More precisely the first *RC* network (*R1, C1*) is employed to model the double layer capacitance and the charge transfer procedures while the second *RC* network (*R2, C2*) is employed to model the diffusion procedures [13].
All the above parameters are strictly dependent on the state of charge (SOC) inside the investigated model.

Chapter 3

Simscape Implementation

The electric circuit model (ECM) described in the section 2.2 has been implemented in the Simscape environment (Figure 14), which it able to separate the physical connection and the electrical ones. The main elements such as resistors and capacitances are not directly represented with their own blocks due to their direct dependence to the SOC and thus, not being constant values. To take care of this relation, look-up tables has been involved, which are responsible for the value of the individual parameters according to the state of charge.
Indeed a mat.file has been introduced with Matlab, containing the different values of *OCV, R0, R1, C1, R2* and *C2* in the eight SOC breakpoints (Table 3).
The look-up table, with a linear point-slope, interpolates the breakpoints and once it has read the SOC value at time 't' the corresponding parameter is calculated.



.Figure 8: ECM implemented in Simscape with parameters regulation thought look-up tables

SOC	OCV	R0	R1	C1	R2	C2
0.3	3.4278	0.0168	0.0047	6.2779e03	0.0030	489.8324
0.4	3.5089	0.0146	0.0042	9.7844e03	0.0016	2.5069e03
0.5	3.6189	0.0145	0.0106	9.2457e03	0.0010	2.8531e03
0.6	3.7177	0.0151	0.0110	4.4346e03	7.5799e-05	1.8556e03
0.7	3.8034	0.0158	0.0074	6.9405e03	1.1222e-04	1.7081e03
0.8	3.9510	0.0169	0.0151	2.3641e03	4.9752e-04	2.6940e03
0.9	4.0307	0.0188	0.0076	9.2927e03	0.0021	3.6471e03
1	4.1392	0.0226	0.0171	2.1592e03	8.1922e-05	1.0105e03

Table 3. Breakpoints values of the main parameters: OCV, R0, R1, C1, R2, C2

3.1 Coulomb Counting

A simpler but useful mathematical model to estimate the state of charge (SOC) of a battery pack is called 'Coulomb Counting'.
The SOC is defined as the ratio of the available capacity and the maximum possible charge that can be stored in the battery:

$$SOC = \frac{Q(t)}{C_{Batt}}$$

The mathematical expression that has been implemented in the Simscape model to monitor the state of charge is:

$$SOC(t) = SOC(0) + \int_0^t \frac{I}{C_{Batt}} dt$$

Starting for the SOC at time zero, which must be perfectly known, a second term is added to obtain the value at each time.
The second term has been obtained from the integration of the current by time to compute the instantaneous *Q(t)* and diving it by the total battery capacity C_{batt}.
Two distinction phase can happened, the charging ones where the added term will be positive, increasing the SOC value and discharging one, where a negative term will be added decreasing the state of charge.
SOC equal to 'one' is used to indicate the case of '100%' full charge while the 'zero' case represent the '0%' charge.

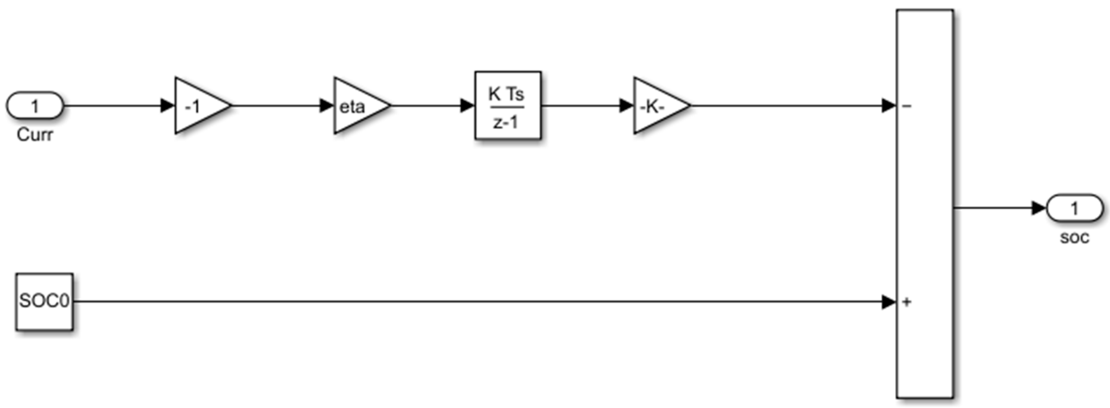


Figure 9: SOC Coulomb Counting

Above we have the formula converted in the Simulink expression, starting from the 'SOC0' and updating this value with the integration of the battery current monitored by the use of a current sensor.
Although this kind of estimation suffer the necessity of a precise knowledge of the initial SOC, its simplicity and low computational effort make it a good solution.

3.2 General Structure Architecture (Simscape)

The Simscape model representing the full system has been divided in two main parts, the battery and the BMS (Figure 16)[14].

- Battery: it contains the full structure of the nines modules in parallel, each one made of twenty cells in series. Each module has its own current sensor allowing the estimation of the SOC through the coulomb counting.
- BMS: it implements all the control logics needed to ensure the battery to work inside the safe zone. When a malfunction is captured it indicates the fault event and make an action to overcome the problem, avoiding the battery to work in dangerous conditions which could lead to possible irreversible damage.

Inside the Simscape it is also present a 'Control Area' that indicates which states are active ('green'), which are off ('red') and which are in a malfunction condition ('yellow').

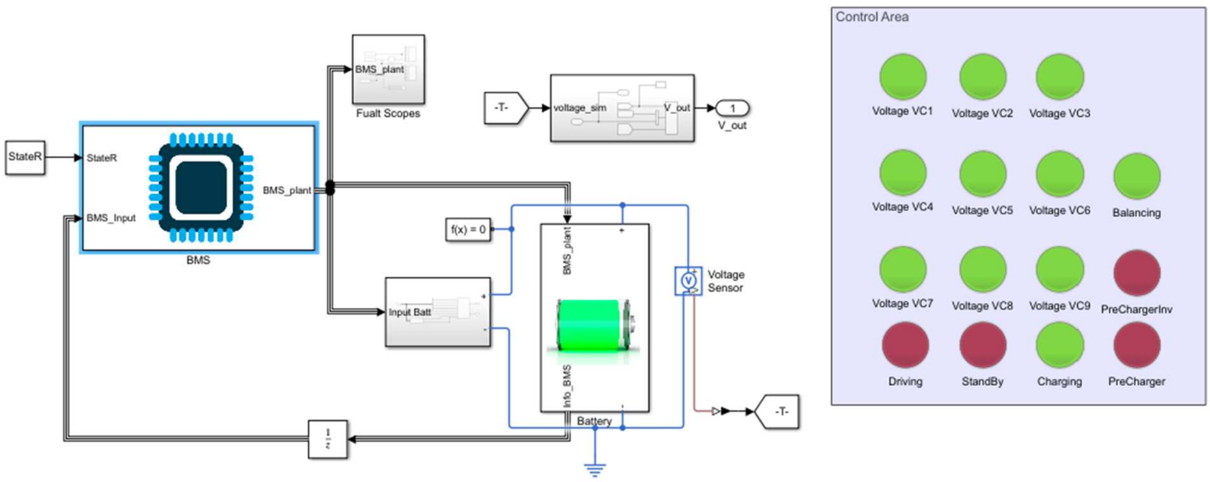


Figure 10: BMS with the battery pack system (right) and control area (left)

3.2.1 Battery Managment System (BMS)

The BMS is composed by three main sub-structure which are the SOC estimator (coulomb counting), the balancing control and the battery control.
The SOC estimator has as inputs the total battery current as well as the single current coming from each module and its purpose is to derive the estimated SOC of the battery pack as well as the modules. These estimations are important in order to apply the balancing method (more details on this later).
The balancing control has the purpose to brings all the modules inside the battery at the same energy level as it is an important aspect to preserve the battery from malfunction and to get a longer life.

Lastly the battery control contains the state flow responsible for performing all the control actions to guarantee a correct behavior of the battery as well as the fault detection and pre-charge activation/deactivation (more on this later).

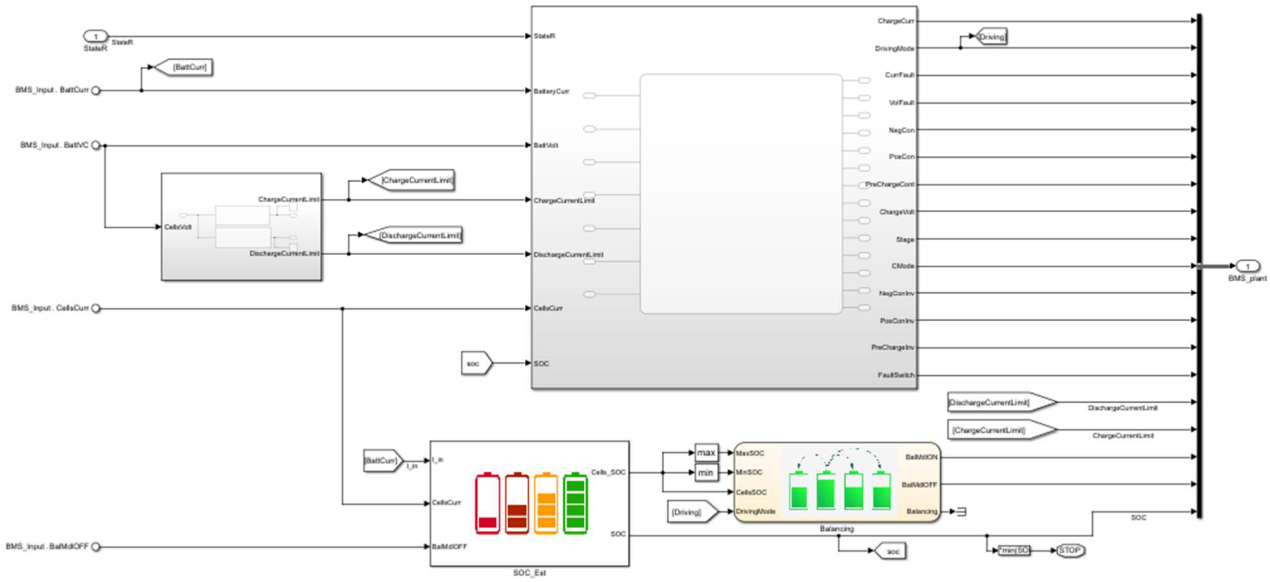


Figure 11: BMS main parts: Balancing Control, SOC estimator and Battery Control

3.2.2 State Flow

The state flow, responsible for battery fault detection and control, is subdivided in four macro structure called: MachineState, Fault, PreCharging and PreInvCharging [14](Figure 18).
They work in a ‘parallel way’, meaning they are executed simultaneously.

- MachineState: it performs the transition between the different main state in which the battery can be located: Stand-By, Driving, Charging, Fault. For each state the BMS implement a different control action.
- Fault: it is responsible for fault detection of the main parameters such as the current, the voltage and the temperature.
- PreCharging / PreInvCharging: their scopes are to avoid high inrush current when the battery is connected to a load (inverter) as well as to a charger, at the beginning phase.

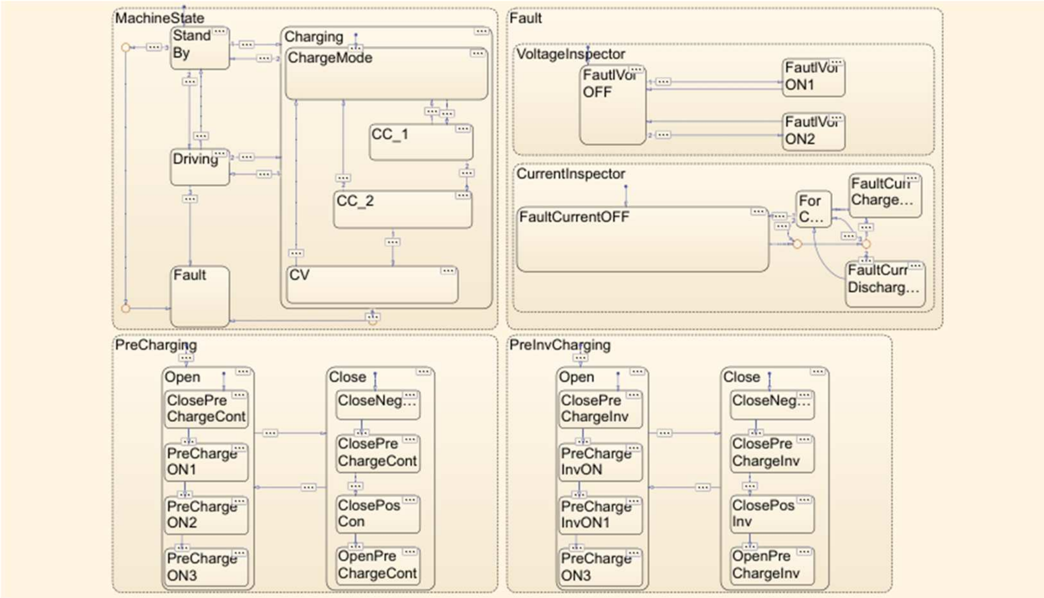


Figure 12: BMS stateflow

3.3.3 Machine State

Inside the machine state 3.2.2 the transition between the different operating mode is implemented. The most interesting is the 'charging mode' where the BMS perform a detection of two important parameters, the SOC level and battery voltage level. Ones these values are known it decides which kind of charging mode must be activated (constant current, CC, or constant voltage, CV) as well as the current/voltage value required to the charger.
In all the states is present the 'fault transition' due to the fact that if a fault is detected no matter which state is active, the battery has to stop.

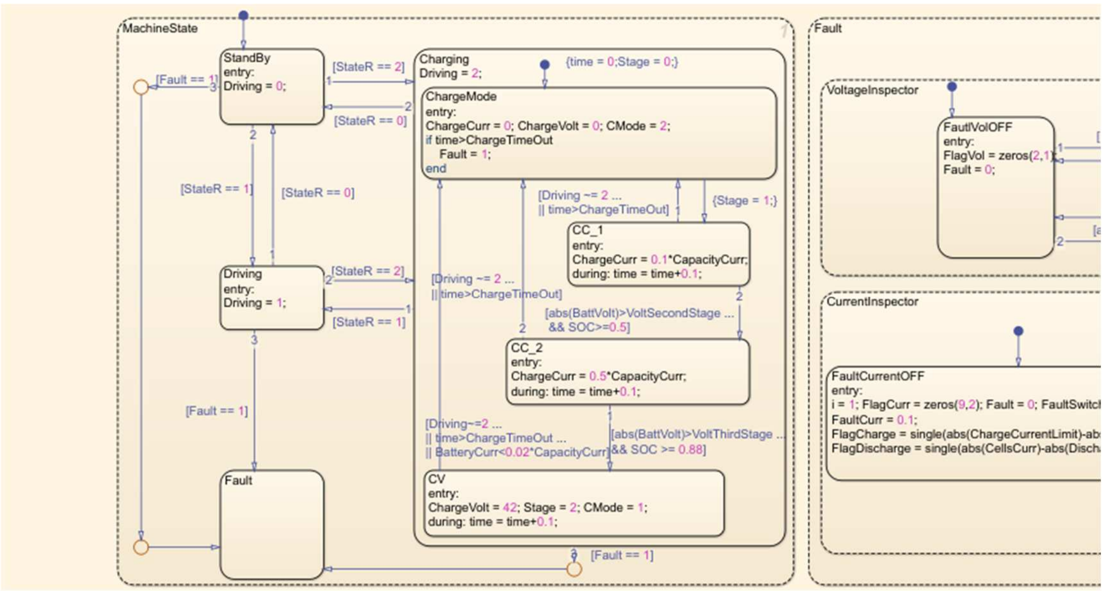


Figure 13: Machine state transition: Stand-By, Driving, Charging, Fault

3.3.4 Fault

The fault state flow has the important task of monitoring the system crucial parameters which are the voltage level, the current and the temperature, for which specific lower and upper bounds has been indicated.
In case one of the events or even both the parameters exceed these bounds a warning is given to the 'MachineState' which will transit to fault state.
Moreover a full data storage is performed each time the program run in order to have a full data access to all the fault detections.

A quick overview is given about how the fault detection works:

- inside the 'VoltageInspector' an output variable 'FualtVolt' of dimension 2x1 is used to take note of the different voltage limit violations during the run time while the variable 'Fault' is used to advise the BMS that a fault has been detected.
- in the 'CurrentInspector' (in further chapter even the 'TemperatureInspector' will be considered) some additive variables are considered. The first, 'FlagCurrent' (9x2), has the scope to take notes of the different current limit violations in case of charge (first column) or discharge (second column) and the second,'FaultSwitch' (9x1), has the important task to open the switches in case of alert. Indeed a system of switches has been implemented inside the battery pack to protect the battery itself (details in further chapter). Both are initialized as 'zero' and just when a fault is detected inside one or more modules a '1' is inserted inside the corresponding positions of the 'FaultSwitch' and 'FlagCurrent', allowing the relative switch to be opened/closed.

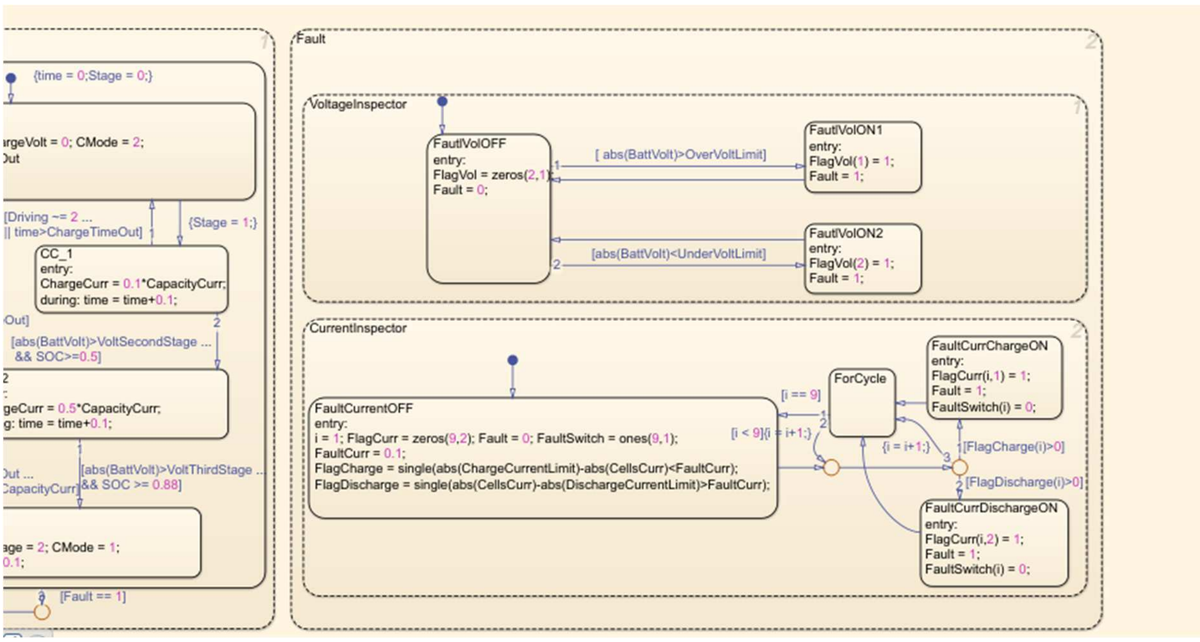


Figure 14: Fault detector

3.3.5 Pre-Charging Overview

As previously introduced in chapter 3.2.2 these states flow are responsible to avoid high inrush current during the stating phase [15][20] (Figure 21).
At the beginning only the 'Pre-Charge' and the 'Main(-)' are switched ON. When the transition current is terminated the 'Main(+)' is switched ON as well and the 'Pre-Charge' is switched OFF, returning to the normal working phase.

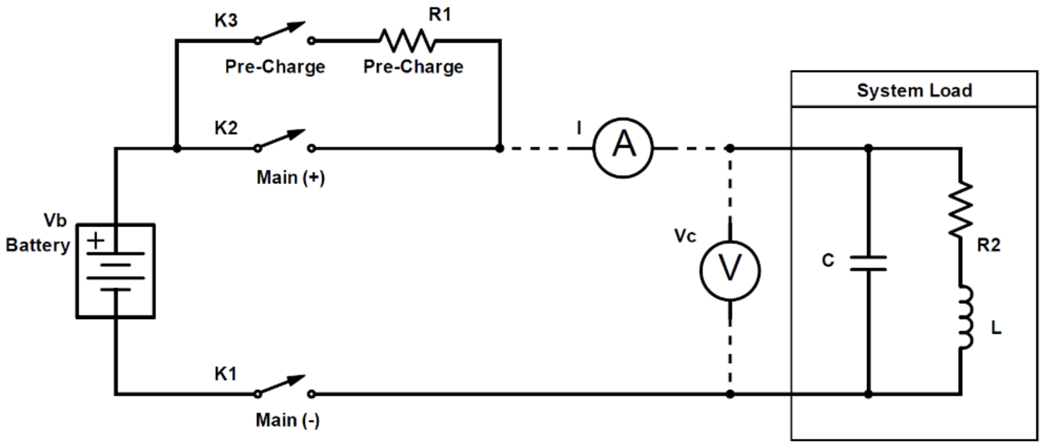


Figure 15: Pre-charging circuit

The Simscape state flow implement the same logics of the electric scheme above passing from the 'open' to the 'close' case and vice-versa, but through the use of stateflow as logic variables (Figure 22).

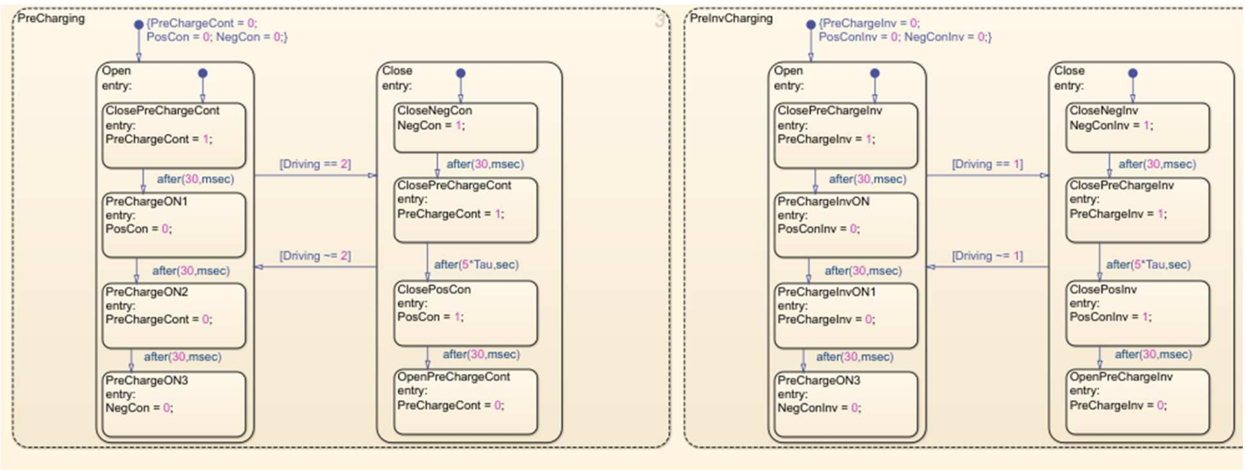


Figure 16: Pre-charging state flow

3.3.5 SOC Estimator

In chapter 3.1 the coulomb counting has been introduced with its mathematical equation to estimate the state of charge (SOC).
The Simscape scheme showed in Figure 23 is subdivided in two parts. In the top there are the blocks referred to every single modules, where each single corresponding current is taken as input and integrated to estimate the SOC as output. Instead in the bottom part the battery pack system SOC is estimated considering the total current, with less precision as in case of errors inside one or more modules they would not be detected here.

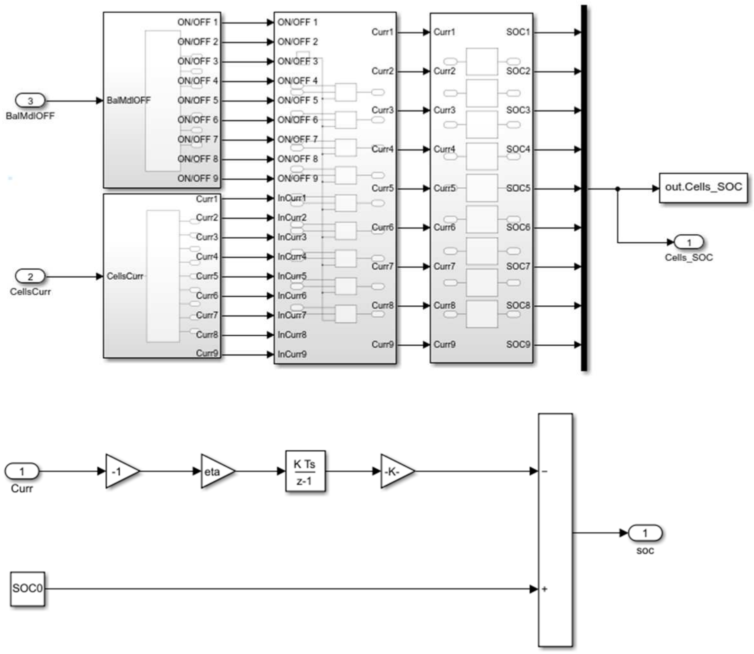


Figure 17: SOC estimator for each module (upper) and for the general battery (below)

3.3.6 Balancing

The balancing mode is activated from the BMS when some particular conditions are satisfied: the ‘MachineState’ is not in the ‘Driving’ state, so no power demand to the battery. When the charging phase is present and the SOC of the lowest module is almost at its maximum value, 95%, or the maximum module is at 97% the balancing acts (Figure 18).
This balancing action solution that has been provided in this thesis is the passive one, meaning that the SOC leveling is made up by usage of parallel resistors to the modules. Since current will be dissipated through resistors, heat production will take place, requiring a well designed cooling system (not treated in the thesis)[16].

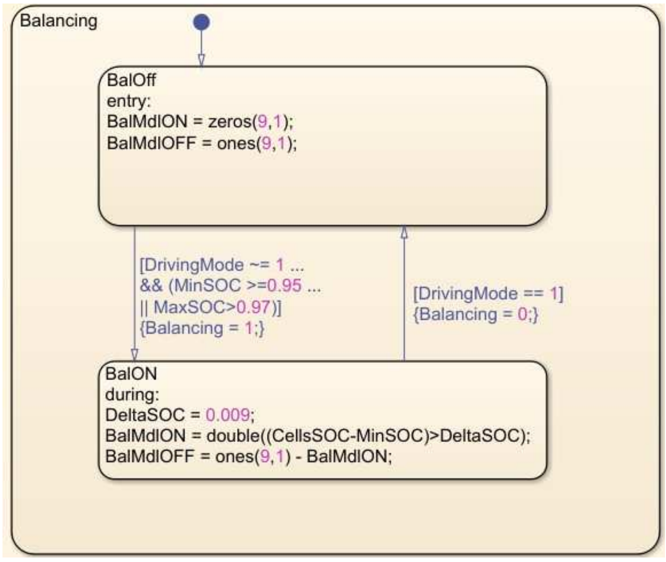


Figure 18: Balancing flowchart

3.3.7 Switching Mode

This subchapter is referred to the balancing action form the point of view of the battery pack. Two switches have been implemented inside the red circle whose purpose is to switch the balancing mode from ON to OFF and vice-versa depending on the input received by the BMS, to guarantee a correct SOC inside each module during the charging phase.
Instead, the green circle highlights the presence of an additive switch of emergency whose scope is to avoid dangerous situation in case of current/voltage faults when a malfunction damage the other two switches (Figure 19).

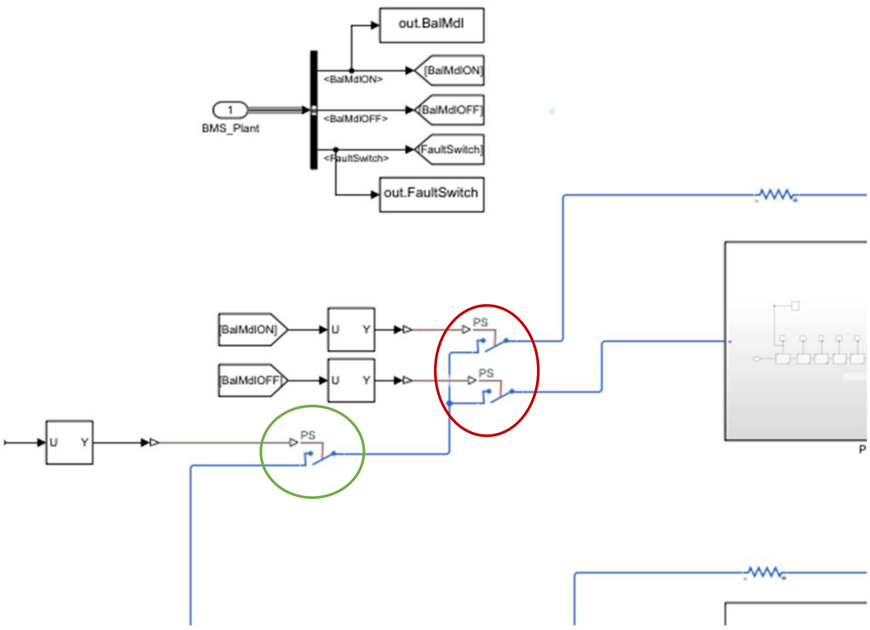


Figure 19: Switches inside the battery pack

3.3.8 Sources

The system can be in two fundamental situations (Figure 20).
In case of ‘Driving Condition’ the battery is connected to an inverter and the current can flow inside or outside depending on the driving phase. A discharging current (-) will be captured during the normal driving while a charging current (+) in case of breaking.
In case of ‘Charging Condition’ the current is flowing inside the battery to restore its energy level and the current demand is directly controlled by the battery itself thanks to the BMS.

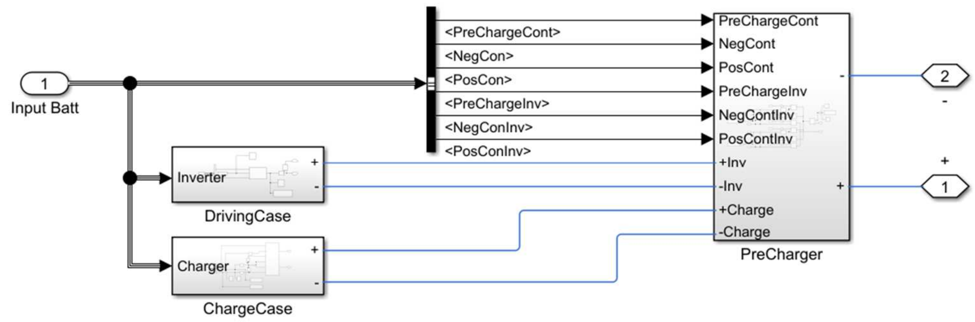


Figure 20: Charging Mode and Driving Mode

In the Simscape representation (Figure 21) there is the block representation of the ‘Charging Mode’ (‘ChargeCase’) respectively. The current flows inside the battery and this can happen in two different ways, with a constant current (CC) or a constant voltage (CV). The right block select the charging mode between these two different ways, based on the input given by the BMS (more on this in later chapter).

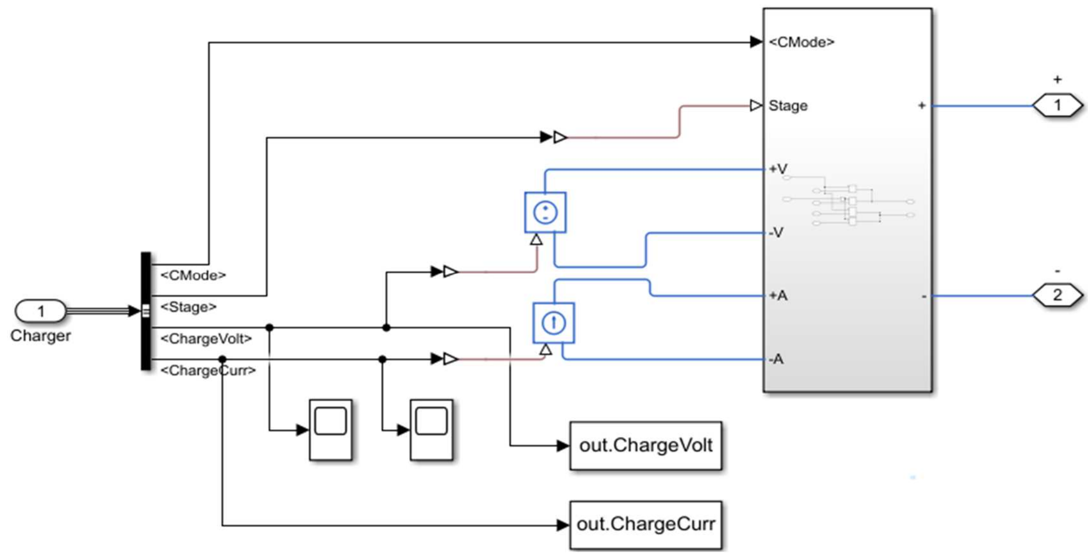


Figure 21: Charging Block

3.3.9 Pre Charger

Since two different sources conditions are present (3.3.8) different pre chargers are required, one dedicated to the case of charging mode and another for the driving mode [14] (Figure 22). Their purpose is to limit the inrush current to prevent the electrical elements from deep damages.
The BMS has the control on the switches and select which one must be opened or closed.

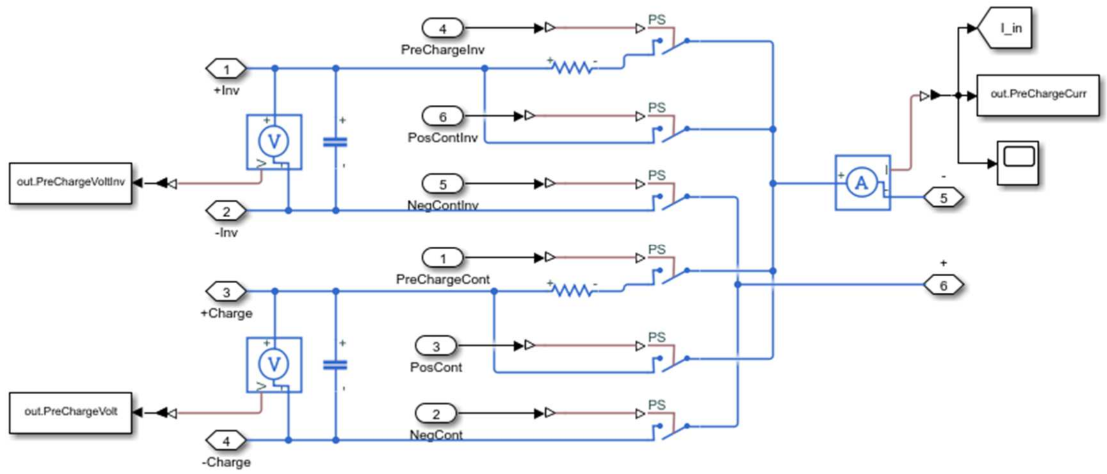


Figure 22: Pre-charging block

Chapter 4

Simulation and data analysis

In this chapter a first part of analysis will be done on the system, testing the BMS logics choice in different situations and checking the results.

4.1 Driving Mode

As first action, the BMS start the flow from the 'StandBy' state, and when an input is received it moves along the different state transition.
In this case the final state will be 'Driving' and once the state will be achieved it will allow the switching inside the sources block (3.3.8) to select the source provided by the 'inverter'. This also imply the switching ON of the pre charger dedicated to the inverter.
In the attached picture (Figure 23) there is the transition to the driving block (highlighted in blue) as well as the selection of the 'open' mode for the pre charger dedicated to charger and the 'close' mode for the ones dedicated to the inverter.

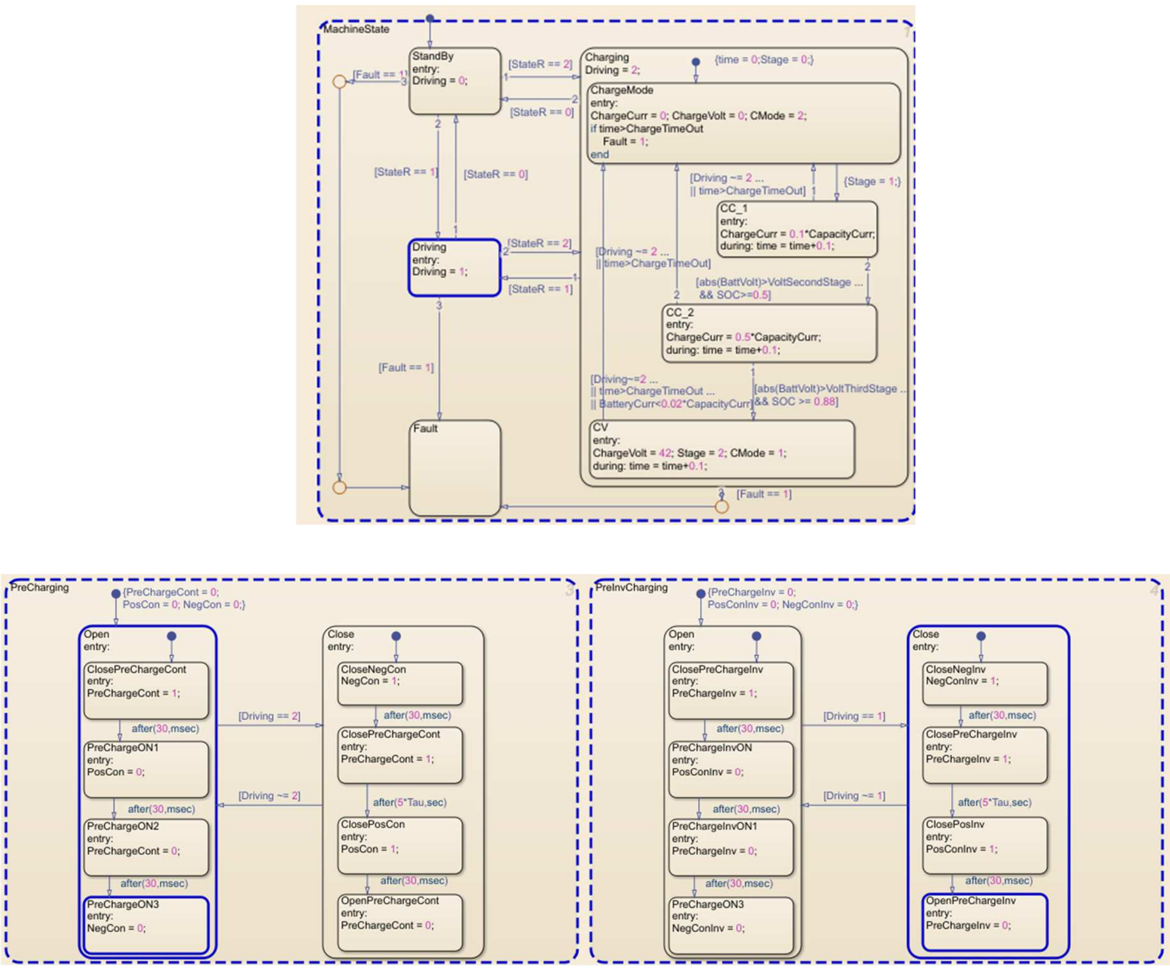


Figure 23: Machine State Transition (above) and Pre-charging flowchart (below)

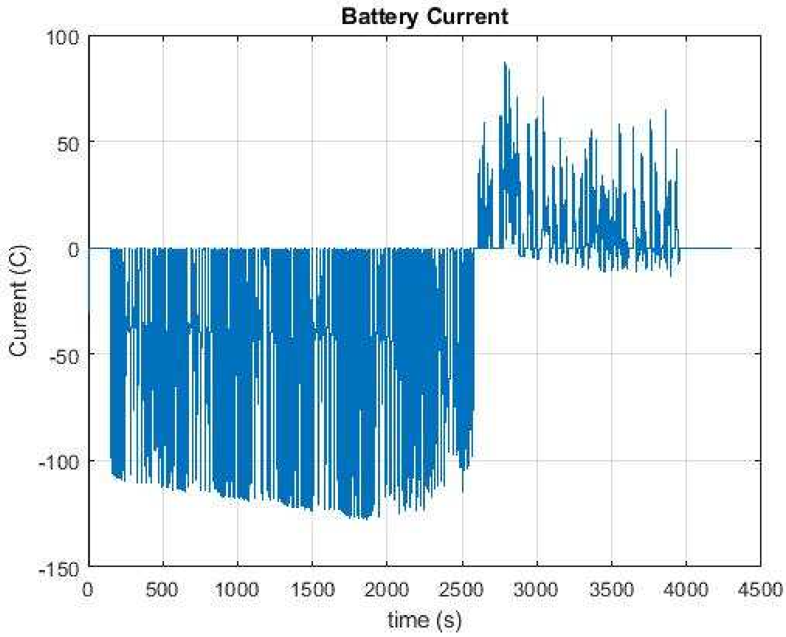


Figure 24: Current Driving Mode

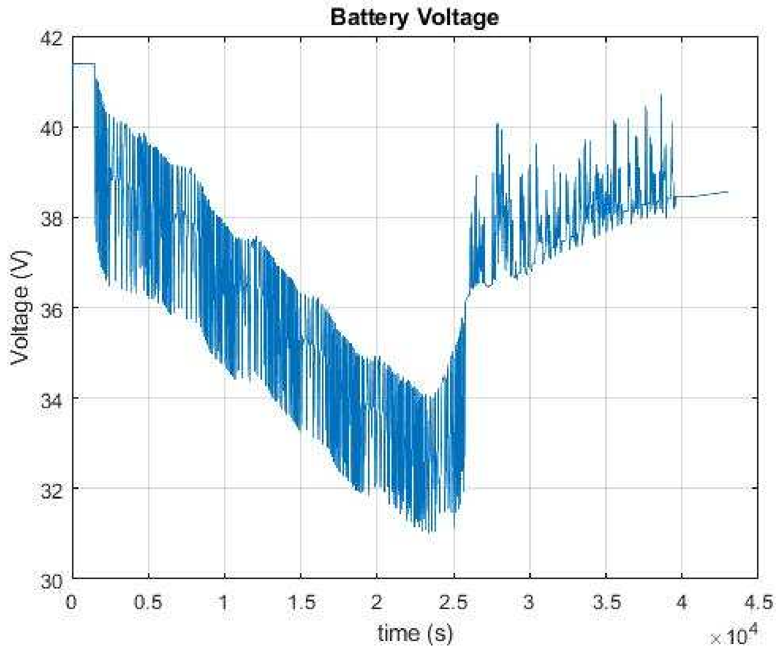


Figure 25: Voltage Driving Mode

In these two graphics (Figure 24)(Figure 25) can be observed the battery behaviour during a driving test where in the first part is applied a discharging method while in the second part there are charging and discharging method mixed. During the discharging part the voltage across the battery decrease due to the fact that its SOC is decreasing reducing its available voltage energy.

4.2 Charging Mode

Fgure 26 showed the charging method applied in the battery model, made of three main phases:

- Constant Current (Low) – CC
- Constant Current (High) – CC
- Constant Voltage – CV

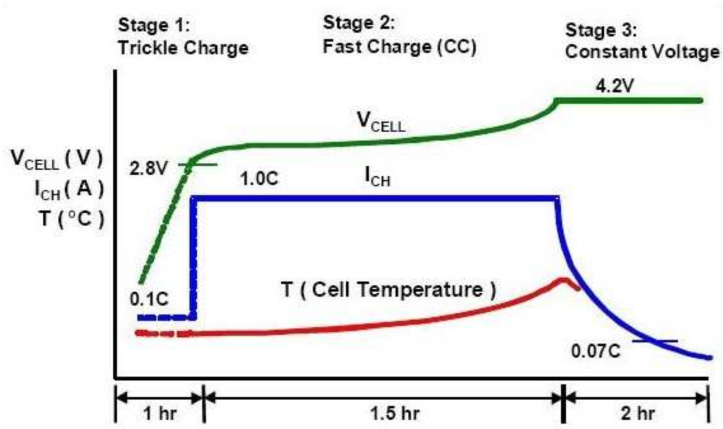


Figure 26: Charging Method

The CC state in the first phase provides a current of 0.1-0.2C while the second state moves on a value of 0.5C for a faster charge.

In the following Simscape state flow (Figure 27) the BMS made exactly the same transitions, passing through a constant current charging mode (CC) to a constant voltage charging mode (CV) based on the parameters of SOC and battery voltage [17].

In addition a third parameter, called 'ChargeTimeOut', is used to detect when the charging has overcome the limit of time and in that case the BMS will make a transition form 'Charging' to 'Fault', stopping the charging execution.

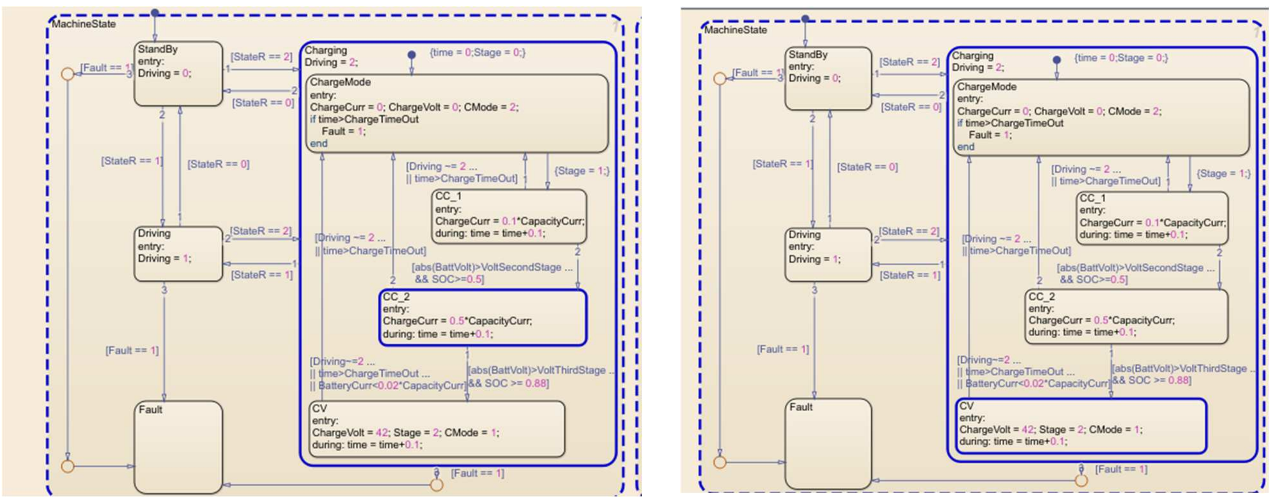
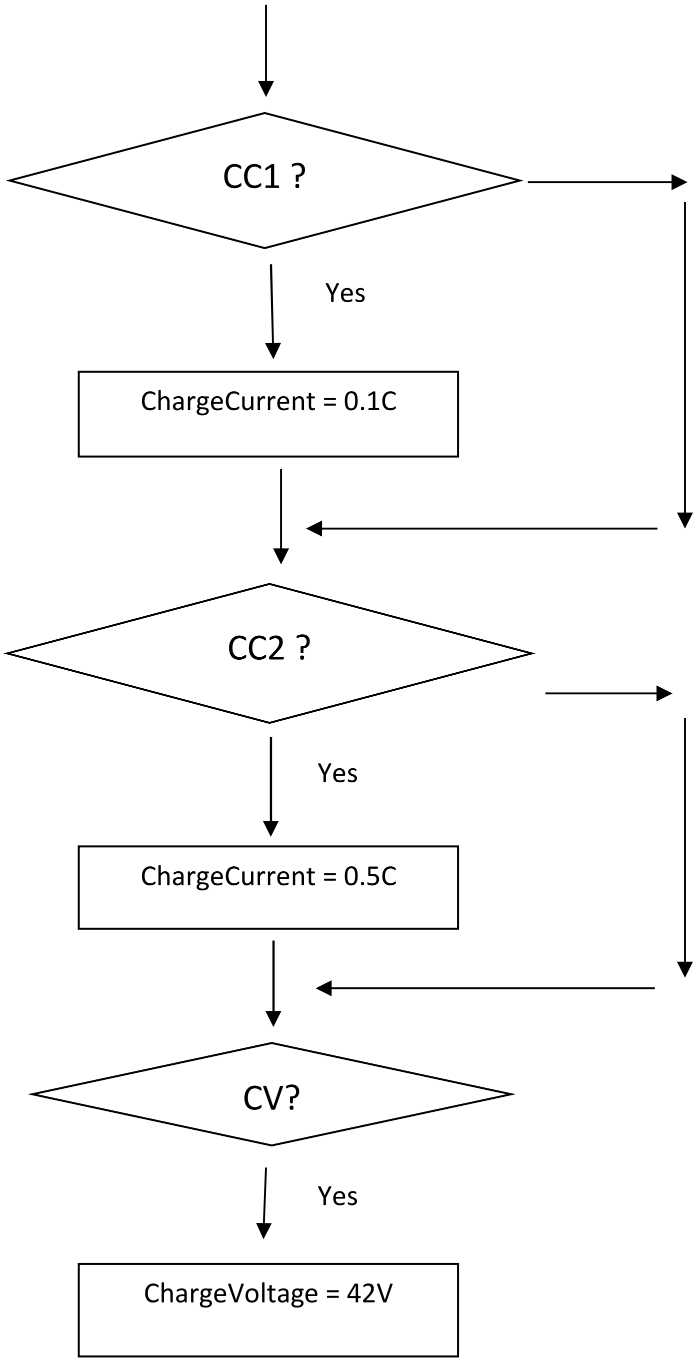


Figure 27: Different Charging Phases on the flowchart (left and right)

In the following is showed a flow chart of how the charging mode works:



When the system enter the charging mode the BMS check in which of the three states it is, based on the SOC level of the battery and on its voltage value.

The charger can have a low constant current, a high constant current or a constant voltage, depending on the state. When the SOC has a low value the initial charger mode is the CC-low, passing then to the CC-high when the state of charge reaches a determined value and the battery voltage is equal to a voltage threshold.

Then it goes to a CV just when the battery is almost at 92-96%.

4.3 Pre charger – Stateflow

Been in a condition of charging mode made the BMS switching OFF the pre-charger dedicated to the inverter and switching ON the one related to the charger. The behavior of the state flow is showed in Figure 28, where the highlighted state are the one which are active.

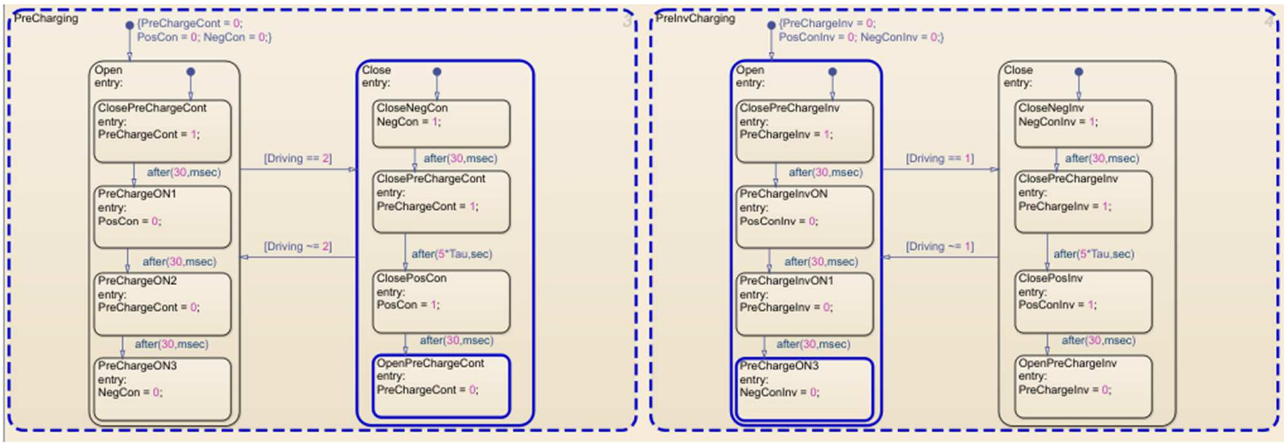


Figure 28: Pre-charger activation for Charging Mode

4.3 Balancing Mode

During the charging mode the BMS control all the significative parameters inside the battery and detect when the balancing mode has been activated, passing from 'BalOff' to 'BalON'. Inside this block the variables 'BalMdlON' and 'BalMdlOFF' are the ones responsible to the switching on/off of the different modules inside the battery to achieve a final levelled energy level (Figure 28).

In order to avoid a too excessive switching on/off a 'delta' parameter has been specified, that is the maximum difference allowed between the different modules.

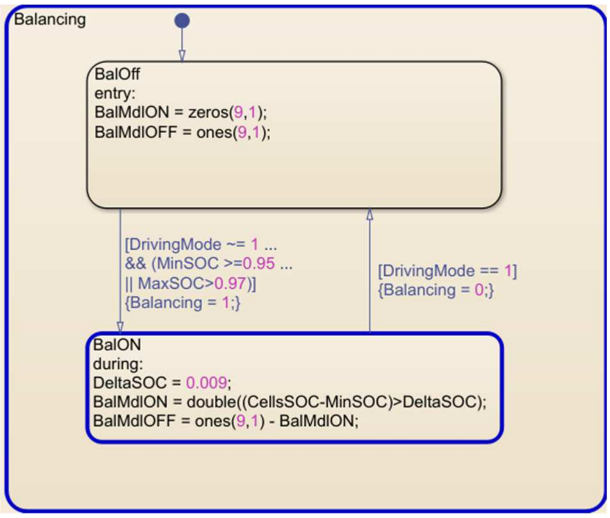


Figure 29: Balancing levelling activation

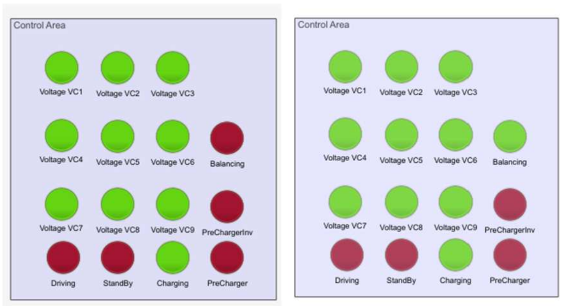


Figure 30: Balancing flag activation

In the 'ControlArea' (Figure 29) can be noted that 'Balacing' become green when the 'BalON' become active.

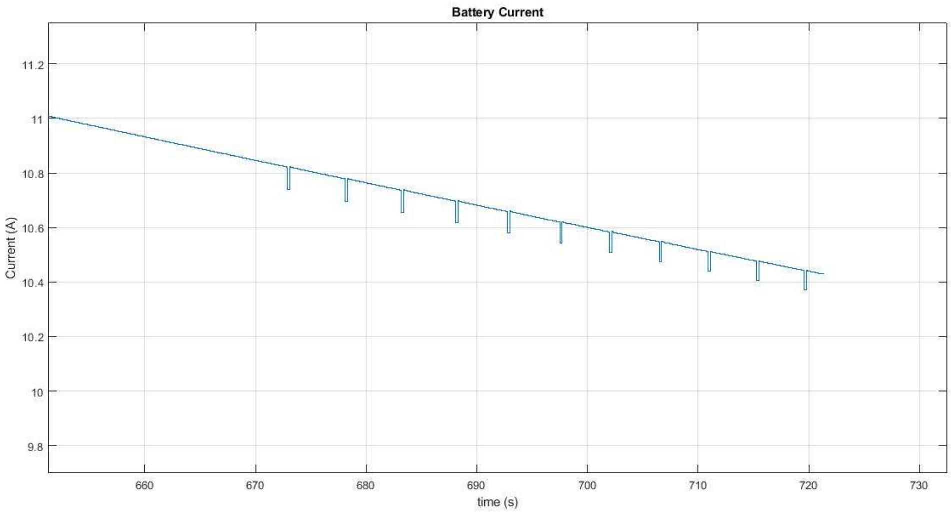


Figure 31: Some low ripple in the current due to balancing activation

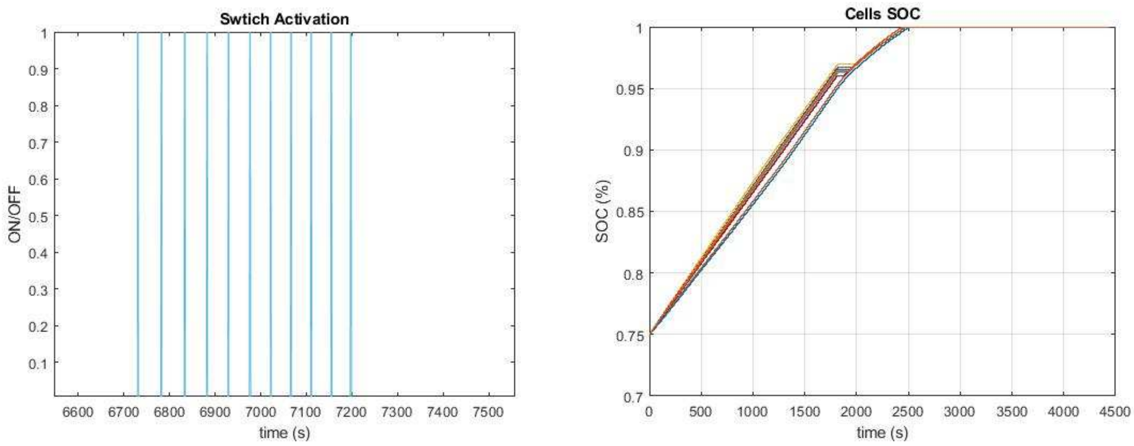


Figure 32: Balancing activation ON/OFF in the modules (left) and SOC convergence (right)

In the charging mode can be appreciated the balancing activation. Indeed, can be seen how the SOC of the different modules converge into a limited bound area reducing the initial gap between them (Figure 30).

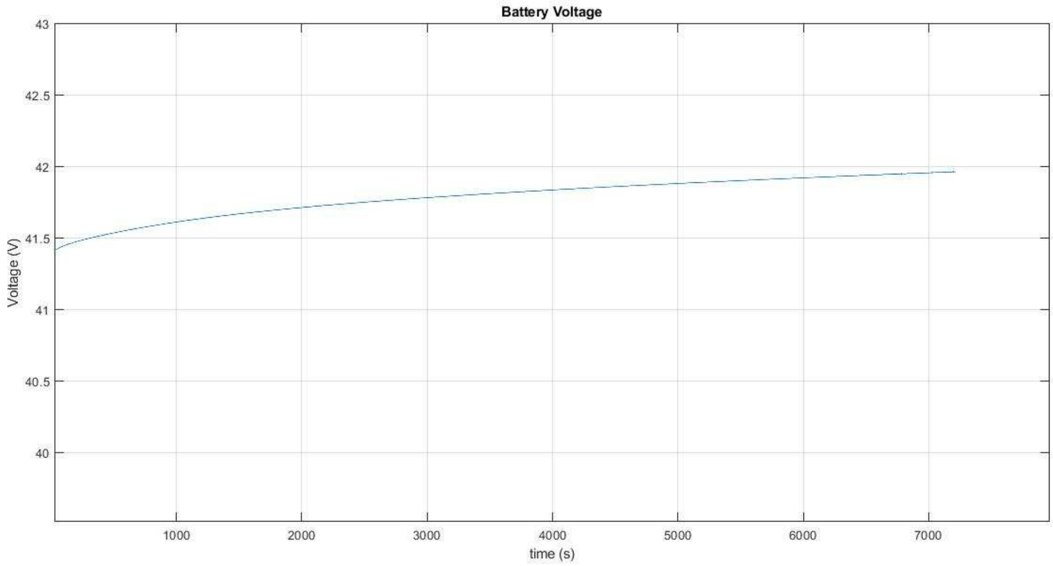


Figure 33: Voltage behaviour during charging phase and balancing activation

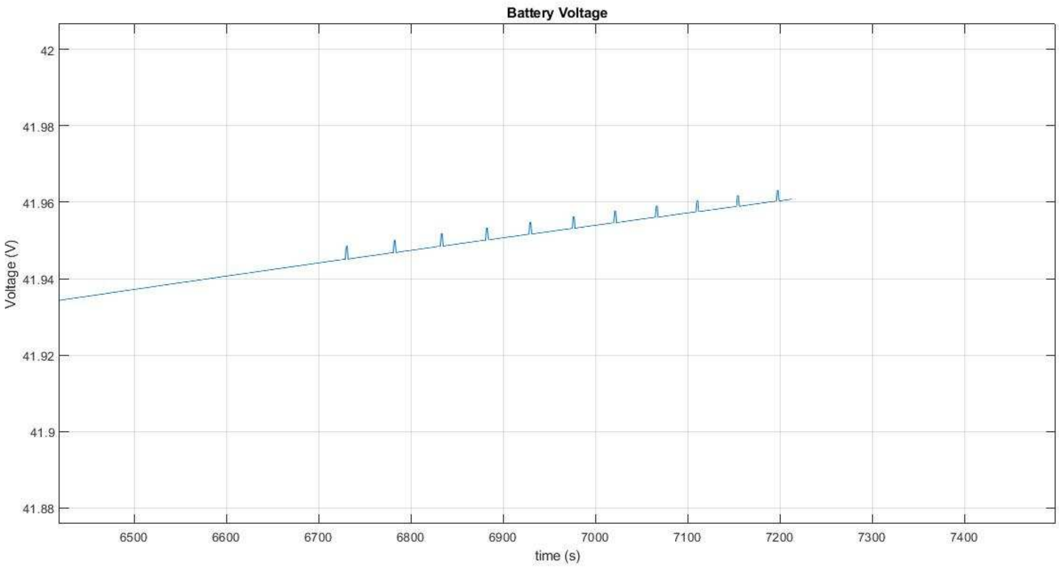


Figure 34: Some low ripple in the voltage due to balancing activation

Instead in the pictures above can be appreciated the voltage behaviour during the charging mode. It increases until reaching the final value of 42 V (100% SOC)(Figure 33)(Figure 34).

Chapter 5

Main issues inside battery faced from BMS

inside the Li-ion battery pack there are still some aspects which can cause critical problems and damage to the battery itself [18].
Among these the most particular treated in the thesis are:

- Over-charge – Over-discharge: undesirable chemical reactions;
- State of Health (SOH): capacity of the battery during its life cycles;
- Temperature: issues and damages that low/high temperature can cause to the battery pack;
- State of function (SOF): capability of the battery to satisfy power demands in different conditions of SOC and SOH;

5.1 Overcharge – Overdischarge

When a battery is in overcharge as well as in over-discharge electrical abuse can be experienced causing undesirable electrochemical reaction.
This can happen during the charging mode since the modules inside the battery pack can have slightly different SOC and the ones with higher SOC can be overcharged if the BMS does not monitored the battery in an accurate way.
Due to the overcharging electrolyte decomposition can be involved at the cathode interface leading to an increasing temperature.
In a similar way behave the battery in an over-discharging situation where the cells forced to continue to discharge leading to a drop voltage and causing possible short circuits inside the battery pack.
To avoid this situation a balancing mode has been purpose (4.3) in order to guarantee that the difference between the highest and slowest SOC are inside a limited percentage.
Moreover in order to delete unwanted peak current, both in charge and discharge cases, a dedicated controller is considered. Its main scope is to open the circuit of the modules of the battery pack with the use of switches whenever the current inside the single module is outside the safe range (Figure 34).

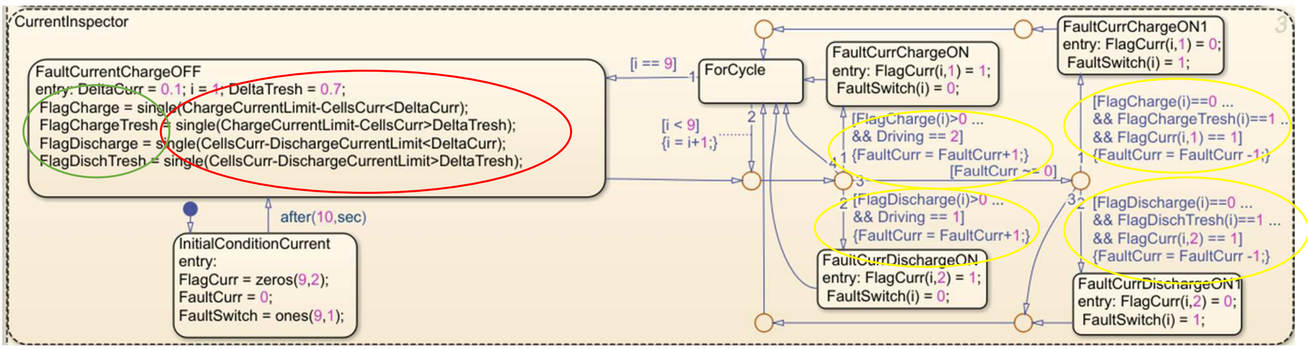


Figure 35: Fault current detector

Figure 35 showed the scheme of control actions and decisions to have the current inside the safe range. The main variables are related to the measured current during the case of charge and discharge.
Whenever the input is over or under the range a flag will turn from '0' to '1' inside the controller and the BMS will act on the corresponding switch avoiding current to flow inside that module.
When the current return inside the safe range then the flag will turn again to '0' and the BMS will allow the current to flow again inside the module previously closed.
In the following image (Figure 36) instead the scheme of actions and decisions referred to the voltage control is showed.
Moreover in the current scheme (Figure 35) are highlighted different parts of the controller:

- in the red circles comparison takes place between the values captured by the sensors and the limit we are imposing;
- in the green circles decision variables take the values of '1' or '0' depending on the result between the comparison;
- in the yellow circles the check of these decision variables is performed and whenever their value is '1' the BMS activates the corresponding switch inside the battery.

As in the current case the BMS turn off the switches whenever the battery reaches unwanted values of voltage and turn them on when they return inside allowed values.

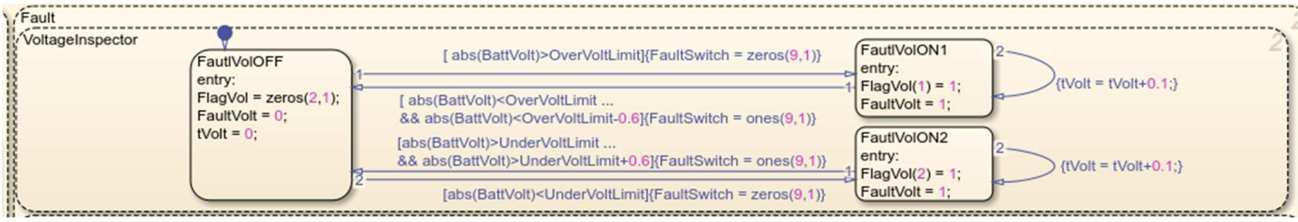
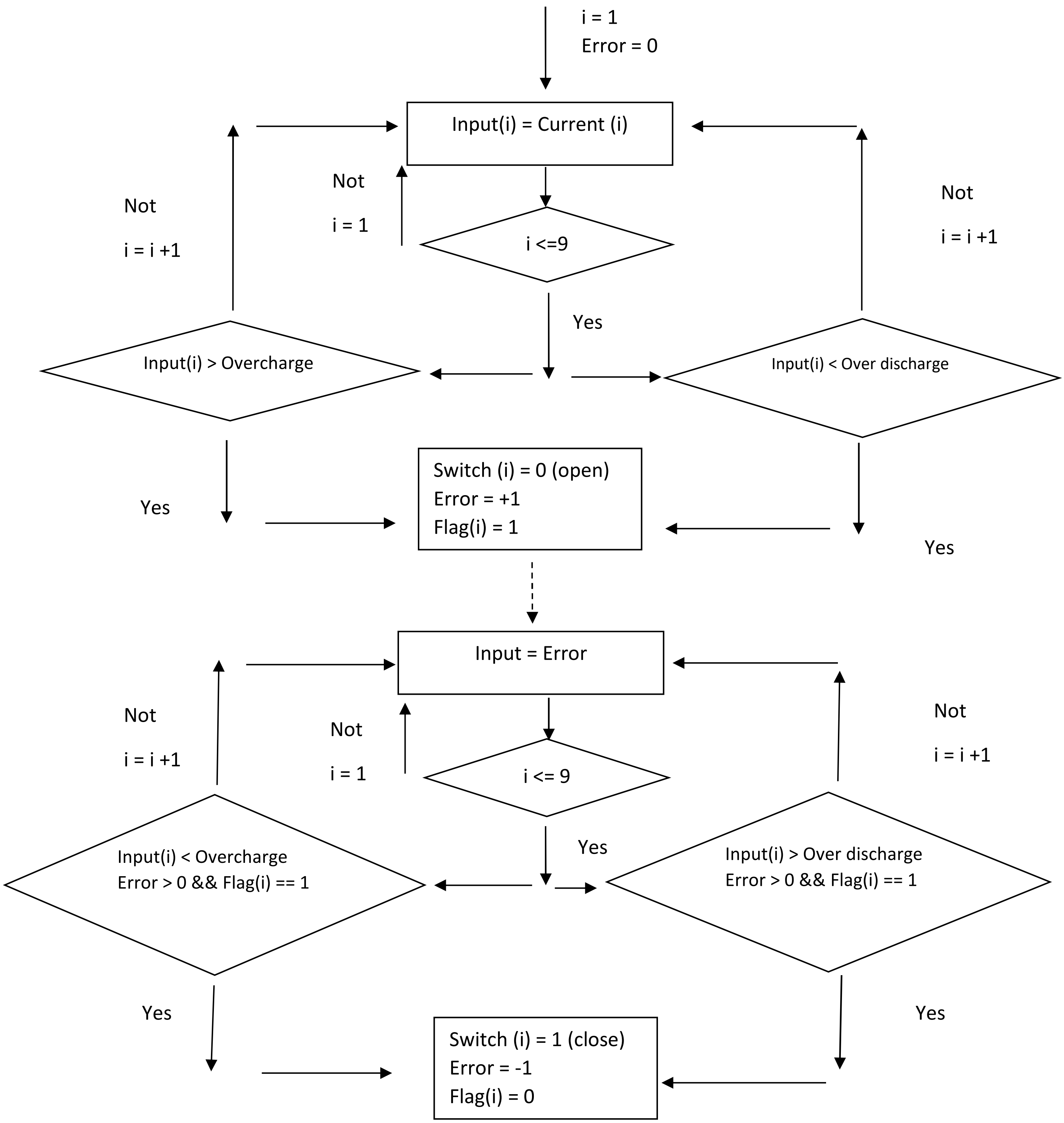


Figure 36: Voltage fault detector

To avoid problems of ripples in both cases of current and voltage faults a threshold is considered. In this way the BMS will prevent the continuous switching inside the battery due to the noise that can found inside the current (voltage) sensors, applying a smoother control action.

In the following is showed a flow chart of how the controller check the current:



As first fault check inside the flowchart there is the volt inspector where is performed the test of the BMS during the voltage control. The two main cases are represented, as follow:

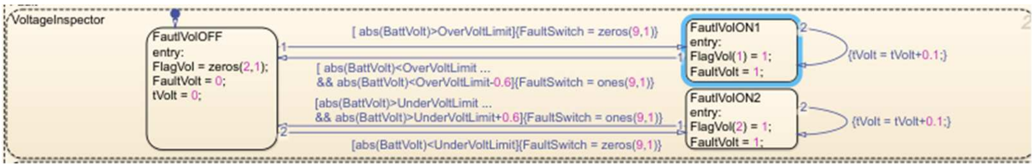


Figure 37: Over-Voltage fault detector

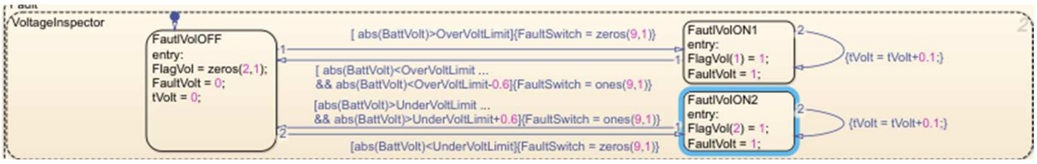


Figure 38: Under-Voltage fault detector

In the following instead the test of the BMS is carried out during the current control and more precisely they represent the four main cases can be found. In order:

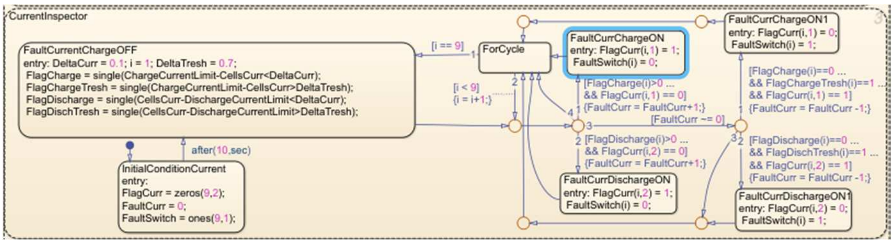


Figure 39: Over-Charge fault detector

Overcharge fault tested, the corresponding module is switched OFF;

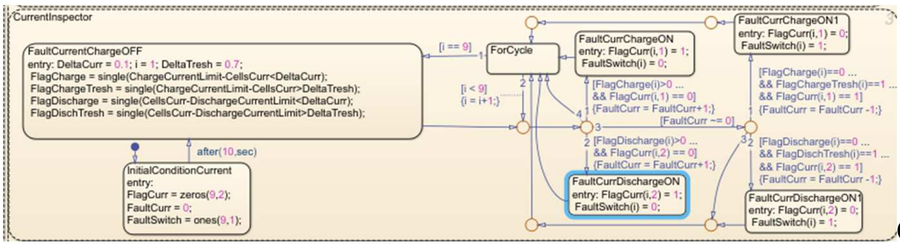


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Figure 40: Over-discharge fault detector

Over discharge fault tested, the corresponding module is switched OFF;

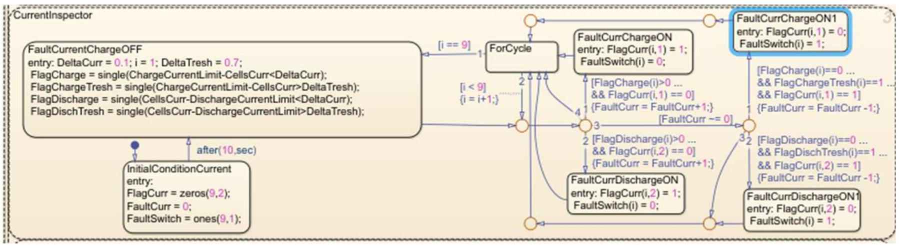


Figure 41: Over-Charge not fault detector

Current of case 1) is again inside the range so the switch inside the module is ON again;

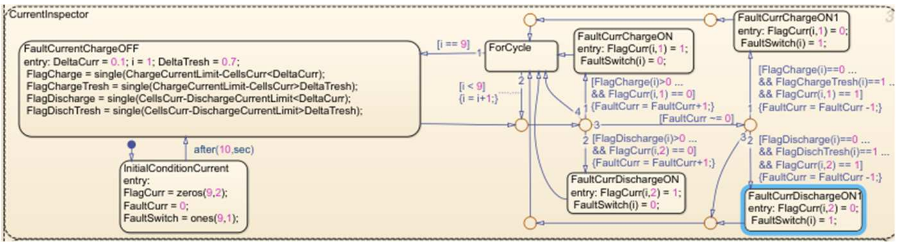


Figure 42: Over-Discharge not fault detector

Current of case 2) is again inside the range so the switch inside the module is ON again;

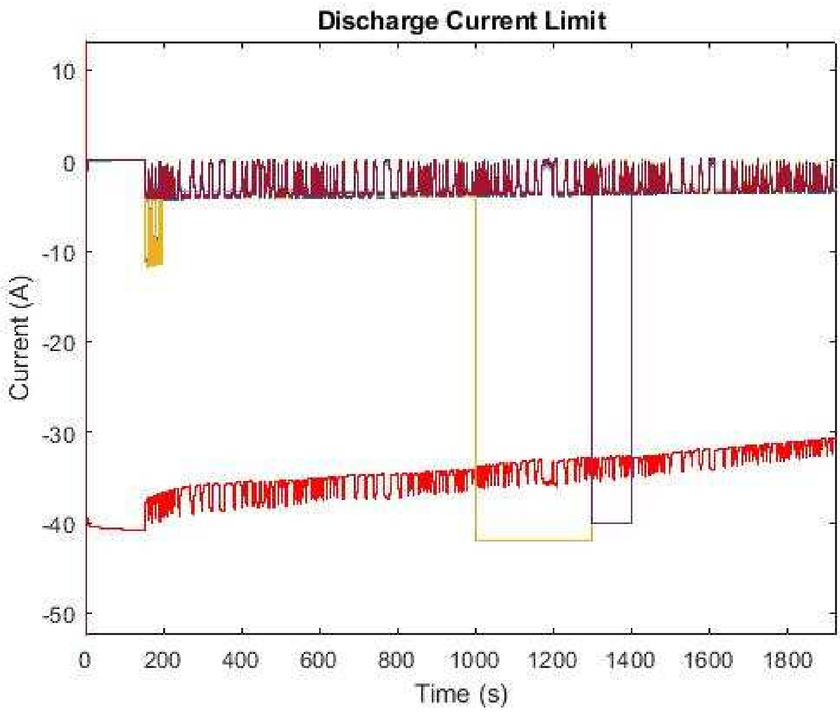


Figure 43: 1-Discharging test BMS

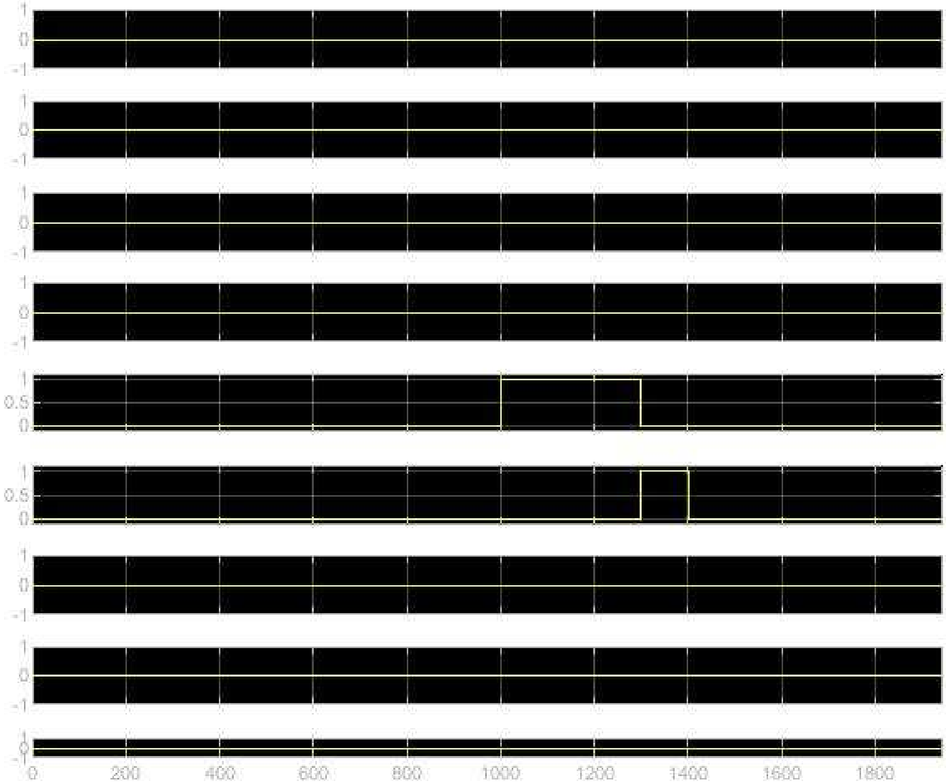


Figure 44: Discharge Flag BMS activation

The discharging case is considered (Figure 43) in the example above where the behaviour of the different switches inside the battery, controlled by the BMS.
The red line is the current limit that cannot be passed during the test and whenever it happens the BMS immediately switch off the module to avoid any dangerous situation, switching it on just when it turn back to safe values (Figure 44).
An example of charging case is considered instead in the following pictures with the same considerations related to the BMS in the discharging case (Figure 45)(Figure 46).

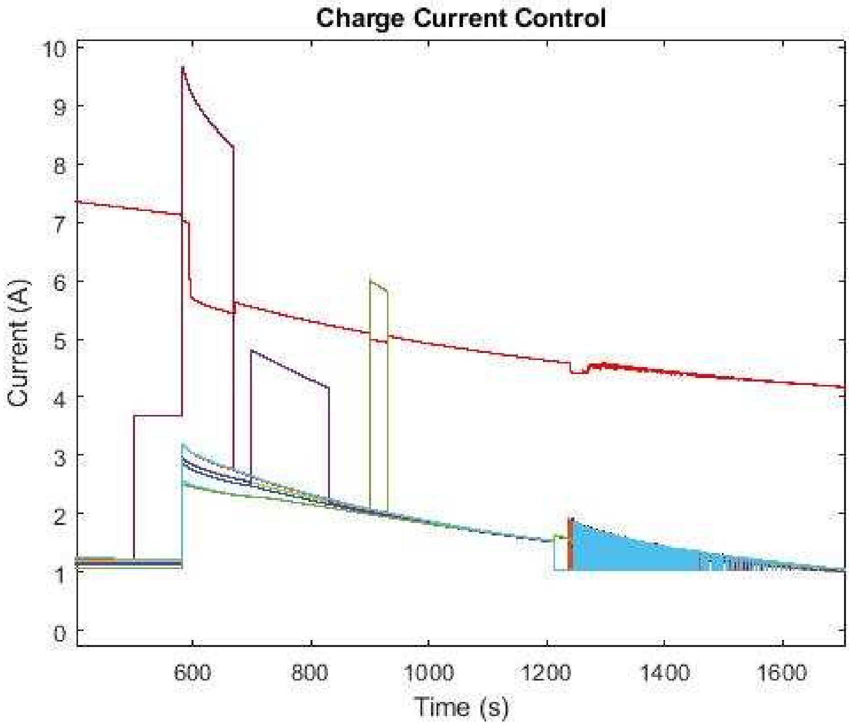


Figure 45: 1-Charging test BMS

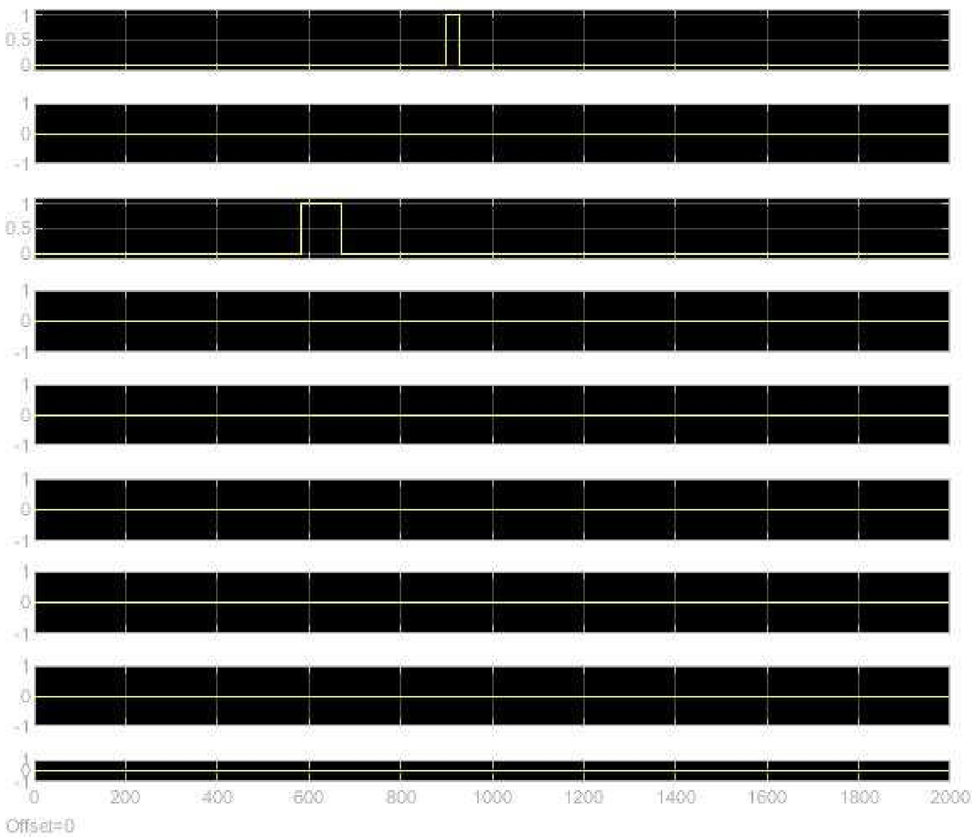


Figure 46: Charge Flag BMS activation

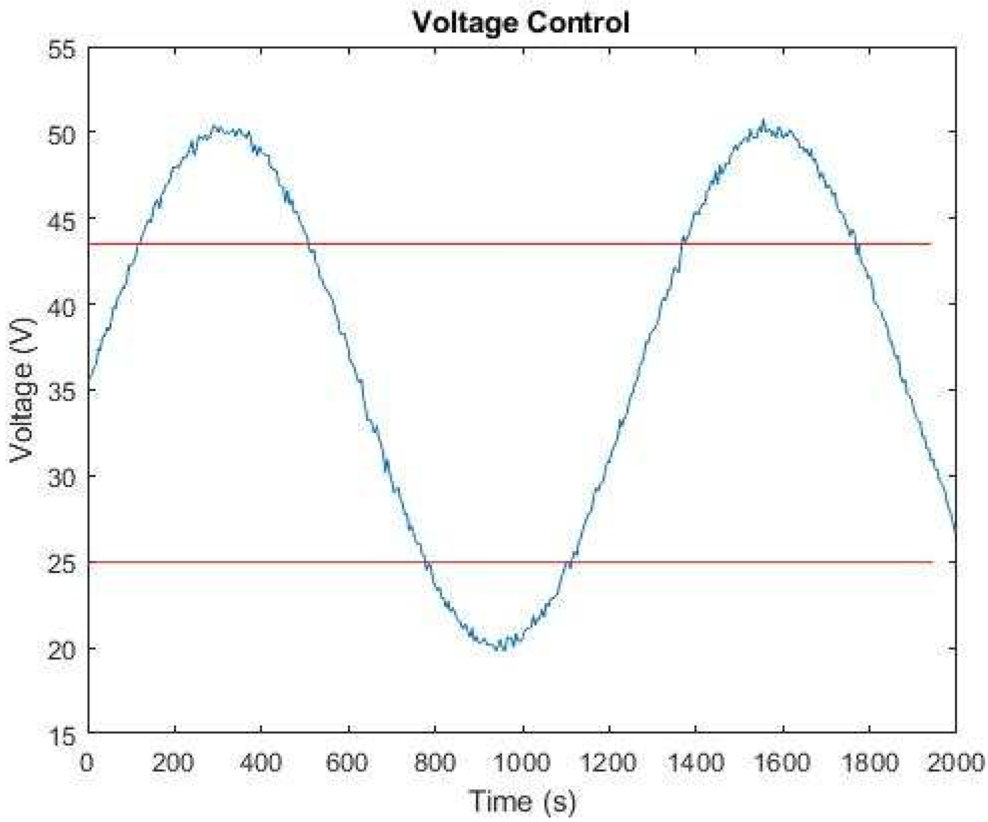


Figure 47: 1-Voltage test BMS

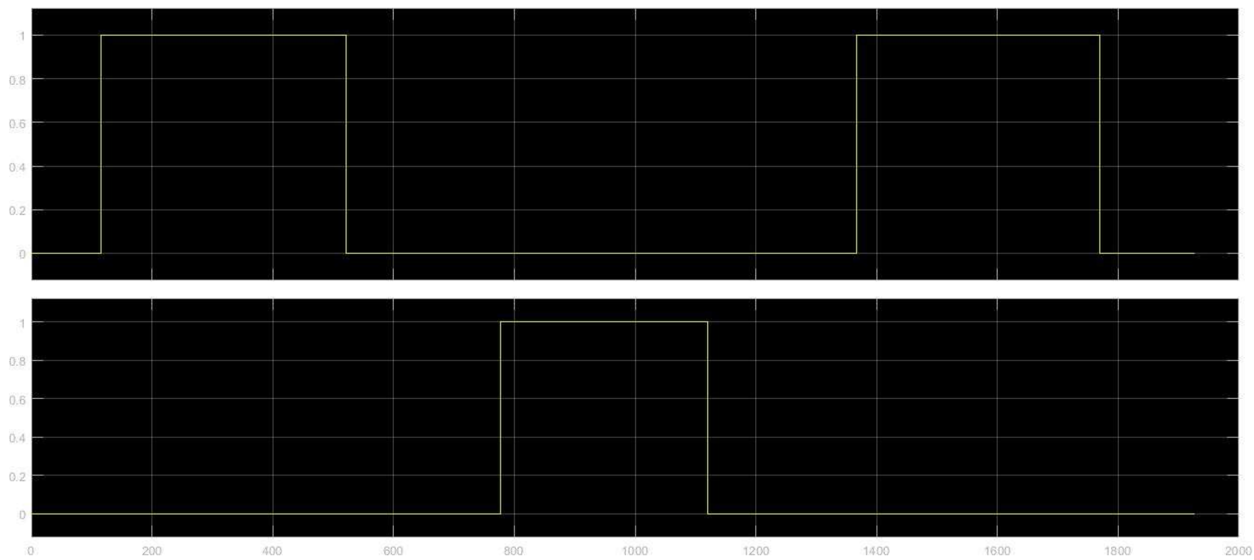


Figure 48: Voltage Flag BMS activation

In the previous two images a voltage fault check was performed to see how the BMS acts when values over (under) the range are captured by the sensors (Figure 46).
As in the current case the BMS switch off or on the battery to ensure a correct behaviour of the battery, avoiding unwanted phenomena (Figure 47).

5.2 State of Health (SOH)

The SOH's issue is related to the aging of the battery since its initial capacity (100%) decreases among the time (<100%). Indeed, each cycle of charge/discharge drains the battery from its ideal situation of full capability. Moreover, if the BMS does not work properly other problems as temperature and unbalancing SOC between the modules can drop the capacity quicker [19].
Related to the SOH there is also the problem of power performances of the battery since the more its percentage drop down the less the total power we can obtain as well as current.
This mean that if we don't have an estimate of the SOH, it can occur a dangerous situation in which supply and demand can't satisfy each other.
The simplest way to represent the state of health is:

$$SOH = \frac{C_{max}(t)}{C_{(0)}}$$

Where $C_{max}(t)$ represent the total available capacity at time "t" while $C_{(0)}$ is referred to the total initial capacity (at time zero).
The SOH can also be split in two different aspects that are related each other:

- SOH capacity: referred to the ampere-hour (Ah) the battery can provide to the vehicle.
- SOH impedance: referred to the internal resistance of the battery which increase during its life cycles of charge/discharge causing a deterioration of the initial full capacity.

The following picture (Figure 49) shows a usual behaviour of the battery and we can immediately see that going towards higher number of cycles the capacity drop while the internal resistance increase causing worst performance.

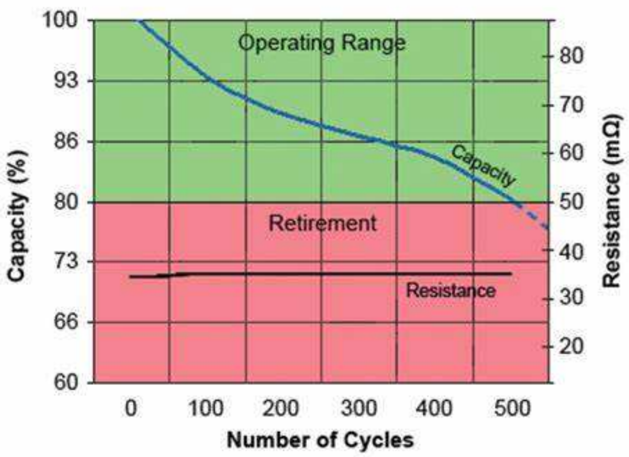


Figure 49: Capacity vs Number of cycles

5.3 Temperature

The temperature inside the battery pack is a critical aspect since it can drop really fast the performances of the battery if not well managed and it can be an accelerometer for the SOH degradation [18].

Every battery manufacturer gives a range between which the battery can work properly and exceeding this safe zone (lower/higher temperature) can damage the battery deeply (temporary or permanently).

For example, going towards low temperature can temporarily reduce the total capacity even of the 40/50% while higher temperature can lead to temporary higher total capacity (10/20%) but at the same time it can reduce the chemical reactions efficient inside the battery causing a fast degradation and possible explosion since unstable chemical reaction can be involved.

Moreover, since each single module inside the battery pack is not affected by the same identical situation the BMS has to be able to detected the different heating situations giving a proper response in term of cooling/heating system for each zone under control.

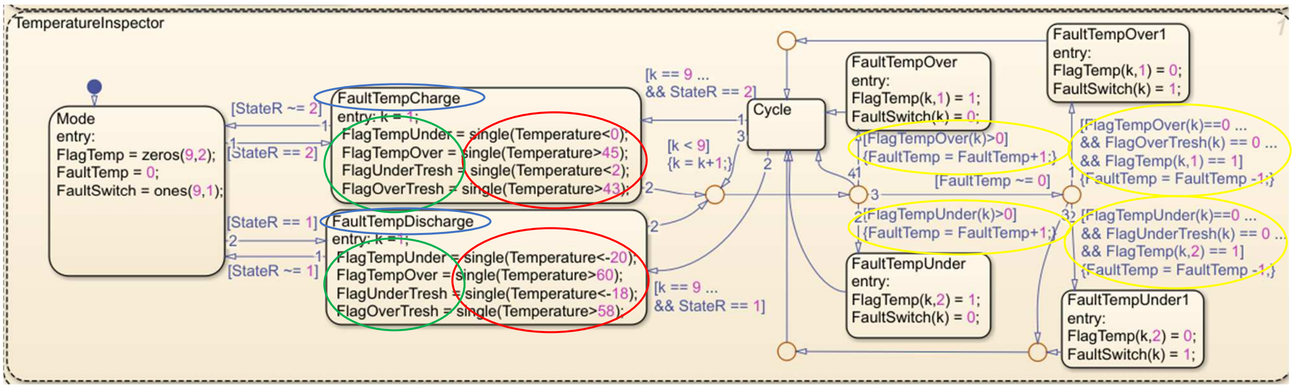


Figure 50: Specific temperature fault detector

The scheme above (Figure50) illustrates the functioning of the BMS related to the temperature control and its corresponding actions in the different situations.

Since the temperature limits are not the same in the charging and discharging phase, two blocks have been implemented, one for each case, based on the driving mode considered.

Figure 51: Temperature limits faults

Whenever the temperature goes over or under the specified limits inside one or more modules the BMS switch it off until its value does not go back inside the allowed range. Again, a threshold was considered in order to avoid any kind of ripples due to the sensor noises.
Moreover, in the scheme are highlighted different parts of the controller:

- in the red circles the comparison between the values captured by the sensors and the limit imposed;
- in the green circles the decision variables that take the values of ‘1’ or ‘0’ depending on the result between the comparison;
- in the yellow circles we have the check of these decision variables and whenever their values is ‘1’ the BMS activates the corresponding switch inside the battery;
- in the blue circles are just highlighted the two blocks related to the charging and discharging phases.

In the images below we have the test of our BMS during the temperature control and more precisely they represent the four main cases we can found out. In order:

1) Over temperature fault tested, the corresponding module is switched OFF;
2) Under temperature fault tested, the corresponding module is switched OFF;
3) Temperature of case 1) is again inside the range so the switch inside the module is ON again;
4) Temperature of case 2) is again inside the range so the switch inside the module is ON again;

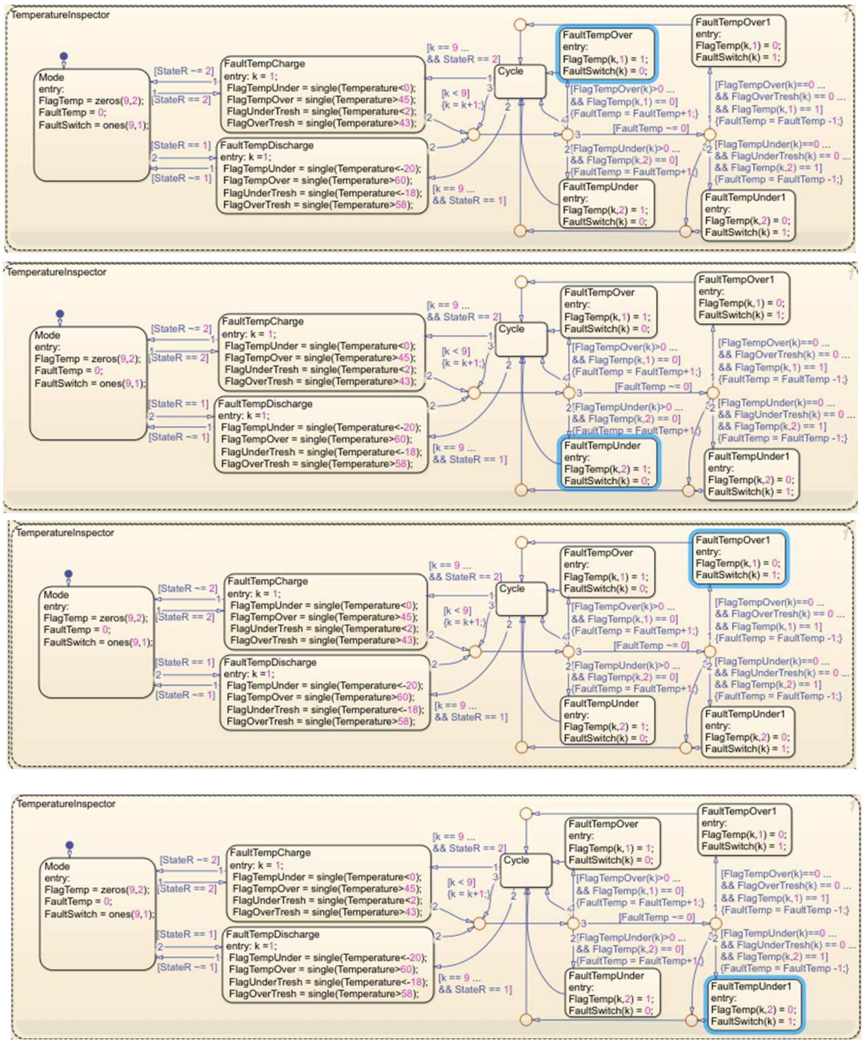
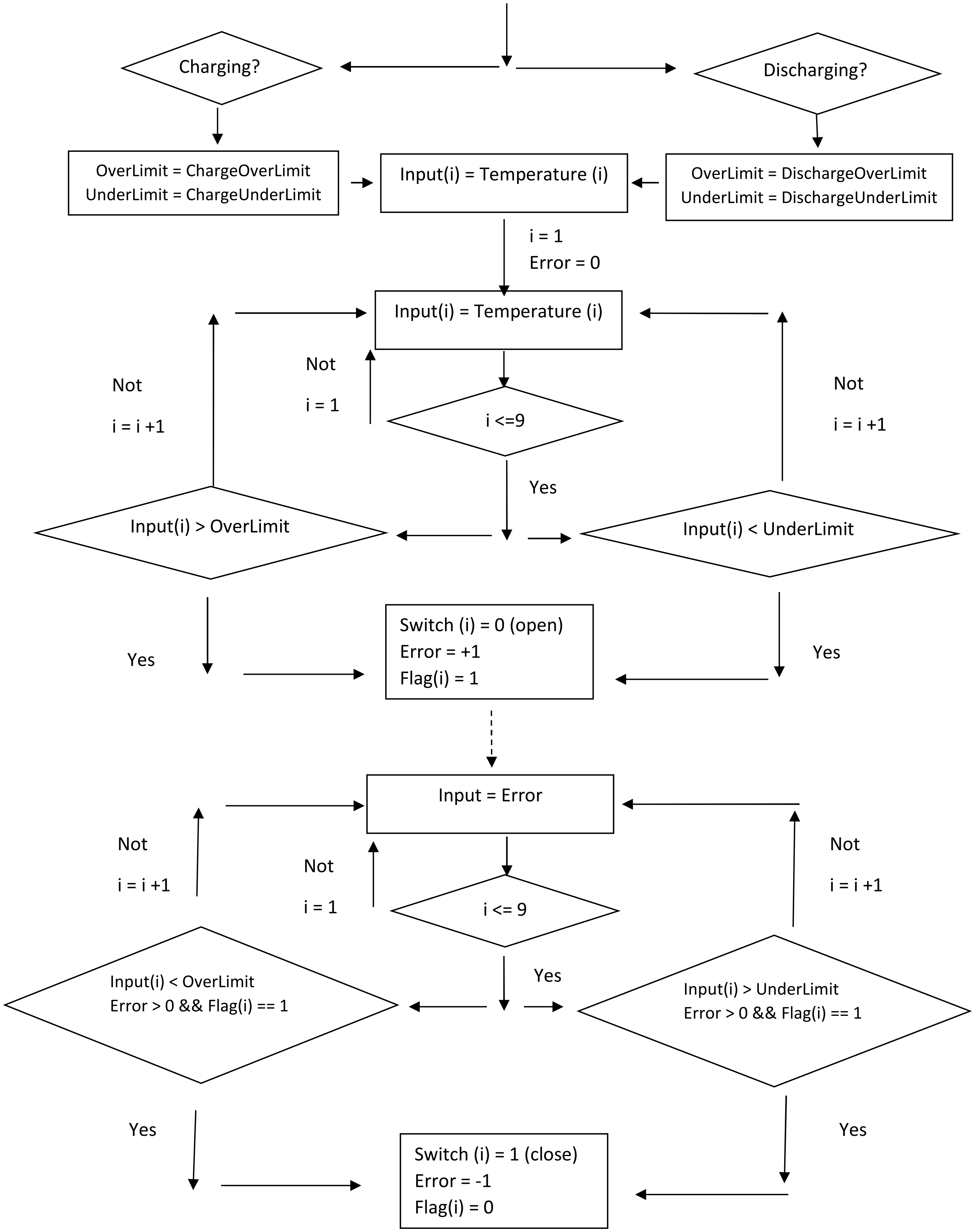


Figure 52: Different Fault test – Over/Under temperature with returning to safety range

In the following is showed a flow chart of how the controller check the temperature:



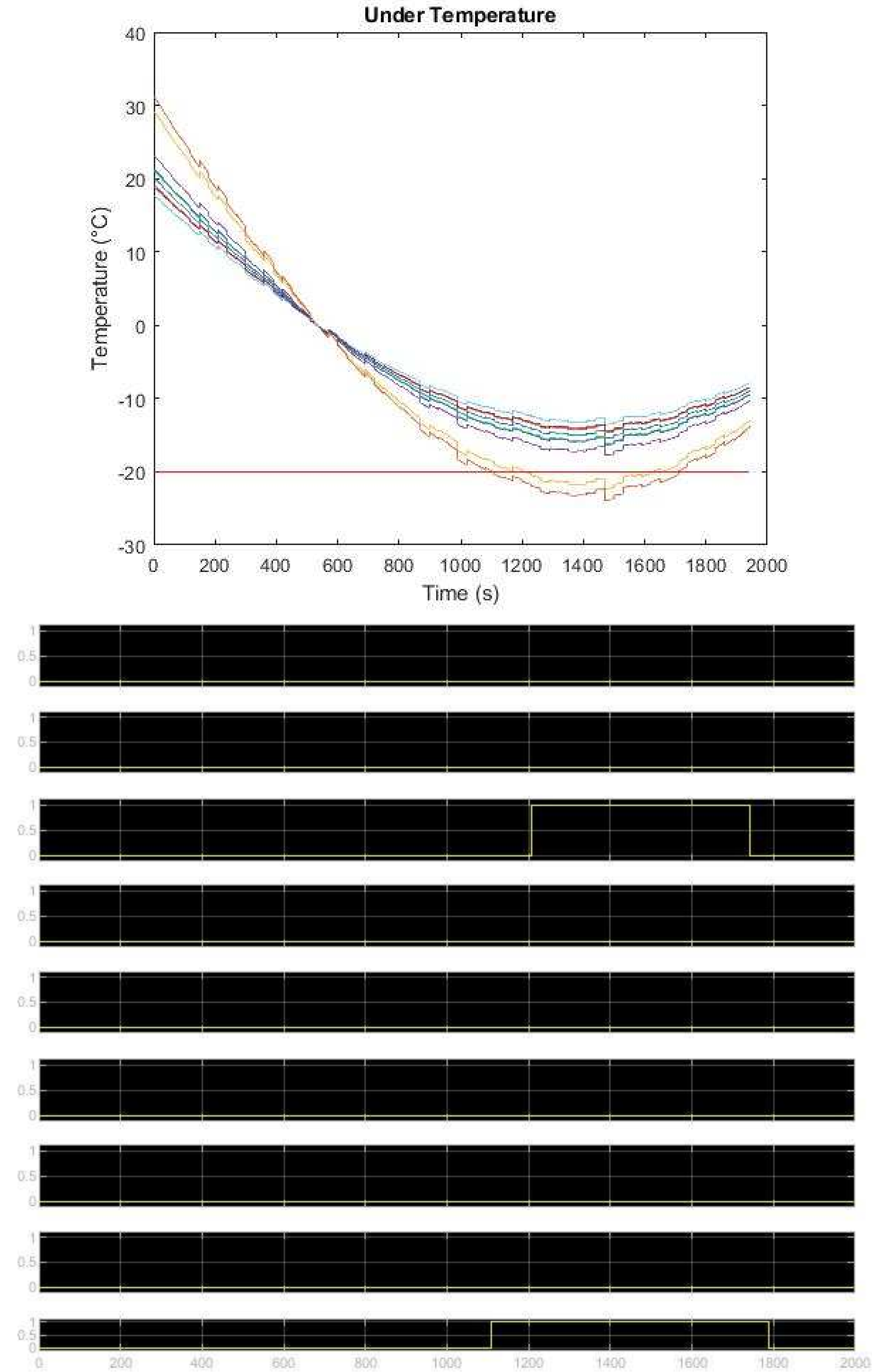


Figure 53: Temperature limits test (upper) and flag detection (lower) – low temperature

In the previous image a temperature fault check was performed to see how the BMS behave when values over (under) the range are captured by the sensors.
In the second image we can see the switch activation during the period of unwanted low temperature until it goes backs to -20°C.

A similar temperature fault check was performed in the case of high temperature and even in this case it was observed the good reaction of the controller that switch off the dangerous modules as expected (Figure 54).

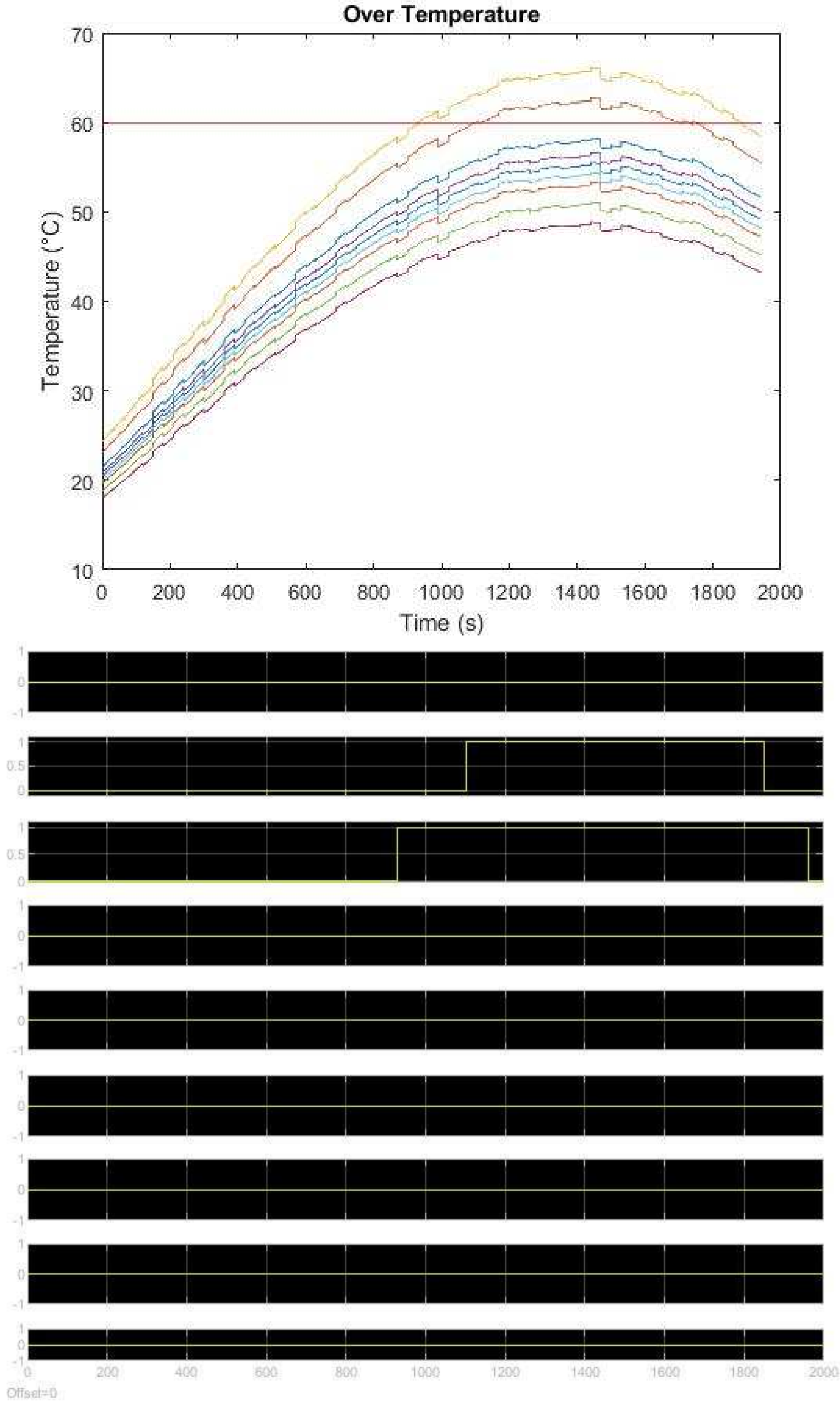


Figure 54: Temperature limits test (upper) and flag detection (lower) – high temperature

5.4 State of Function (SOF)

As we previously told the SOC describes how far the battery is from its fully charged condition while the SOH describes how far the battery is from its fresh capacity.
The state of function (SOF) is used to describe how the battery performance meets the vehicle demands and it is determined by the SOC, SOH and operating temperature [19].
The SOF could be defined in different ways, depending on what we're focusing on:

- the ratio of the remaining available energy in the battery and the maximum possible energy could be stored in the battery.
- as a yes/no logical variable inside systems which requires specific supplied power where the SOF describe if the battery meets the power demands: a value equal "1" means the battery could meets the demands while "0" means not.

At least a possible way to define the SOF in a useful way is:

$$SOF = \frac{P - P_{demands}}{P_{max} - P_{demands}}$$

where P means the possible power the battery could supply, $P_{demands}$ means the demands of the power, and the P_{max} means the maximum possible supplied power of the battery.
This give us the possibility to see (even in the case $P > P_{demands}$) how much far we are from the best possible situation in which $P = P_{max}$
In the following a graphical representation of the relations between SOF, SOC and SOH is showed (Figure 55).

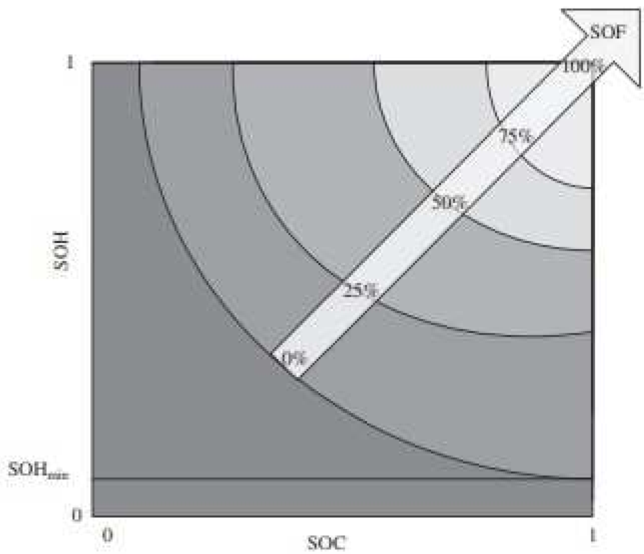


Figure 55: Relation between SOH, SOF and SOC (Source: Ping Shen, Minggao Ouyang, Languang Lu, Jianqiu Li, Member, IEEE, and Xuning Feng. *Co-estimation of State of Charge, State of Health and State of Function for Lithium-Ion Batteries in Electric Vehicles.* IEEE Transactions on Vehicular Technology, vol. 67, No. 1, January 2018)

Another possible way to define the SOF is:

$$SOF = \frac{P_{max}}{P_{max,0}}$$

Where P_{max} is the maximum discharge power that the battery can support, and $P_{max,0}$ is the initial maximum discharge power of the battery when it leaves the factory. The physical meaning of SOF is clearly defined as the ratio of the current power output capacity of the battery to the initial one.

The SOF is strictly related to the possible maximum charging/discharging current and voltage the battery can develop in a specific moment as well as long distance terms, for example. Indeed, it is crucial to know whether a certain action can be performed or not, such as tackling a certain slope or having enough power to get a certain distance maintaining a specific speed.
Several methods have been studied in the last years and among all of them a nice interest has the co-estimation of SOC, SOH and SOF.
Without going deep in this section, a fast view on state of health definition is considered.
The battery SOH is set as 100% when the battery is fresh and 0% when the capacity decreases to a specific lower level decided by the user, in this case for example a 70%. Assuming the capacity of the battery at time t_0 to be C_n (full capacity) and the current capacity to be C, the battery SOH can be defined by:

$$SOH = (C/C_n - 70\%)/30\%$$

Presuming V_{max} and V_{min} are the voltage limits, the maximum available current ($I_{max,t}^{charge}$, $I_{max,t}^{discharge}$) under the voltage limits are calculated by (1) and (2), where OCV could be obtained by the SOC estimation results through a look-up table, and the resistance R0 can be identified, for example, by a recursive least square algorithm, used inside the SOH estimation. Taking the current limits into consideration, the maximum available charge/discharge current is determined by (3) and (4), where $I_{max,limit}^{charge}$ and $I_{max,limit}^{discharge}$ are the current thresholds given by the supplier (Figure 56). The maximum available charge/discharge power is predicted by (5) and (6), based on the model below [18].

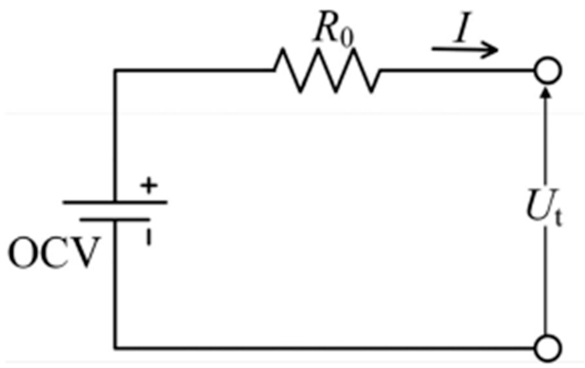


Figure 56: Electric circuit - SOH

$$I_{max,t}^{charge} = \frac{V_{max} - OCV}{R_0} \tag{1}$$

$$I_{max,t}^{discharge} = \frac{OCV - V_{min}}{R_0} \tag{2}$$

$$I_{max}^{charge} = \min\left(I_{max,t}^{charge}, I_{max,limit}^{charge}\right) \tag{3}$$

$$I_{max}^{discharge} = \min\left(I_{max,t}^{discharge}, I_{max,limit}^{dicharge}\right) \tag{4}$$

$$P_{max}^{charge} = I_{max}^{charge}\left(OCV + I_{max}^{charge} R0\right) \tag{5}$$

$$P_{max}^{discharge} = I_{max}^{discharge}\left(OCV - I_{max}^{discharge} R0\right) \tag{6}$$

5.5 No load battery state

Another possible error that can occur inside the system is an unbalanced battery state when no load is connected and in this case inside the modules the SOC could have different values.
Anyway, if the battery is correctly connected and the BMS works properly the initial unbalanced phase would end up with a balanced one since the modules with a higher SOC will lower their values until they reach the other ones.
To recreate this kind of situation some examples have been simulated where the battery has been discharged at different level of SOC and then the system has been opened as it was connected to any load.

First example

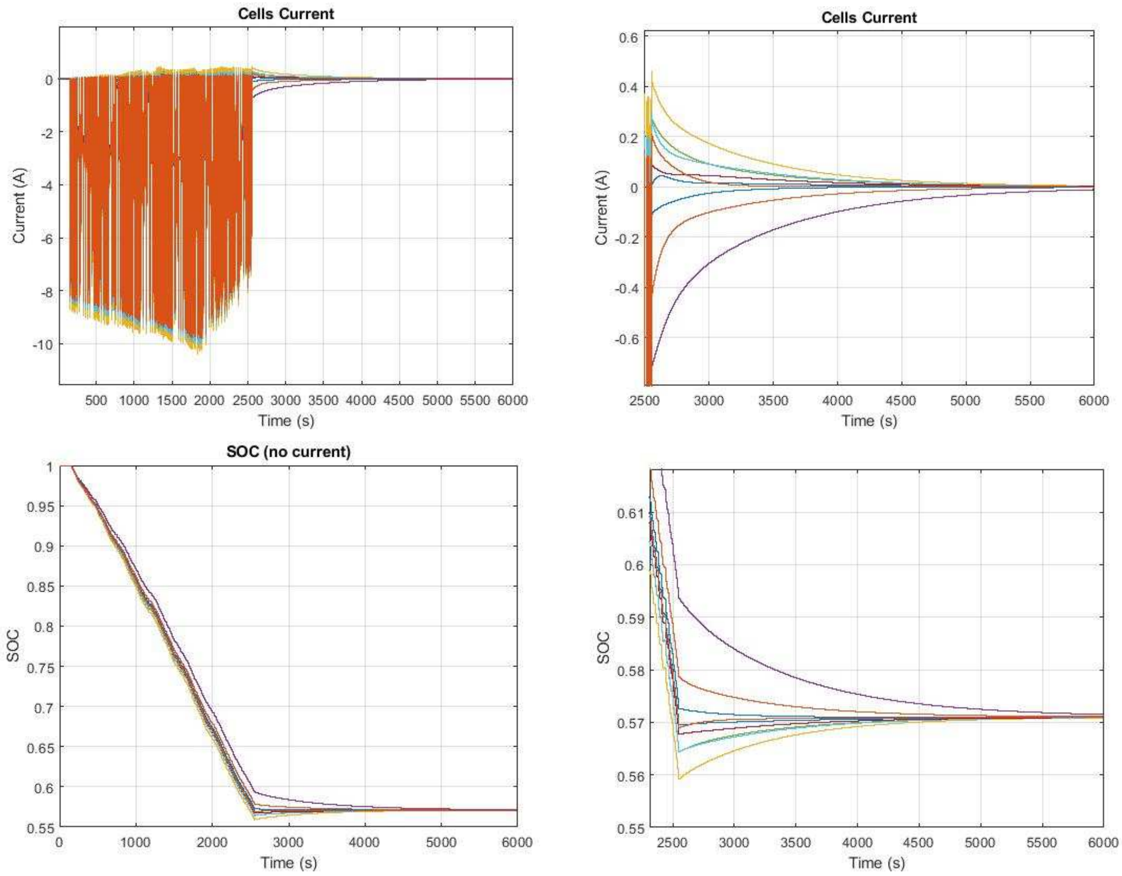


Figure 57: 1 - Flow current inside the battery during the balancing (upper) and SOC balancing (down)

The SOC in this case is about 0.6 to 0.56 when the load is detached from the system and as it was expected the initial differences between each single modules in terms of state of charge tends to zero over time (Figure 57).
This is also reflected in terms of currents since although the load is not anymore present a passage of small currents persists until the modules reach an equilibrium in terms of charge.

Second example

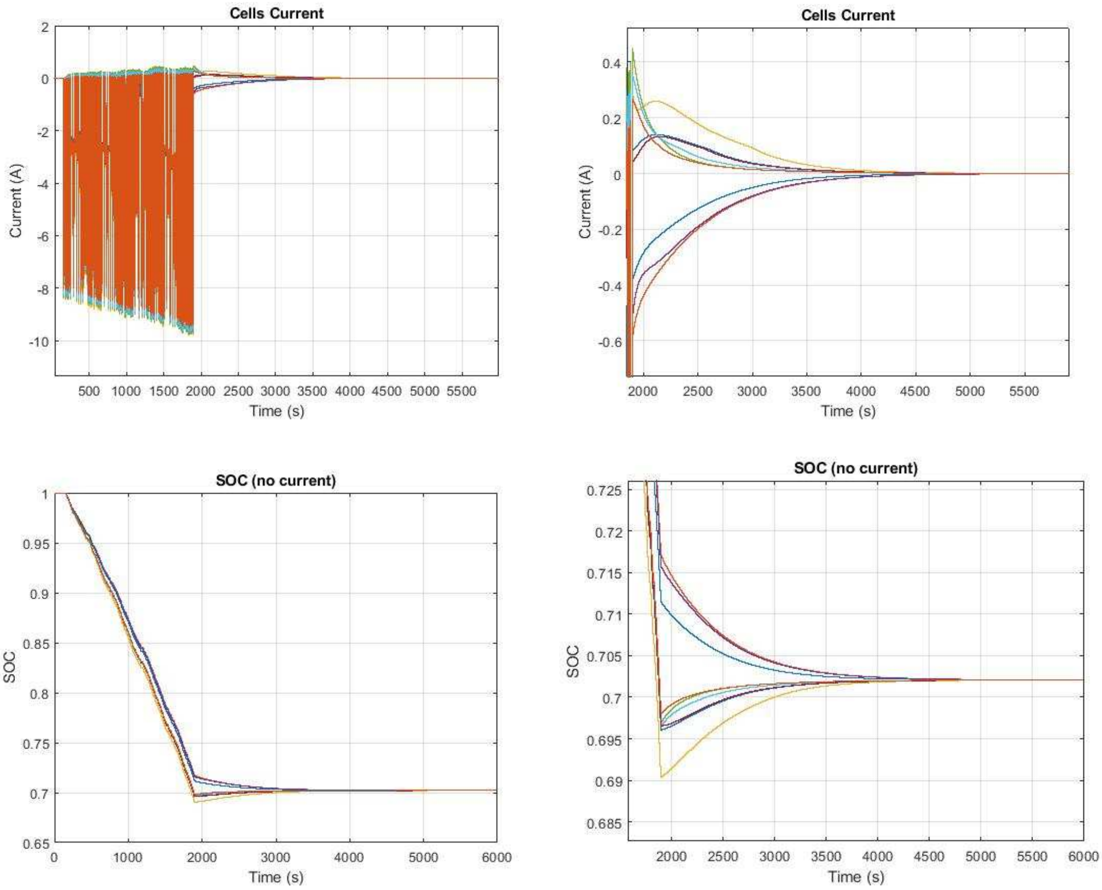


Figure 58: 2 - Flow current inside the battery during the balancing (upper) and SOC balancing (down)

The SOC in this case is about 0.72 to 0.69 when the load is detached from the system and again as it was expected the initial differences between each single modules in terms of state of charge goes to zero over time.

Third example

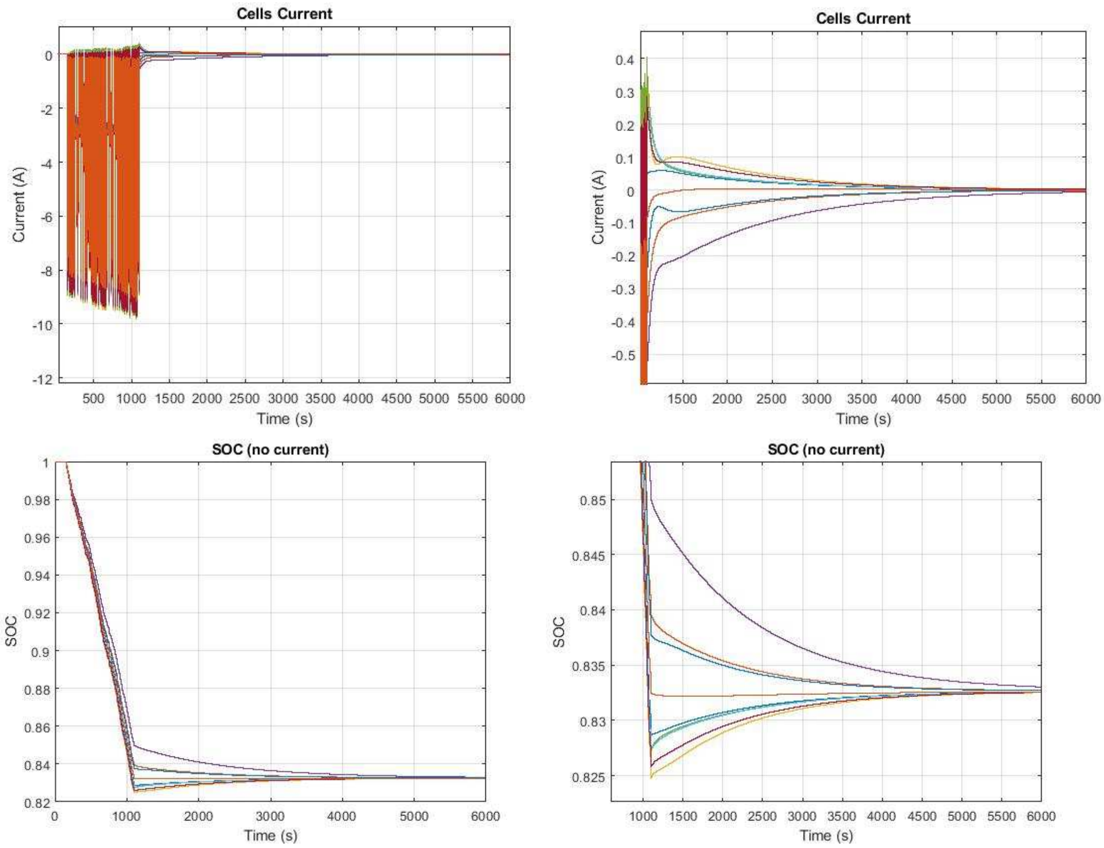


Figure 59: 3 - Flow current inside the battery during the balancing (upper) and SOC balancing (down)

The SOC in this last example is about 0.85 to 0.825 when the load is detached from the system and as in the previous cases the initial differences between the modules in terms of state of charge becomes minimal over time.

Chapter 6

Error testing

In this section will be analyse the results obtained from the system by testing the BMS with different kind of faults, seeing how it faces and overcome them when they act all together.
Moreover, a more complex current control has been employed with the integration of a timer (6.1).

6.1 Overcharge – Overdischarge with time controller

In the previous chapter this problem has been already afford but in a simpler manner.
Here we have tried to solve it in a more sophisticated way, employing a time control (Figure 60) on the overcharge (over discharge) phase such that the BMS allow the current to reach values over and under the range we are imposing if they occur inside a specific time interval.
In this way the current will not being cut off immediately whenever it takes values out of the range, avoiding problem as ripples.

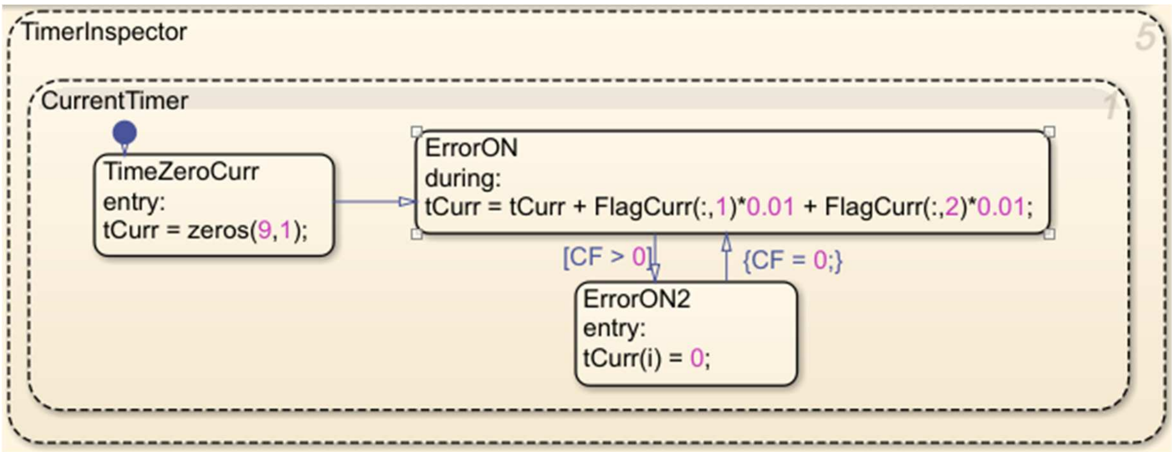


Figure 60: Timer-Current Flowstate

Its main function is to capture when the currents inside the modules are out of the allowed range and whenever this happen to count for how much time this dangerous situation is happening.
If the current return inside the range before reaching the time limit the controller will be advised by the 'CF' variable and it will bring back to 'zero' the timer otherwise it will switch OFF the corresponding module.
This more sophisticated current control is useful to avoid continuing switch ON/OFF of the modules when the currents overcoming the limit for short time since this could damage the battery itself.

The simple block inside the BMS defined in section 5.1 has been changed as follow:

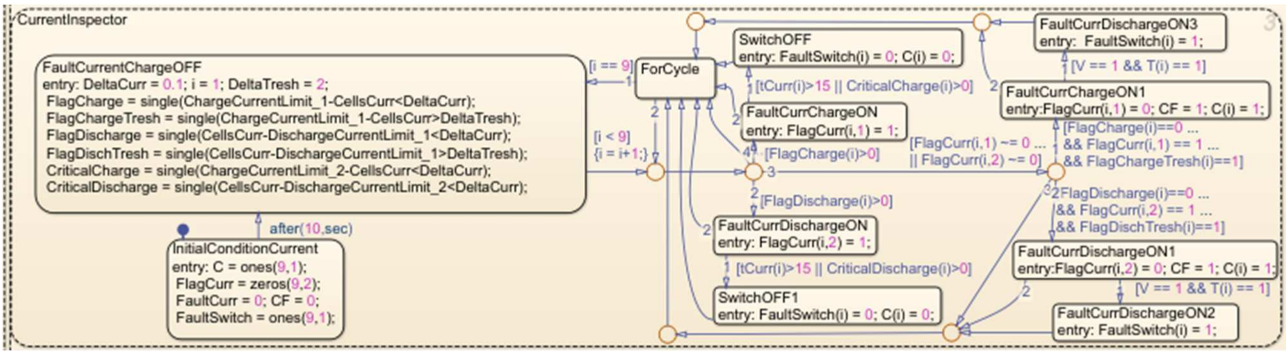
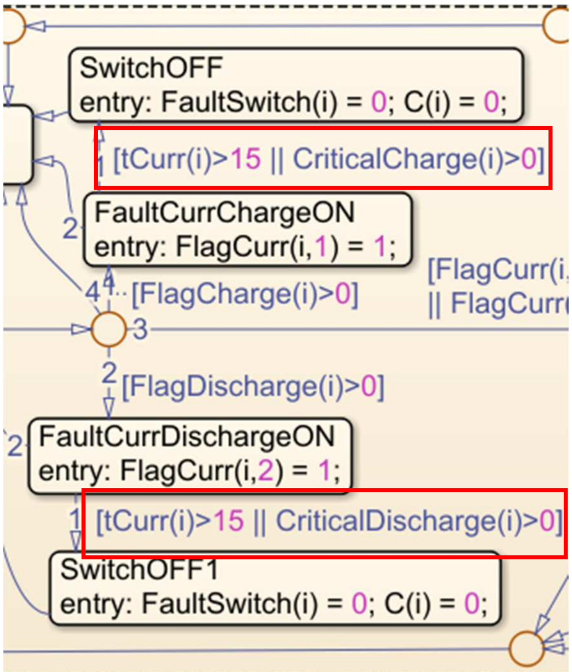


Figure 61: Upgraded fault current detector



In case the current inside the modules is over the safety range the controller will apply two different checks:

- Compare if the time interval out of current limit is more or less than 15 second (a fixed time we decide)
- Compare the values of the currents with the critical one provided by our supplier (read on the datasheet)

Then just in case at least one of the two check is positive the BMS will switch off the corresponding modules.

Figure 62: Timer controller inside fault current detector

In the figure below (Figure 63) is illustrated the currents inside the modules during battery operation in 'driving mode'.

There are two straight line (red and blue) which are respectively the two critical discharge current limits read on the datasheet and their values are 9,8 A and 14,7 A.

However, the first limit is for continuous discharging current, so below it the currents can assume any values for an unlimited period of time while the second is a limit for not continuous one, so in the latter case the current is allowed to reach that value without exceeding it but just for a short period of time.

In the example several critical operation points has been introduced to see if the system works properly as well as the time control box which is located inside the BMS.

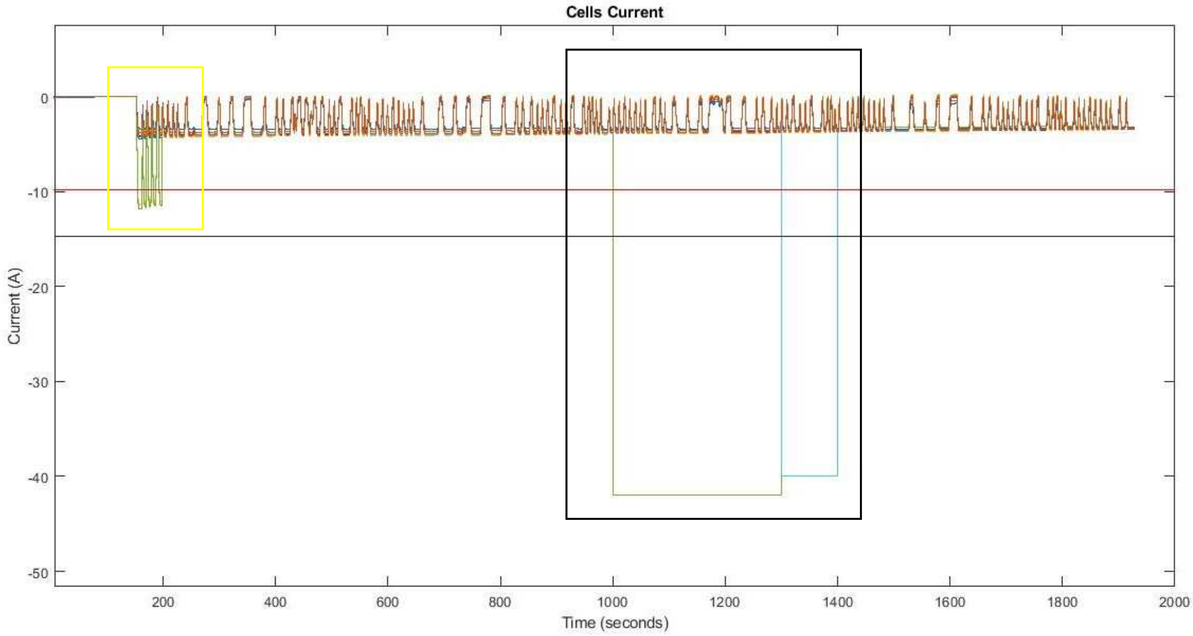


Figure 63: Current test with timer controller inside the BMS

Moreover, some important points are highlighted with the yellow and the black boxes where the currents are overcoming respectively the first and the second critical discharge current limits.
Two currents inside the black box are largely overcoming the critical limit of 14,7 A which cannot be exceeded and so they will be immediately switched off by the BMS.
Instead, a clearer view of what is happening inside the yellow box is illustrated in Figure 64, where can be noticed that some currents are in between the two current limits.

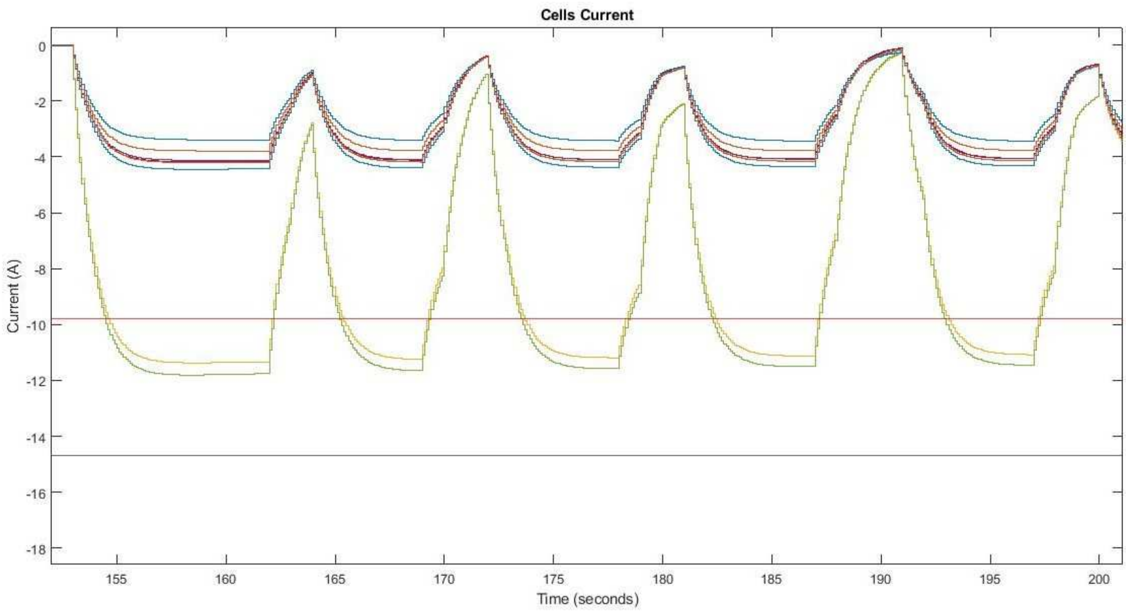


Figure 64: Zoomed area to show currents through the two limits

This mean that the controller will check if the time interval of the currents outside the safety range is more or less than the allowed one and just in case of positivity they will be switched off.
As shown below, the total cumulative time never exceeds the maximum allowed interval which in the case considered is of 15 seconds (Figure 65).

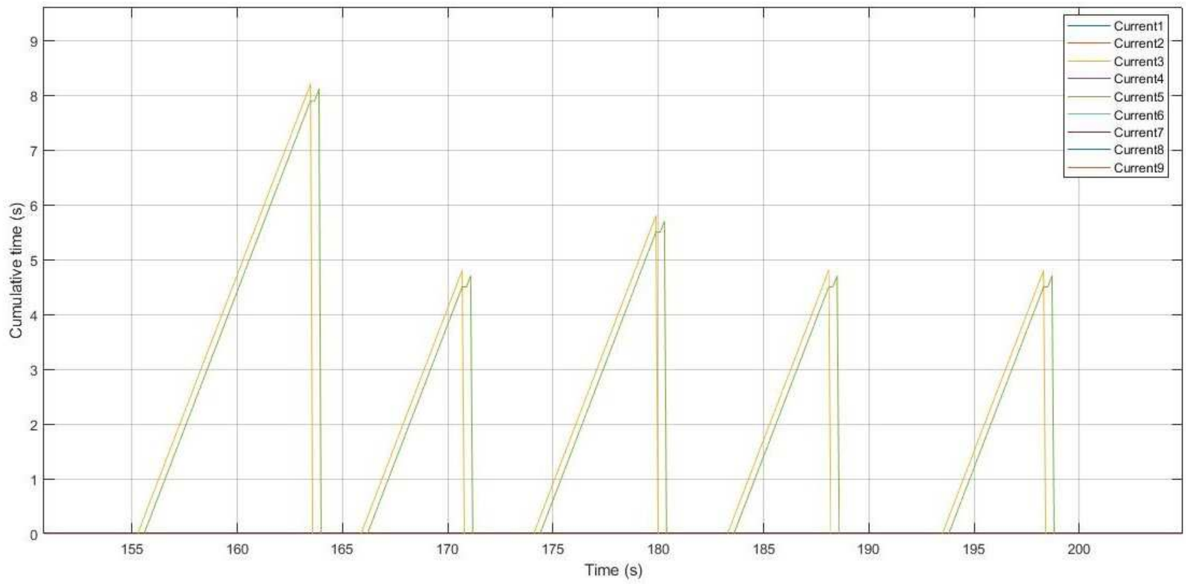


Figure 65: 1 - Time counter application

Furthermore, another important point to notice is that even if the currents inside the black box were below the maximum limit, their cumulative time would have been largely beyond the maximum interval with values of 300 and 100 seconds respectively, as illustrated in the following graph (Figure 66).

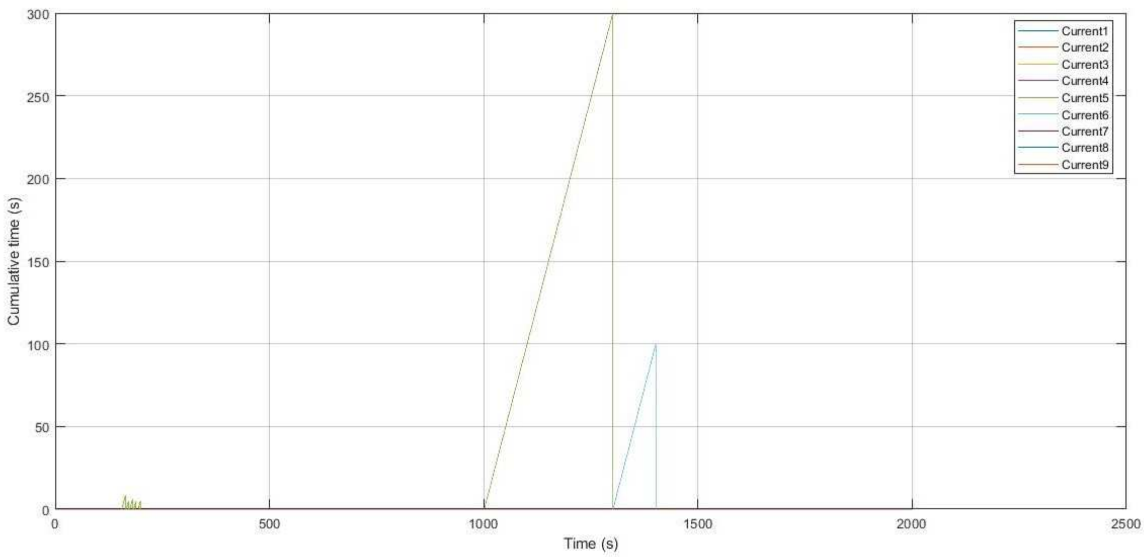


Figure 66: 2 - Time counter application

From the point of view of the BMS can be also analysed an interesting aspect inside the fault scopes.
In the first figure below are highlighted the behaves of the current fault scopes where the current inspector turns on/off a warning whenever the limits are exceeded.
However, these warnings do not directly activate switches as in the case without time controller.
This is quite clear looking at the second image which is referred to the switches.
Although different warnings are turned on the switches are not activated in the blue box while they are turned off inside the red one and this corresponds exactly to what has been explained previously.

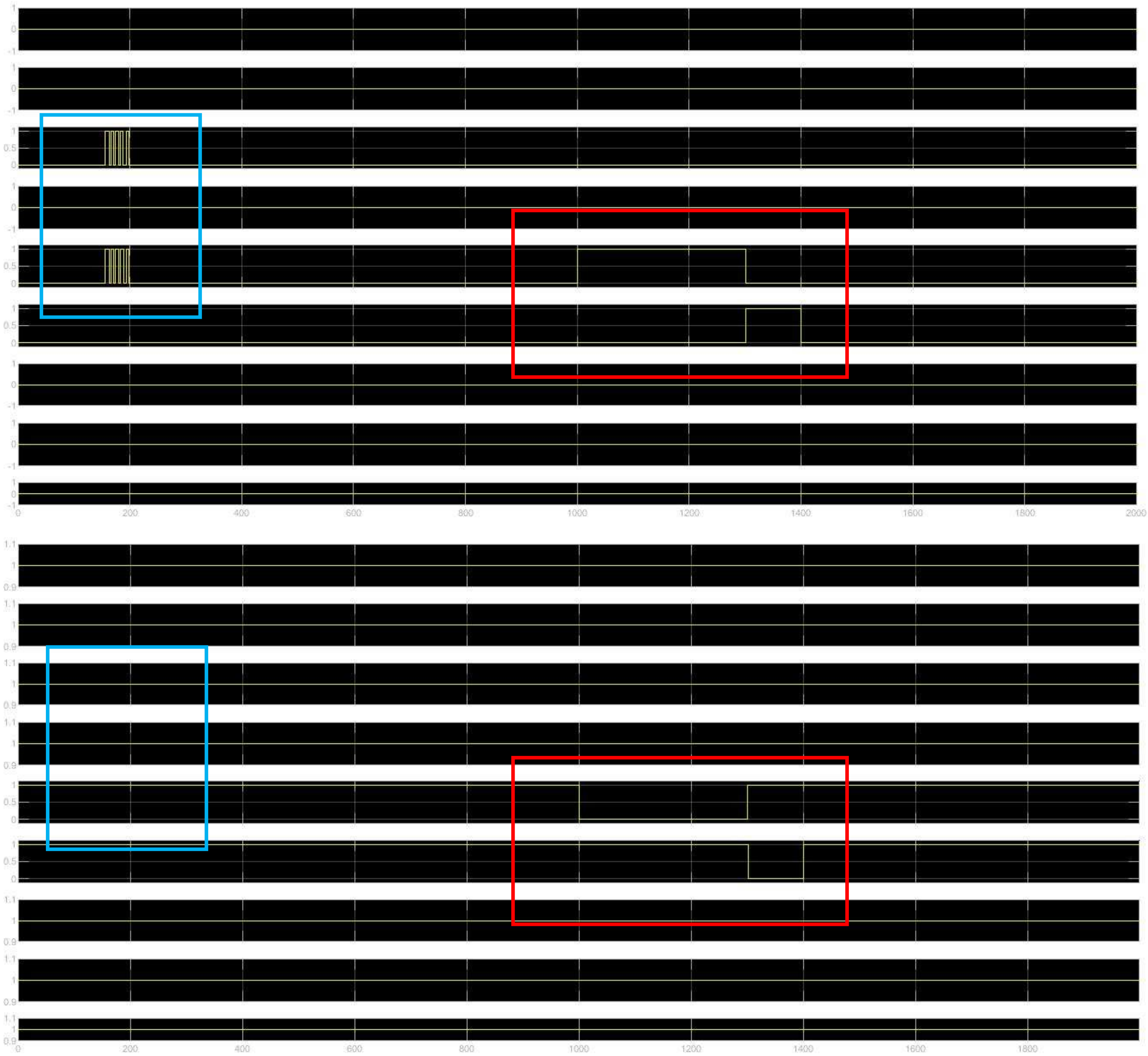


Figure 67: Flag activation and switch activation with timer controller

6.2 Temperature, voltage and current faults faced together

The goal of this fault test is to see how the BMS reacts when the three signal of temperature, voltage and current act together with possible values that could be outside the respective safety range.
Indeed, in the previous chapter we have analysed each of the signal alone, a simpler situation for the BMS to control.
To accomplish the correct actions towards this new possible situation a further step has been added inside the signal inspectors, to get a mutual control between all the three signals.

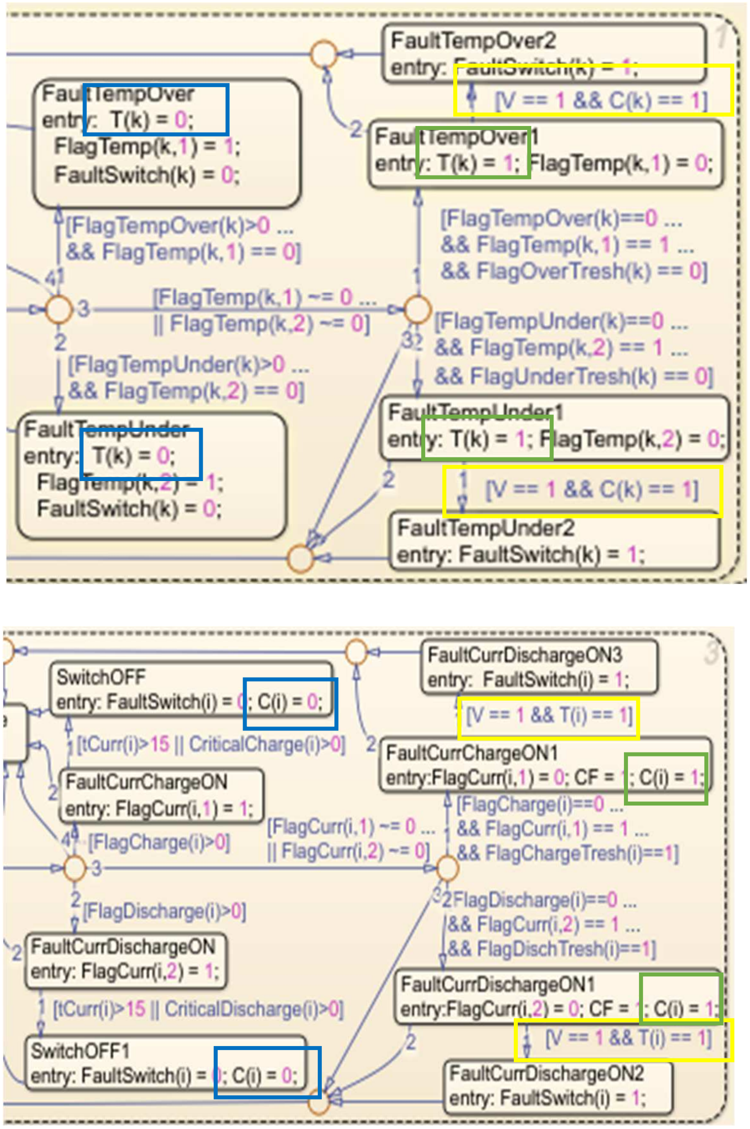


Figure 68: Simultaneous check of current, temperature and voltage

Three variables has been added as small memories which inside will store information about the switches activation.
They are 'T', 'C' and 'V' and they are related respectively with the temperature, the current and the voltage signal control.
The first two has a structure of 9x1 since nine are the total modules while 'V' is just a 1x1 because whenever a voltage error is detected the entire system is switched off.
Any time a switch activation is detected inside one or more modules due to a signal error the corresponding variable/s ('T','C','V') will turn to '0' its i-th position/s related to those modules.
Then when the signal is again inside the safety range the i-th position inside the variable is turn to '1'.
Anyway, to turn on the previously disconnected modules a full analysis of the three variable is made and just in case the i-th position/s inside 'T', 'V' and 'C' are all equal to '1' the i-th module/s is turned on.
Even if only one of the three variables has still a '0' in the i-th position/s the relative module/s will not be reactivated.

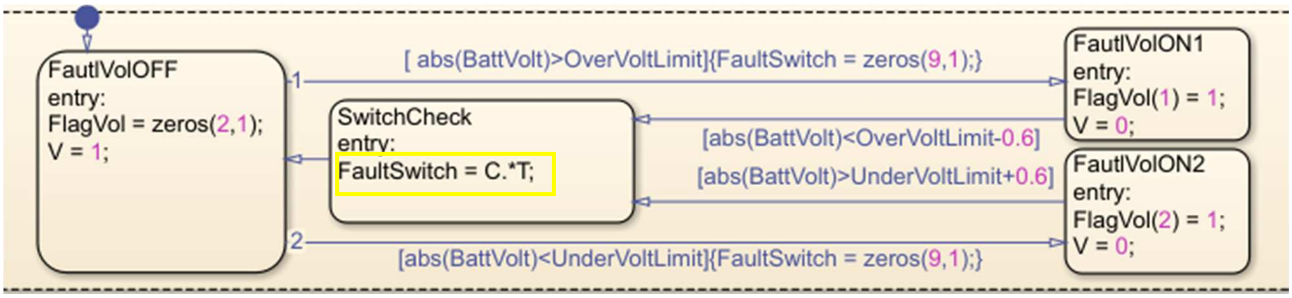


Figure 69: Voltage check related to current and temperature

'T' and 'C' are structured as a 9x1 where in each position there will be a '0' (error) or a '1' (inside the range) and so in case of a voltage error followed by a return of the values within the limit range a simple way to know which switches has to remain active is multiplying them obtain a vector in which each position has one of the following results:

- 1x1 = 1 → safety (module activation)
- 1x0 = 0 → error (switch activation)
- 0x0 = 0 → error

First fault test

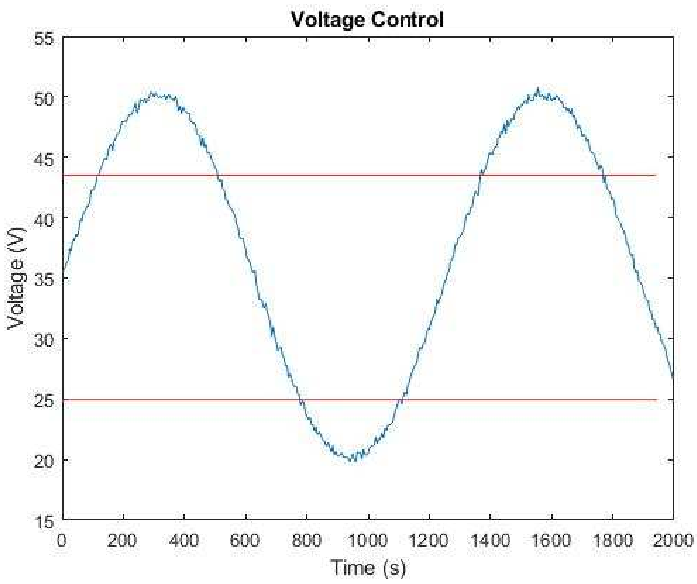


Figure 70: Voltage check – first test

On the left the voltage input signal is showed with the two red lines to indicate where the safety range is limited (43.5 V to 25 V).
Below instead they are the corresponding actions of the voltage inspector.
The results are these three distinct areas where an error is detected (Figure 70).

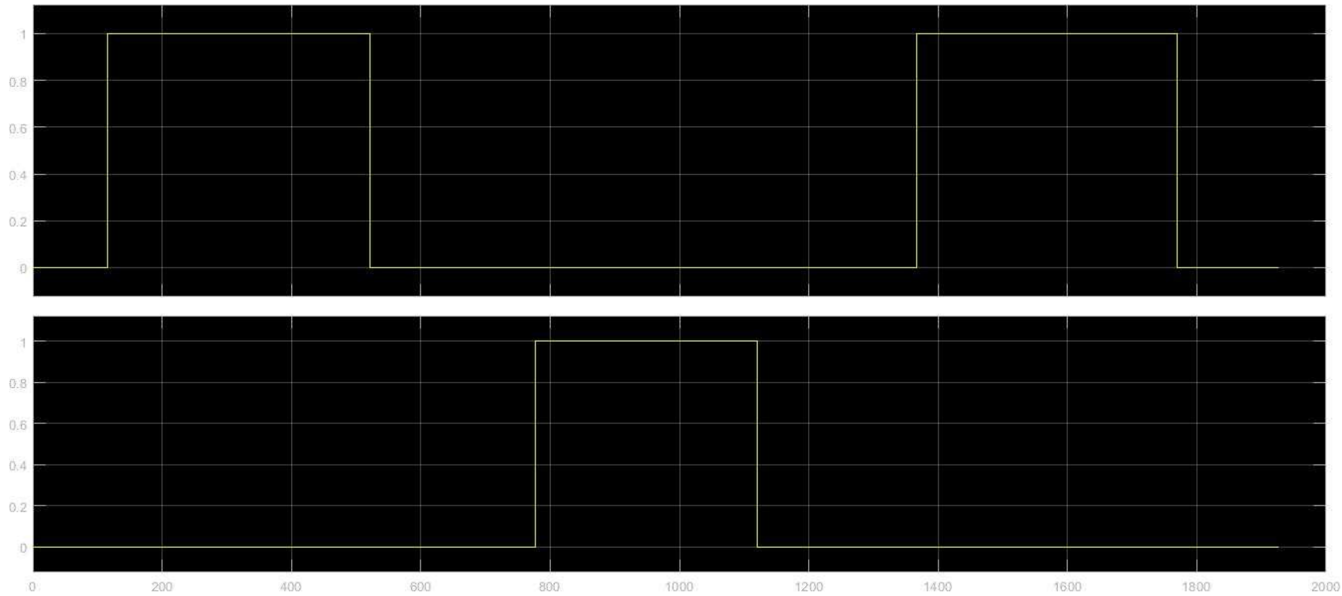


Figure 71: 1 - Voltage switch activation with completed BMS

Since the input current signal (Figure 72) is the same as in the case analysed in 6.1 the same conclusions have been achieved in terms of warnings, fault and switch activations.

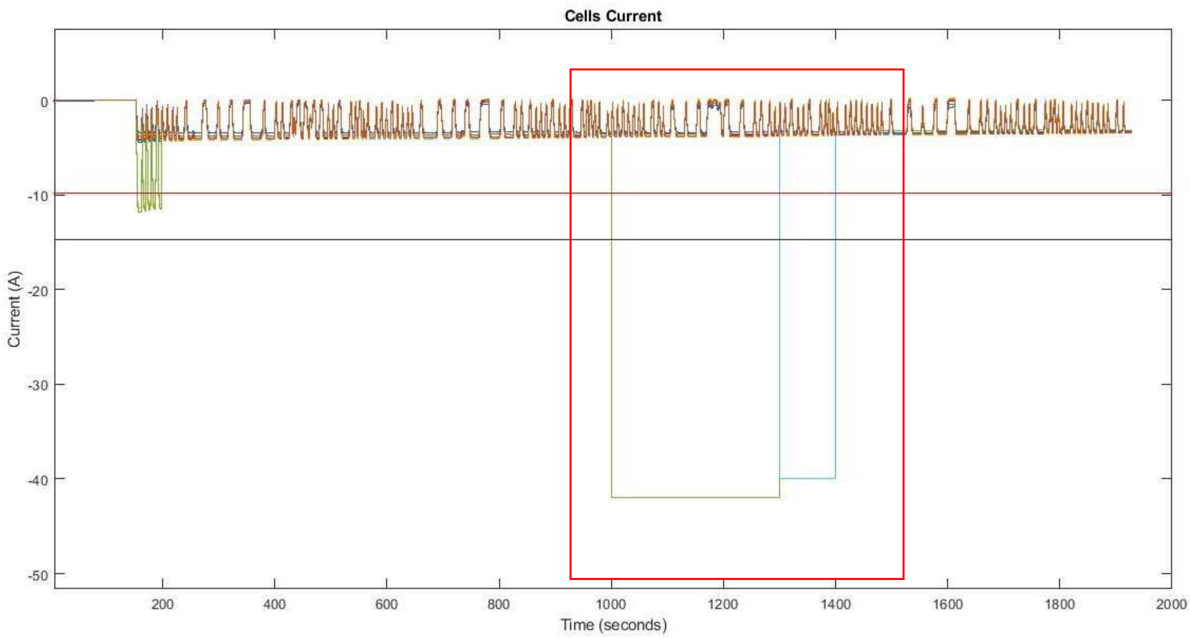
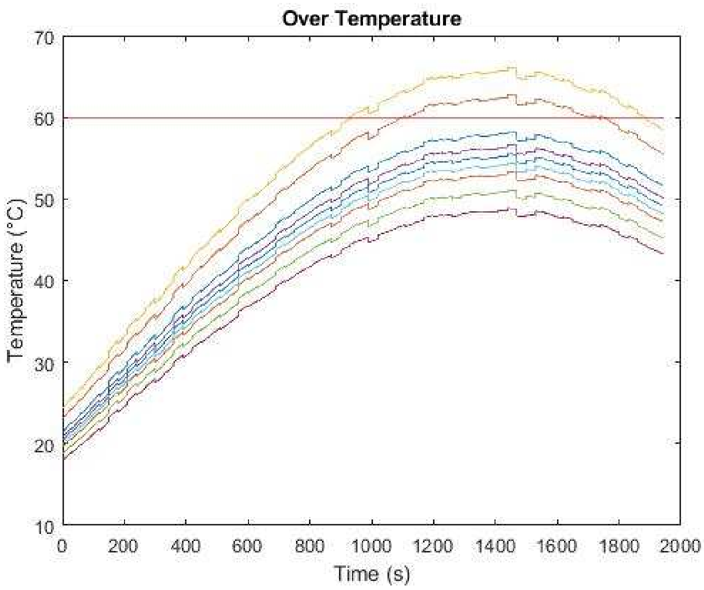


Figure 72: 1 – Current limit test completed BMS

Figure 73: 1 - Current flag activation with completed BMS



On the left (Figure 74) the temperature input signal is showed with the red line to indicate where the upper safety range (60°C) is limited. Below instead the are the corresponding actions of the temperature inspector.
The result is an identification of two modules with a temperature over the limit.

Figure 74: 1 – Temperature limit test with completed BMS

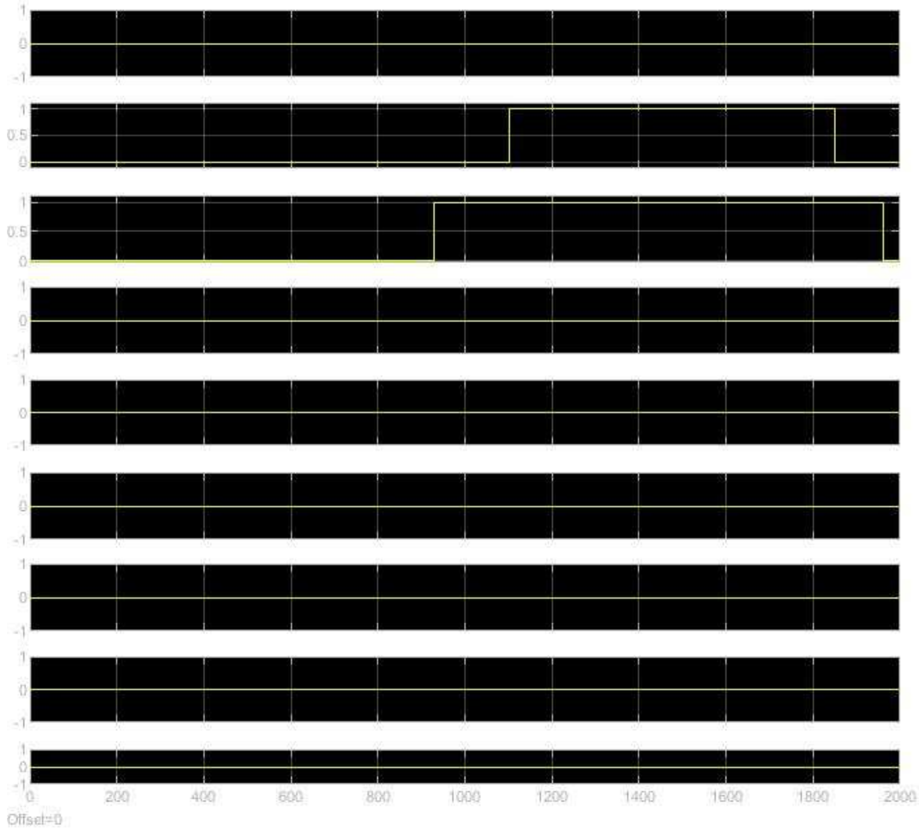
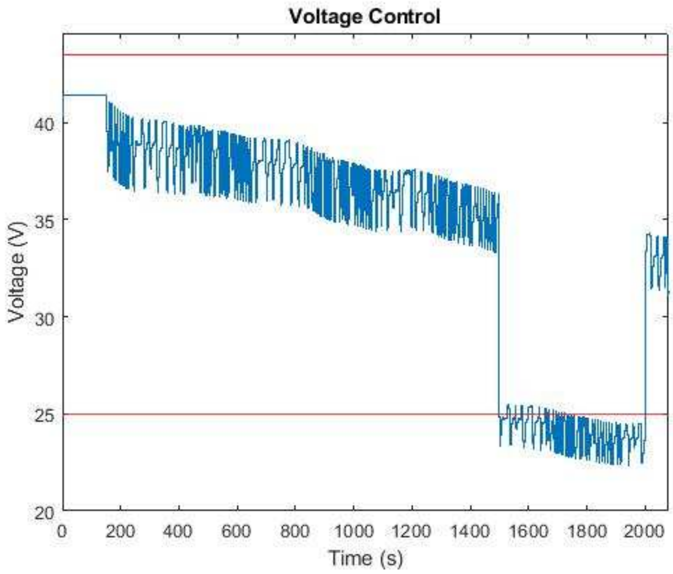


Figure 75: 1 - Temperature flag activation with completed BMS

Figure 76: 1 – All switches activation due to current, voltage and temperature

As a result has been obtained the fault switch inspector where all the faults previously seen are analyzed together, so whenever one of these three signals is outside its proper range the corrisponding module is turned off.

Second fault test



As in the first test on the left (Figure 77) the voltage input signal is showed with a different behaviour.
Below instead the are again the corresponding actions of the voltage inspector.
The result in this case is a unique area where an error is detected.

Figure 77: Voltage check – second test

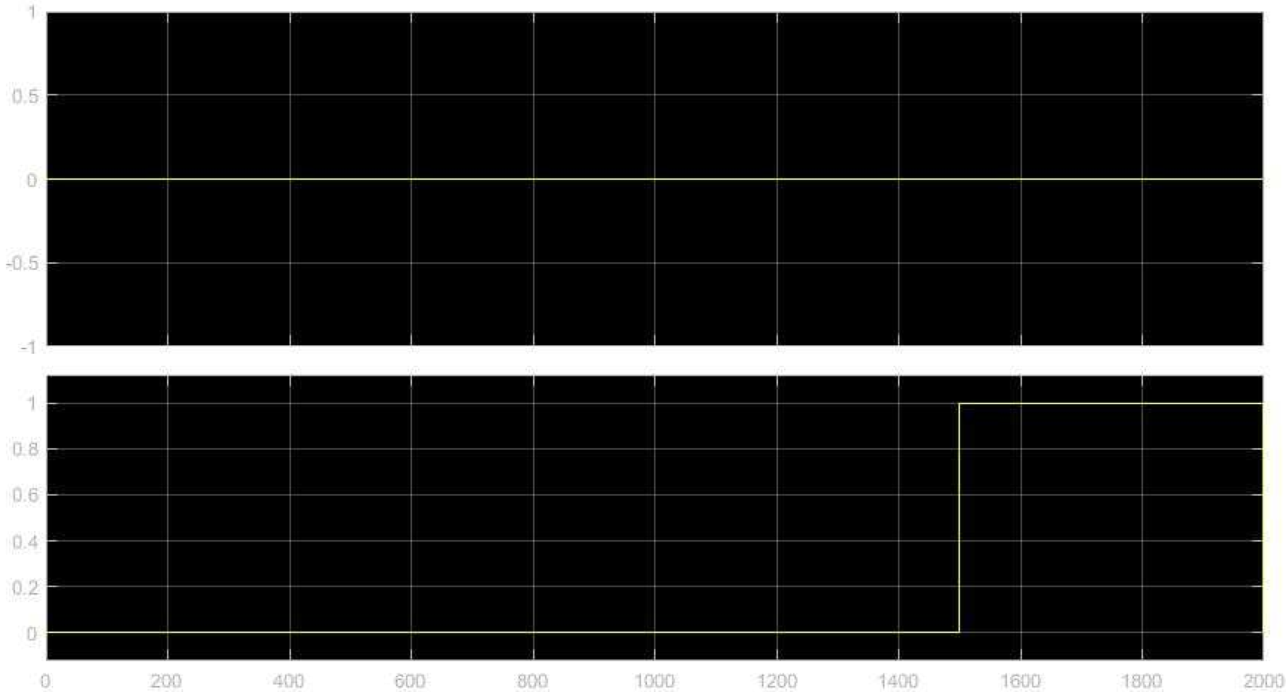


Figure 78: 2 - Voltage switch activation with completed BMS

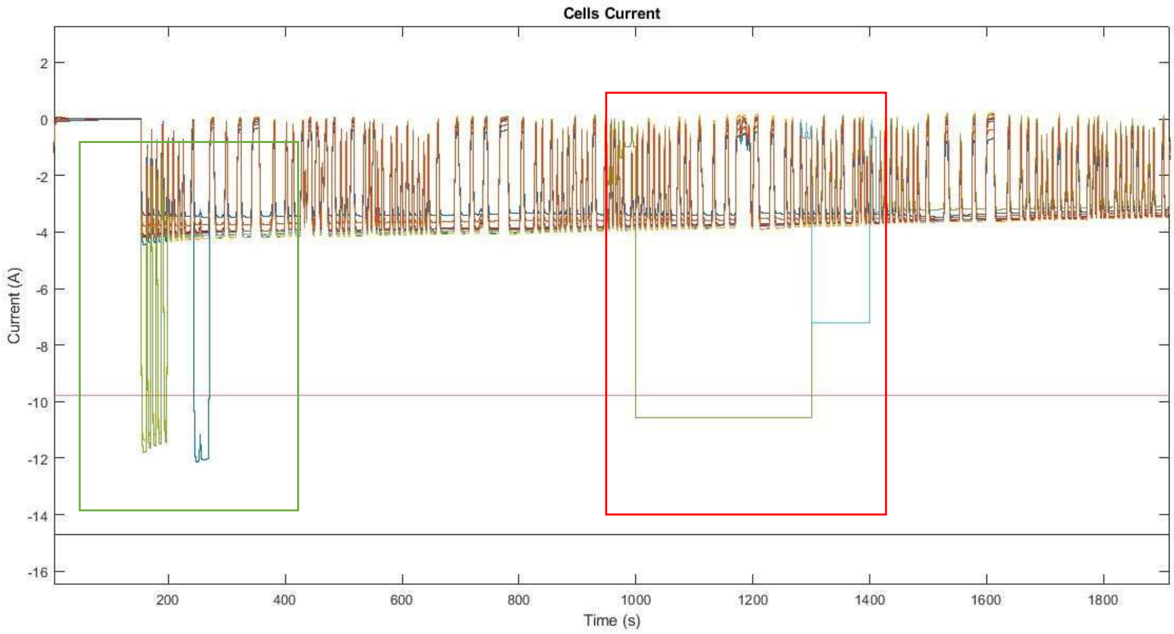


Figure 79: 2 – Current limit test completed BMS

In order to have a deeper knowledge on how the BMS works a total different current is provided as input signal where more than one outsider is present, to check if it is able to find them all.
In the red box a module has a current that is overcoming the critical value of 9,8 A for a time interval largely bigger than the allowed value.
Instead to have a better view on what is happening inside the green box a 'zoom' is provided below.
In this case they are more than one current that are in between the two critical value but just the blue one on the right has a time interval again bigger than 15 seconds.

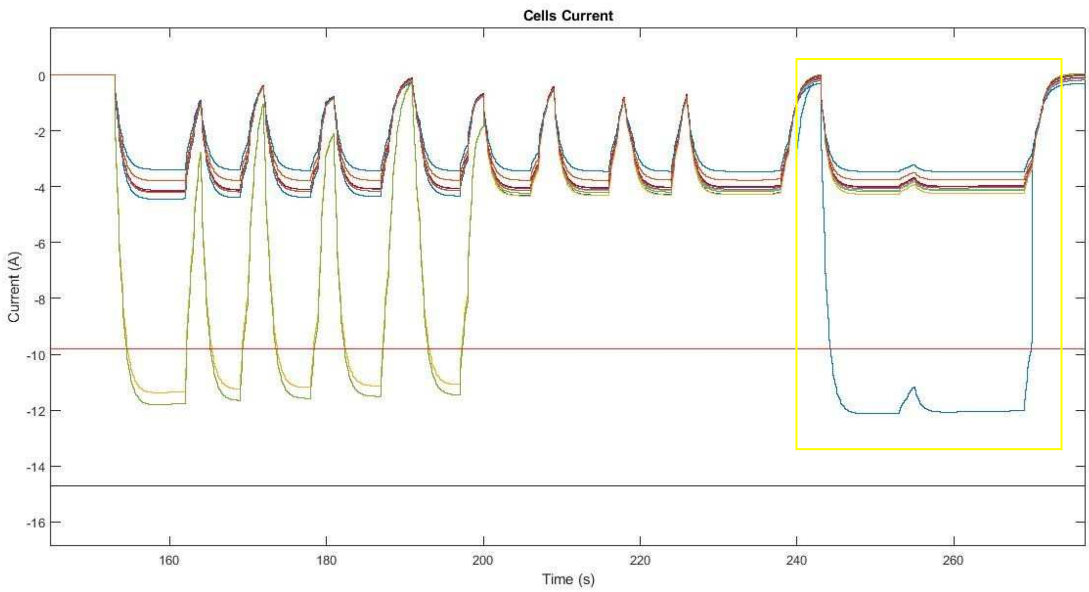


Figure 80: Zoomed area to show current outside the allowed range (yellow box)

To better understand the time interval of the different current outside the safety range the following two images are showed.
In the first graph a time interval of 300 seconds is discovered and so an action made by the BMS is expected.
In the second one a time interval of more than 25 seconds is found and so again the BMS must intervene, switching it off.

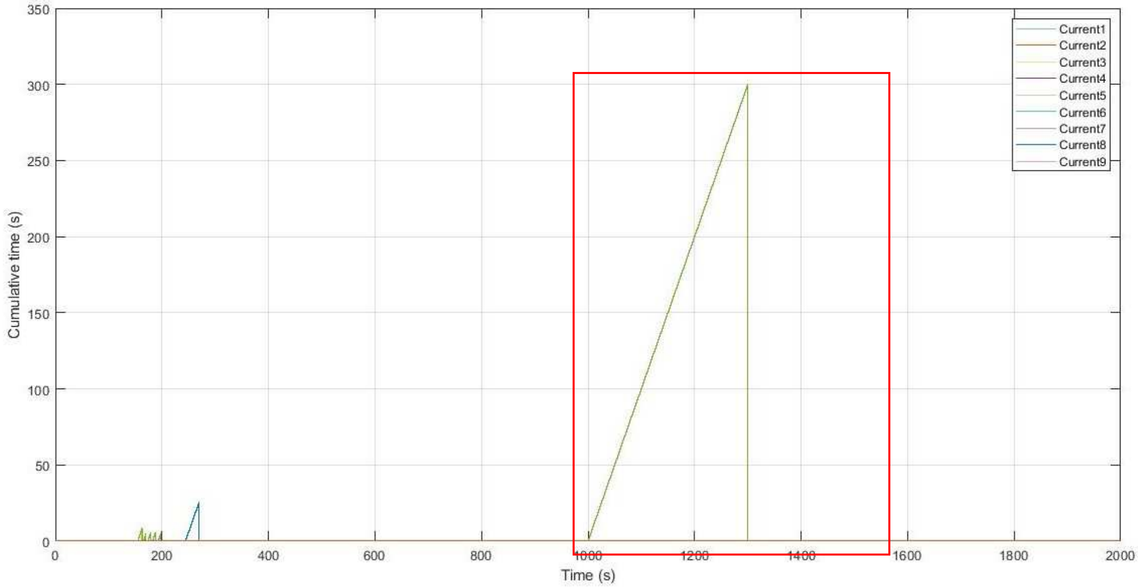


Figure 82: Timer control cumulative time

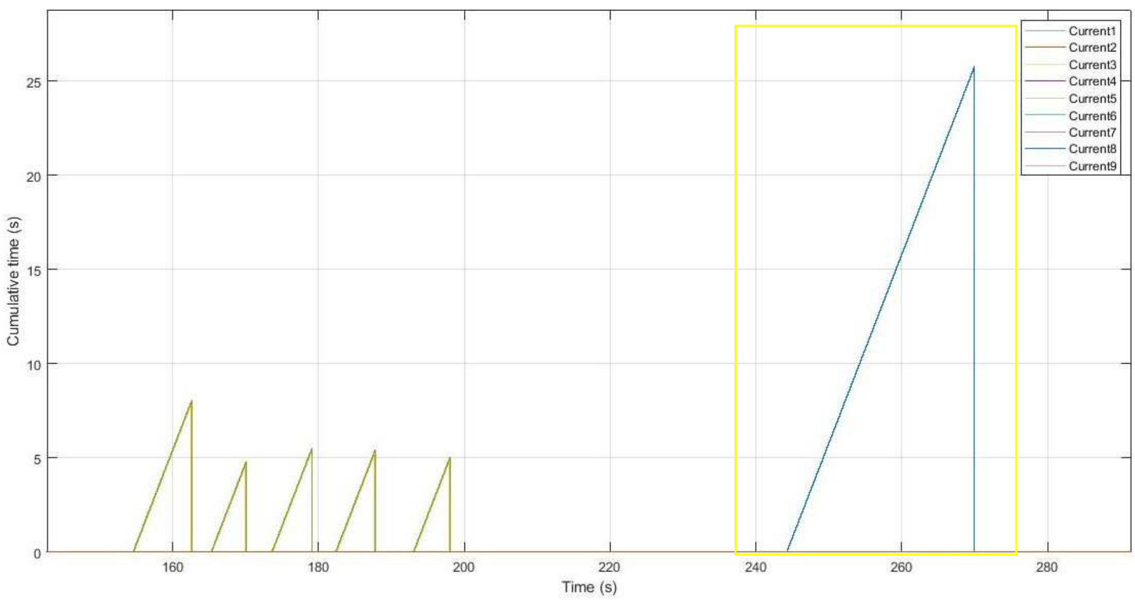


Figure 82: Zoomed area to show cumulative time exceeding

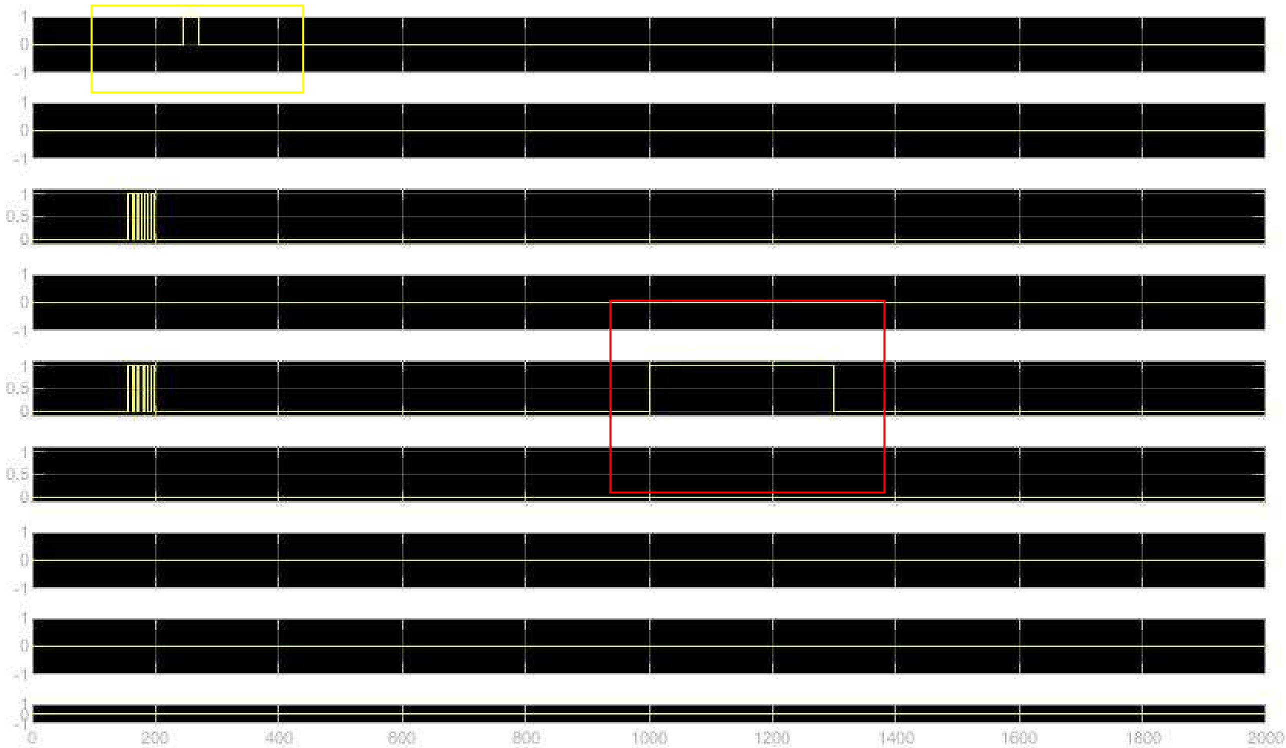
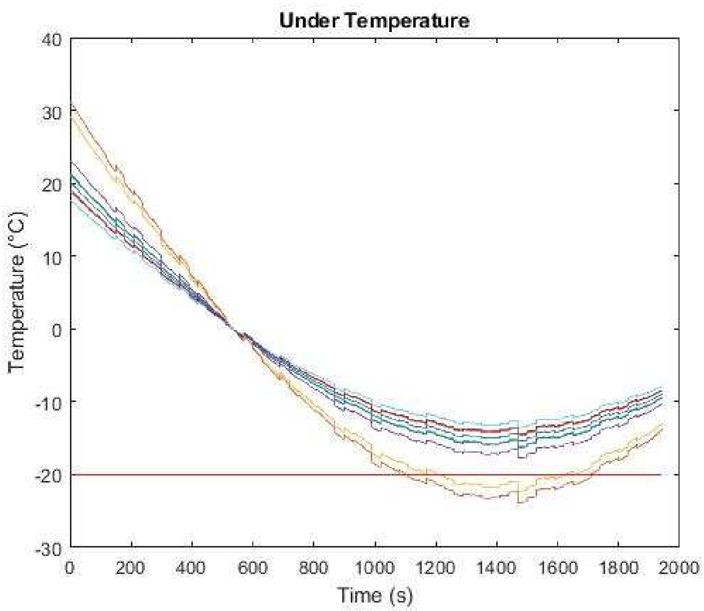


Figure 83: 2 - Current flag activation with completed BMS



On the left the temperature input signal is showed with the red line to indicate where the lower safety range (-20°C) is limited.
Below instead the are the corresponding actions of the temperature inspector.
The result is an identification of two modules with a temperature under the limit.

Figure 84: 2 – Temperature limit test with completed BMS

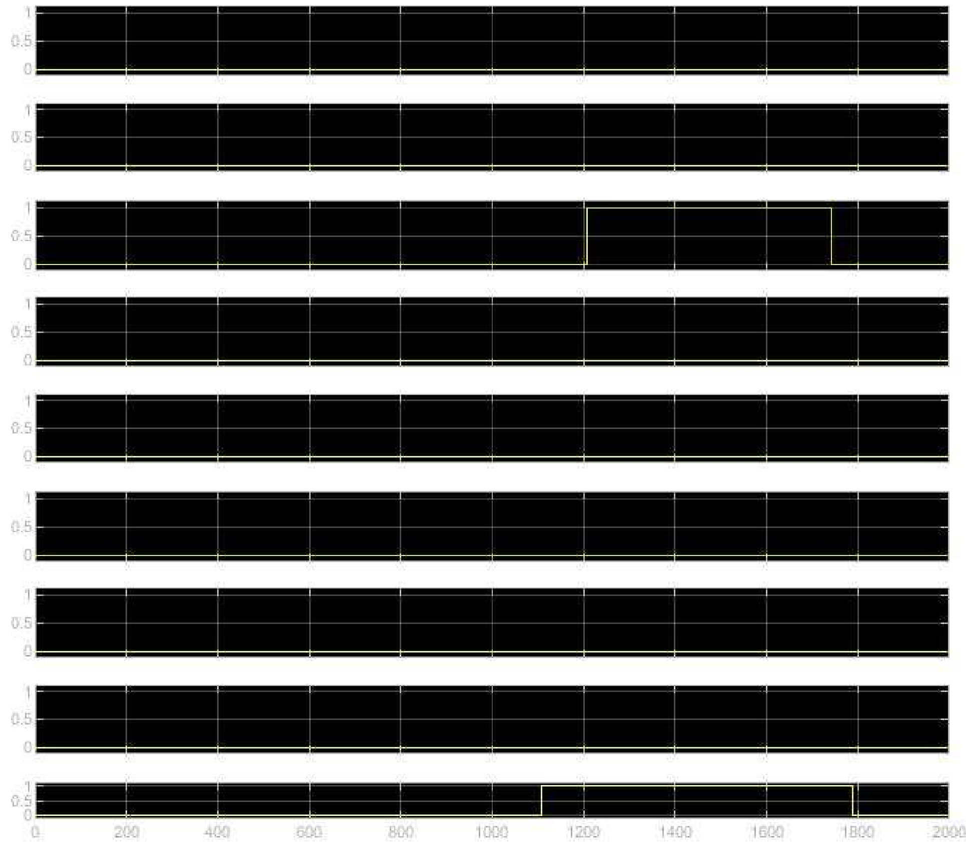


Figure 85: 2 – Temperature flag activation with completed BMS

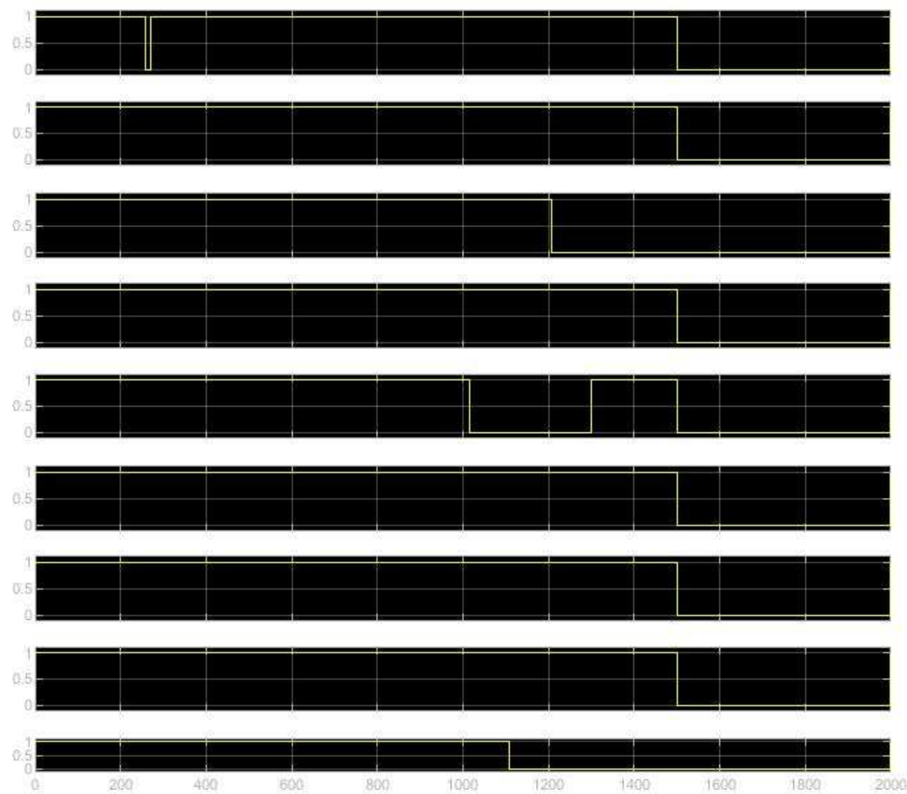


Figure 86: 2 – All switches activation due to current, voltage and temperature

6.3 SOC - Error test during charging phase

Each of the modules inside the battery can have a little difference in terms of SOC that can be accepted in a range of few percentages.
As seen when the difference between the modules overcome a certain value during the charging mode a balancing control is activated.
Some recharging test have been made to see how the BMS and the battery behave to control these differences and if they are as we expected.
In the follow some tests are shown:

First case – Initial SOC 0.35

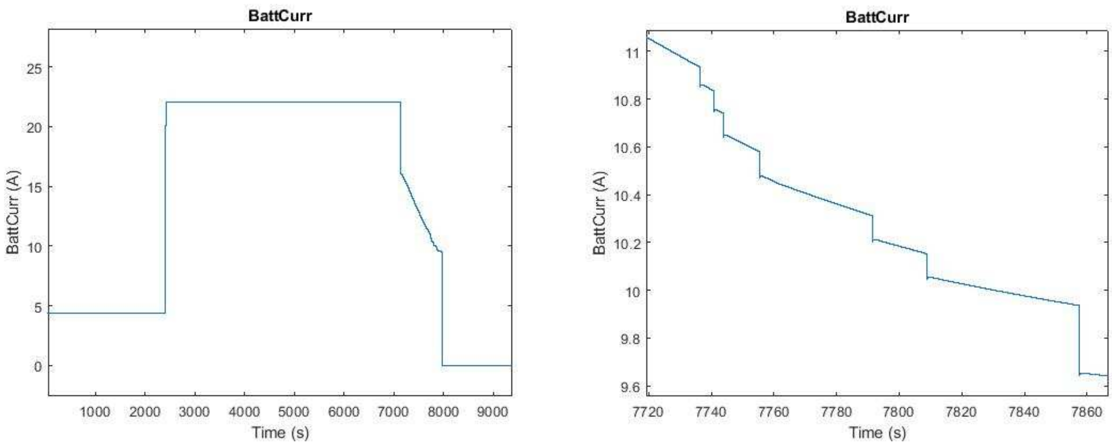


Figure 87: Current flow inside the battery (0.35 SOC) (left) and zoomed image (right)

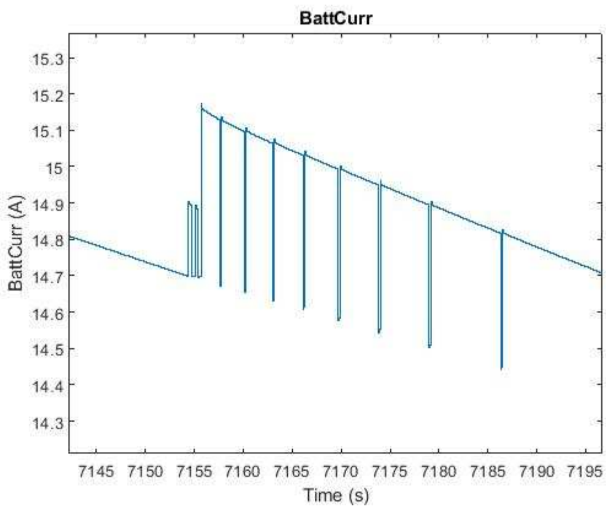


Figure 88: Ripple in the current flow (SOC 0.35)

In this case there is the presence of a ripple, anyway it is small and happen for a short period of time so it is acceptable.
Indeed, this is one of the worst situation for the battery because we simulate a very low initial SOC also imposing a huge difference between the SOC of each modules before the balancing activation.

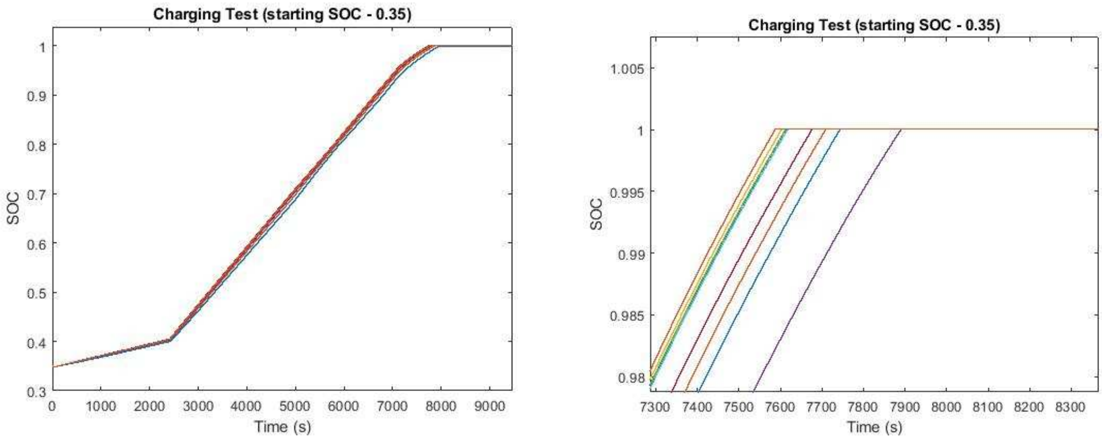


Figure 89: Balancing activation (0.35 SOC) (left) and zoomed image (right)

Second case – Initial SOC 0.55

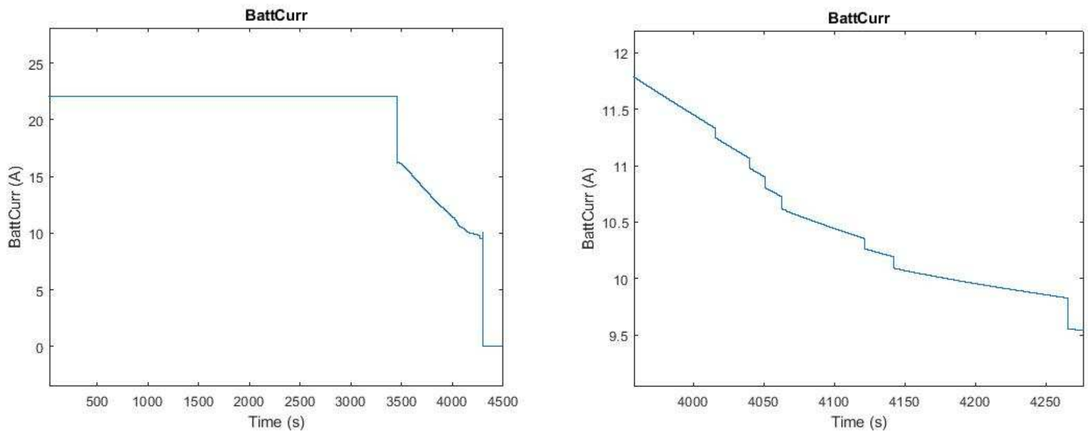


Figure 90: Current flow inside the battery (0.55 SOC) (left) and zoomed image (right)

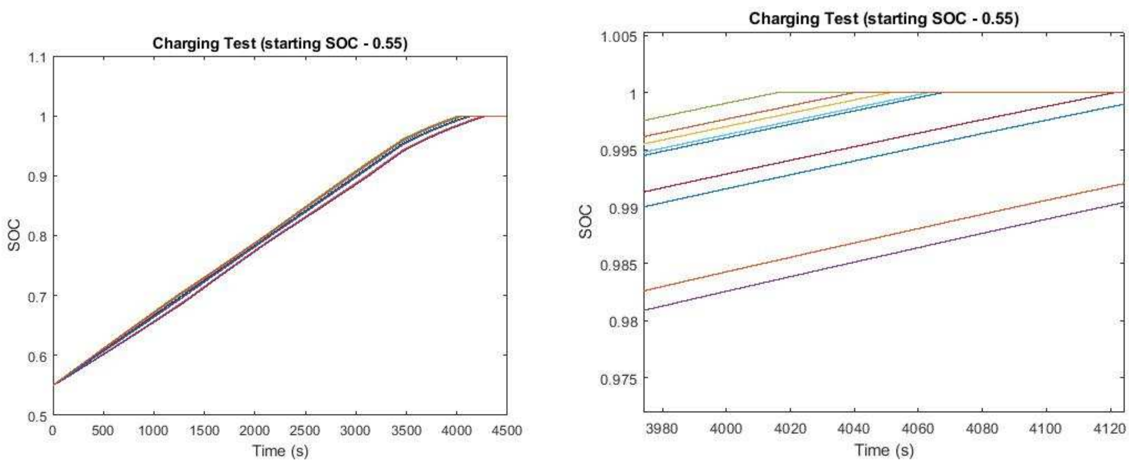


Figure 91: Balancing activation (0.55 SOC) (left) and zoomed image (right)

Third case – Initial SOC 0.6

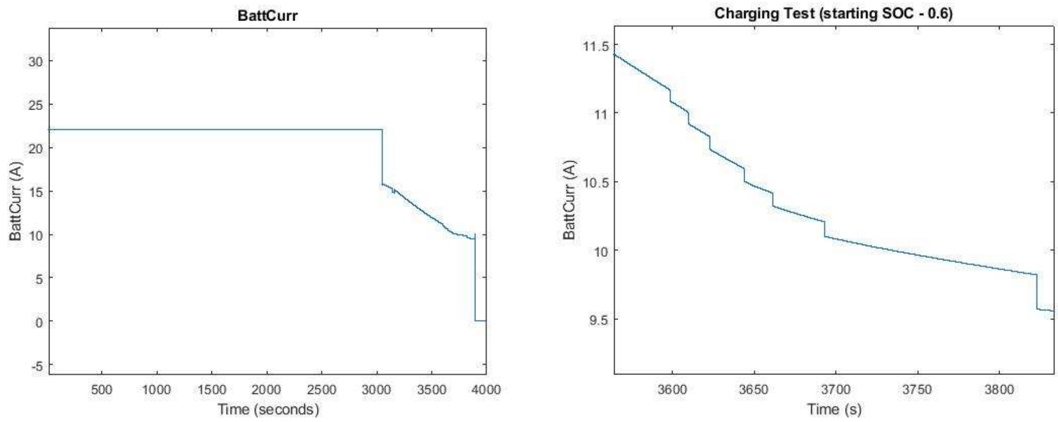


Figure 92: Current flow inside the battery (0.6 SOC) (left) and zoomed image (right)

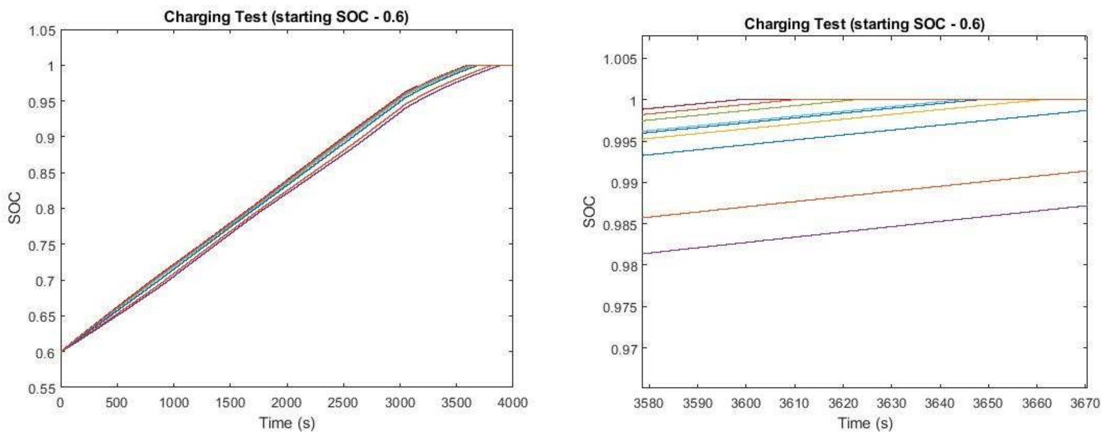


Figure 93: Balancing activation (0.6 SOC) (left) and zoomed image (right)

In all the cases that have been considered the system works as expected, without the presence of ripple inside the battery current (except for little one in the case of initial SOC of 0.35) while the difference between the maximum and the minimum SOC inside the modules goes to 0.02 when the balancing is activated.

Chapter 7

Conclusion

The results obtained in the thesis can be considered quite satisfying and BMS works in proper manner ensuring an optimal control on the main parameters of the battery.
As first the choice of an ECM with two branches has proven to be a nice solution, let the battery pack system to simulate different cases such as driving or charging phase realistically.
The starting management system results were good in the easier failing test case, considering the parameters one a time and when the BMS has been made more complex, i.e., implementing a timer controller the results have continued to remain positive even in case of simultaneous values out of range.
The balancing control as well works quite well bringing all the SOC levels at close values between a minimum gap of 3% which is acceptable in realistic application. The proposed balancing system is one of the simplest as a result of choosing a passive one which involves the use of parallel resistors but nowadays it is still an employed method, for cheap solutions.
A great mental effort was required to pass form the simplified BMS to the completed ones and several hours has been employed to get the correct interaction between the main parameters. The flags used to let them talk to each other are quite intuitive theoretically but not so in practice. They can be considered as a kind of buffer where a storage value of '0' or '1' let all the other parameters know about a specific situation.
Equally good were the results obtained during the charging phase where the BMS works precisely through the different CC-CV stages.

7.1 Improvements

Possible improvement inside the BMS is the implementation of a EKF or KF for the SOC estimation, to thus have greater accuracy especially in case of initial error. It is quite known that coulomb counting is good for its complexity and velocity but suffer initialization errors since it is not able to recover the right SOC whenever they occur. On the contrary EKF and KF are robust against error and interference making them an optimal solution.
Another possible improvement can be made moving from the passive balancing method to active balancing one thus allowing less wasted power and less heat generation.
In addition, more security systems could be inserted inside the model such as the use of diodes to prevent unwanted current returns.

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