BACHELOR PAPER

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AN EFFICIENT CELL BALANCING METHOD FOR LiFePO4 BATTERIES BASED ON INDUCTORS

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Wien, 16/06/2021

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Abstract

Nowadays, transportation is living through a great transformation motivated, among many other reasons, by the pollution caused by combustion vehicles. Faced with this change, other more renewable forms of transport, such as the electric car, are increasing and being introduced weighty in the market. Due to the great monopoly of the combustion car in recent years, this type of technology is not yet fully developed and there are many areas for improvement, especially in the plot of electric batteries. Within these devices, most of the studies and efforts are focusing on these two topics:

- New materials for battery construction with better chemical characteristics, such as graphene.
- New systems to supervisor and control the battery in a more efficient way, BMS (Battery Management System).

Currently most companies design their BMS through capacitors, which decrease the cost and complexity of system control, in exchange for increasing the balancing time. This fact reduces the useful life of the cells. Motivated by the dissatisfaction of a market that tends to lead mobility soon, this thesis is studying, implementing, and developing an innovative cell balancing circuit through inductors.

It is theoretically (through equations) and practically (through simulations) created to simulate the behavior of an electric vehicle battery. To obtain simulations and results that will make the industry think about the possible incorporation of this system to the electric vehicle, two types of balancing (with inductors and with capacitors), have been simulated and compared in the PSIM tool in three different situations .After visualizing the graphs of the three cell voltages, the cell power, and the total current of the circuit, it can be concluded that with the inductor method, more precision and speed is achieved when charging the inductors.

The realization of a PSIM circuit with the same design but with a larger number of cells, as well as the integration of this three-cell circuit with physical elements, is being considered for future studies.

Keywords: batteries, BMS, cell balancing, inductors, PSIM circuit.

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1. Introduction

This section will explain the reason for writing the thesis, the goals to be achieved by doing it and will summarize the other sections that make up the thesis.

1.1 Topic/Motivation

Nowadays, transportation is living through a great transformation motivated, among many other reasons, by the pollution caused by combustion vehicles. Faced with this change, other more renewable forms of transport, such as the electric car, are increasing and being introduced weighty in the market. Due to the great monopoly of the combustion car in recent years, this type of technology is not yet fully developed and there are many areas for improvement, especially in the plot of electric batteries. Within these devices, most of the studies and efforts are focusing on these two topics:

- The materials of which the battery is composed. Discovering and developing new materials, such as graphene. More oriented to the field of chemical engineering.

- Systems to supervise and control the battery in a more efficient way, BMS (Battery Management System).

Currently many large companies in this sector were investing large amounts of economic resources to find new systems that could replace the use of capacitors, with which, although good results are obtained, the balancing time is still high.

Between the other possible methods (inductors and transformers) to perform the balancing of cells in an electric battery. This thesis will focus on study a circuit through inductors, since with the use of transformers a very efficient balancing is performed, but the price increases a lot, and it would not be profitable for the electric vehicle companies.

1.2 Problem/Goal

The present thesis aims to demonstrate through equations and simulations thanks to the PSIM program that the use of inductors to balance the cells can provide the same or better results than using capacitors.

This is because with capacitors good balancing is obtained, but sometimes it takes a long time to perform the balancing of cells, besides when the cell voltages have very similar values it is very difficult to tune it more by discharging or charging them. It is believed that using inductors can achieve greater accuracy when balancing, and it is a topic that we want to study and demonstrate.

1.3 Structure of the work

This section will briefly explain how the other chapters of the thesis will be distributed:

State of the art:
It will be explained: why is fundamental the use of BMS in an electric vehicle, the different techniques to perform the balancing (passive and active) and the two possible ways to perform the balancing of cells, using inductors.

Circuit developed in PSIM:
In this section it will be explained: how the circuit has been developed in PSIM and the different blocks that conform it. In addition, it will be explained how the elements have been parameterized, through a theoretical study of the power, settling time and sensitivity, and the programming that has been carried out to perform the balancing.

Circuit programming
In this section we will study the programming that has been carried out to obtain a correct cell balancing
Results and discussion:
The circuit will be simulated in three possible situations (Vcell1> Vcell2> Vcell3, Vcell2> Vcell3> Vcell1 and Vcell3> Vcell1> Vcell2) And through of graphs of the cell current, cell voltages... it will be demonstrated if the circuit has been performed correctly and if it is well parameterized.

Conclusions:
Everything studied in the thesis will be compiled and it will be verified that the objectives that were in the section "Problem /Goal" have been achieved.

2. State of the Art

To see the importance of the method developed in the thesis, we will explain the functions of a BMS in an electric vehicle, and the different forms of balancing that exist today.

2.1 BMS (Battery Management System)

Before focusing on the development of the circuit, it will be explained the reason why the BMS is so important for the correct operation of the battery.

Initially, the BMS get emerge like an electronic circuit to control that the cells of these did not go out of their operating range, since this could cause accidents or even the explosion of the battery.

Over the years, this concept has been changed and currently a BMS in an electric vehicle is a system whose main purpose is still the safety of the battery, but now it also takes information and parameters that improve the operation and efficiency of the vehicle. [1][2]

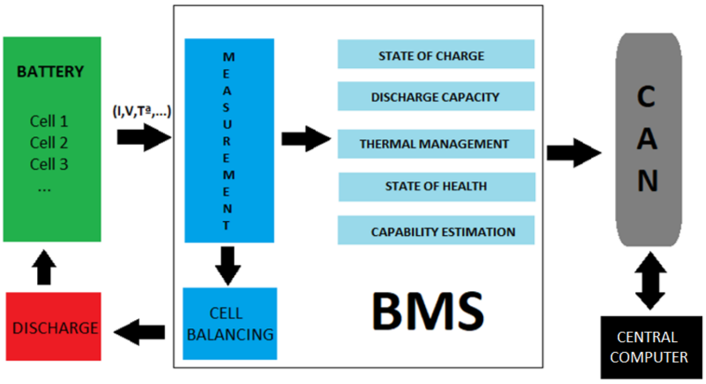

Figure 1:Functions of the BMS in an EV [3]

As can be seen in Figure 1, the BMS measures parameters (such as current,voltage,temperature…) of each of the battery cells and transmits this information, through the CAN communication protocol, to the vehicle's central computer. In this way, if for example BMS receives a very high Tº value, it will transmit this information to the central computer which will activate a fan or other cooling system, to try to maintain this parameter between optimal values. [4][5]

Although the BMS monitors many parameters such as: health status, load capacity or discharge capacity, all of them depend on a correct balancing of the cells. That is why the development of the thesis will focus on this aspect, cause studying the cell balancing other aspects will be improved indirectly. [6]

In order to understand the concept of cell balancing, a similarity will be made with the operation of a horse-drawn carriage. Let us imagine that our battery is the cart and the different cells that compose it are the horses, for the cart to advance all the horses must go at the same speed, this happens in the same way in the battery pack, all the cells will have to be in the same voltage range for the battery to work correctly. [7]

This can be achieved through different techniques, which will be shown below:

2.2 Techniques used for cell balancing.

Depending on how this balancing is done, two methods can be found:

2.2.1 Passive methods

In these methods, the SOC (State of Charge) of all cells is matched to the cell with the lowest SOC, in the case of Figure 2, to cell 1. Although the design and programming of these methods are very easy, due to the use of resistors, much unusable energy is lost in the form of heat during balancing. [8][9]

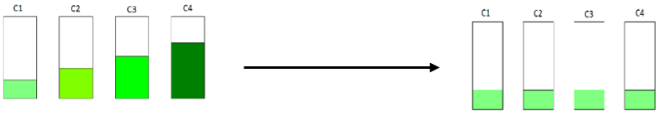

Figure 2:Balancing with passive methods [12][13]

2.2.2 Active methods

In these methods balancing is performed by transferring energy from one cell to another, so that all cells have the same SOC value. In this way, the balancing time is reduced by increasing the complexity of the system and its programming. [10][11]

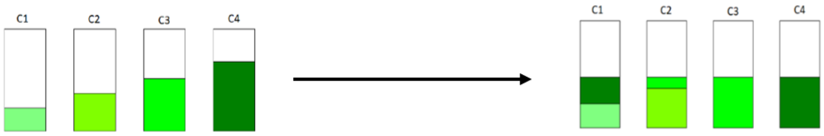

Figure 3:Balancing with active methods [12][13]

Within the active methods there are three different methods depending on the elements used to transfer energy: capacitors, inductors, and transformers. In this thesis we will study the balancing through inductors, depending on the number of inductors used, two other methods can be differentiated:

2.2.2.1 Single inductor equalization circuit

Balancing is done by discharging and charging only one inductor and transfer can be made between any of the battery cells. System cost is increased due to the use of many switches. [14][15]

2.2.2.2 Multiple inductor equalization circuit

In this method, each cell is connected to the next through an inductor and energy can only be transferred between two adjacent cells. Balancing is done faster than using capacitors and costs less than using transformers, which is why we want to implement cell balancing in electric vehicles.
Although there are many advantages to this method, the balancing time becomes longer the greater the distance between the cells where the energy is transferred. This time will be imperceptible in the circuit developed in the thesis since there will only be three cells, but it is a factor to consider when the battery consists of many cells.[16][17].

3. Circuit developed in PSIM.

In this section the circuit is modelled with its three fundamental blocks (cells, control circuit and power supply circuit), making the equations in the starting situation, and parameterizing the elements by performing: power studies, settling time and sensitivity. In conclusion, the objective of this section is to obtain the most efficient and fast circuit, to be able to model it and to obtain conclusions about it.

3.1 Solution Aproach

To be able to perform simulations and obtain conclusions of the cell balancing method with several inductors, this circuit has been realized in the PSIM application that resembles the behavior of an electric car battery. Although a battery really consists of many more cells, only three cells have been implemented in order not to saturate the system and make programming more difficult.

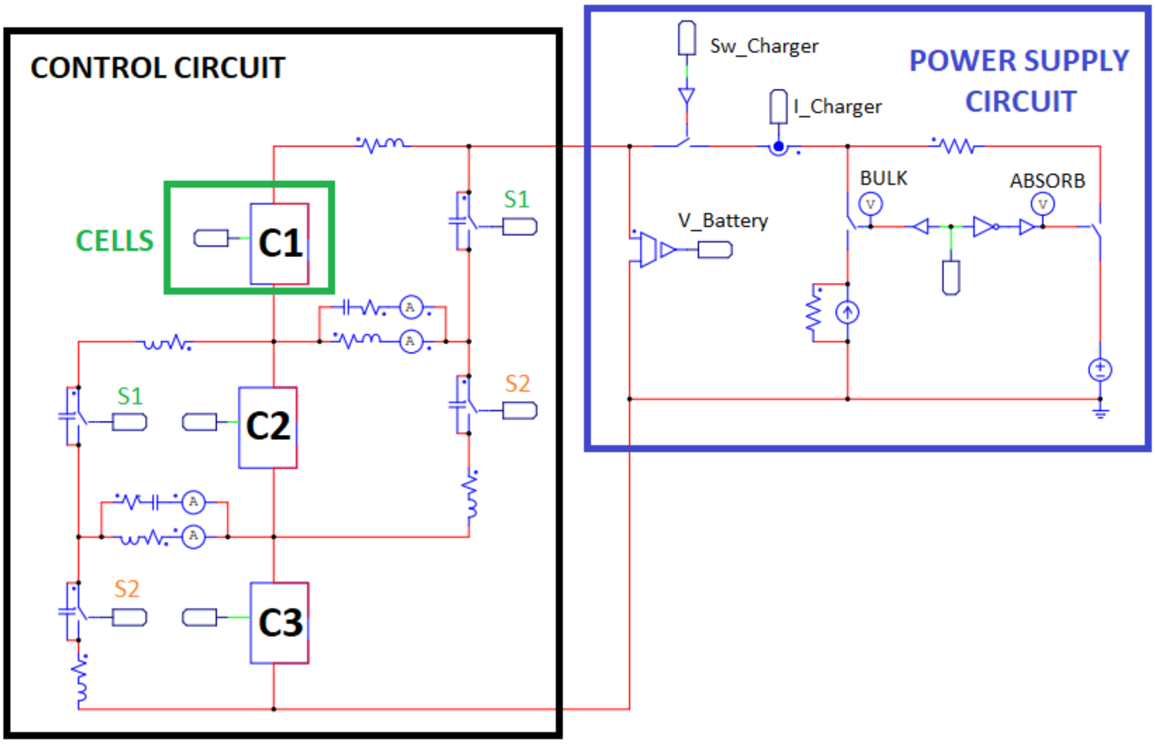

Figure 4:Circuit simulating the behavior of a LiFePO4 battery in PSIM.

As shown in Figure 4 , three distinct parts can be distinguished:

- Cells (C1,C2,C3): blocks that mimic the behavior of a cell.
- Control circuit: formed by the inductors, capacitors and switches, with which the energy transfer between the cells is carried out.
- Power supply circuit: on the right side, with which the cells are charged.

3.1.1 Cells (C1,C2,C3)

Although the cells could be assumed to be a constant voltage element, in reality the voltage varies over time. In order to mimic this behavior, this circuit has been developed [18][19] :

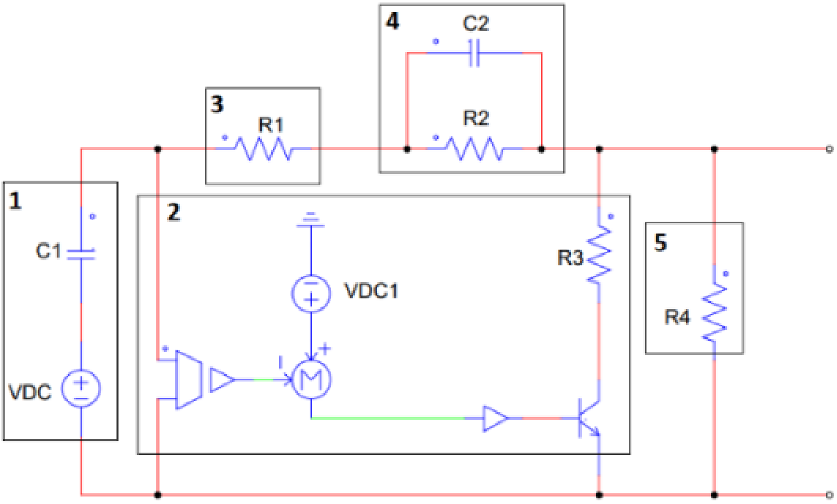

Figure 5:Circuit simulating a cell in an electric LiFePO4 battery.

Block 1: is in charge of defining the battery voltage at instant zero. Knowing that the operating range of a LiFePo cell varies between (3.2V and 3.7V) and that the elemente VDC in Figure 5 has a constant voltage of 2V, the initial capacitor voltage will be chosen between the range (1.2V and 1.7V).

Block 2: when the cell voltage decreases below 3V through the NPN (Negative Positive Negative transistor), current will be passed through the branch of R3, making the battery charge decrease in a faster way.

Block 3: represents the internal resistance of the cell.

Block 4: it will be in charge of filtering the noise caused by the continuous closing and opening of the switches.

Block 5: this block represents the self-discharge resistance, i.e., even if the battery is not being used, the cell charge will decrease as time goes by.

3.1.2 Control circuit

This circuit oversees transferring energy between the different cells to balance them. Inside it we find four switches that will be controlled in pairs. In the left circuit of the Figure 6 the switches S1 are closed making the inductors are charged, while in the second figure closing the switches S2 they will be discharged.

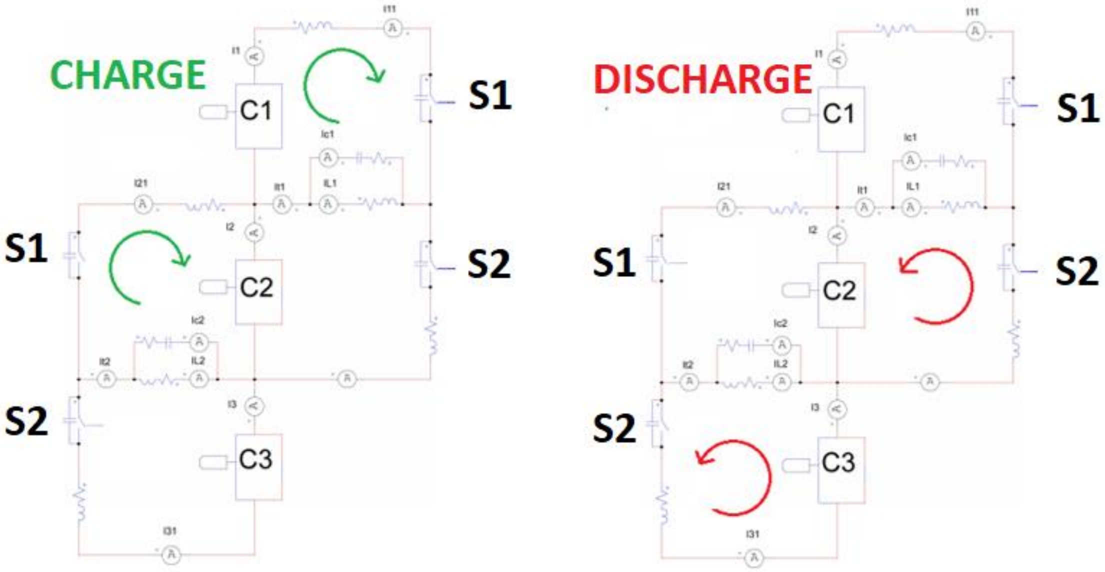

Figure 6:Situations of charge and discharge in inductors

It could be assumed that the circuit will consist only of inductors. This for practical purposes could be a serious problem because when the circuit is closed a lot of current passes through the inductor and opening the switch will create a huge potential difference between the ends of the switch, which could even burn it.

To solve this problem a capacitor has been placed in parallel, so that when the circuit is closed the inductor will charge it and when opening the switch it will discharge feeding the inductor, serving as protection against the switch.

Once the circuit to be used is known, the parameters (R, L and C) must be parameterized in order to get the circuit to behave in the best possible way.

Theoretical study

The circuit will be studied in starting situation when the switches controlled by signal S1 are closed. Since in the other situations there is not enough data to obtain the parameters C and L, and in the initial situation the current through the initial inductor and the initial voltage of the capacitor are available.

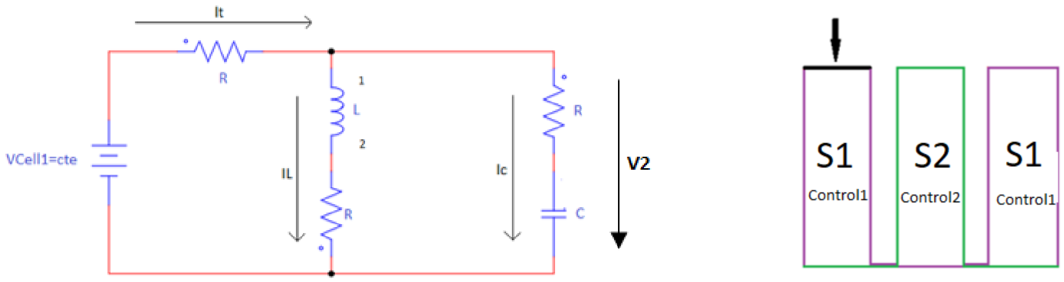

Figure 7:Resulting circuit when the switches controlled by signal S1 are closed.

The current $I_{L0}$and the voltage V_{c0} will be the initial values of the current $I_L$and the voltage V_c, i.e., at t=0.The following equations are obtained from the circuit shown in the Figure 7:

$$It(s) = I_L + I_C \qquad [1]$$

$$V_2 = RI_L + L(sI_L - I_{L0}) \rightarrow \ \boldsymbol{I_L}(s) = \frac{V_2 + LI_{L0}}{(R + Ls)} \qquad [2]$$

$$V_2 = I_cR + V_c \rightarrow \ I_c = C(\ sV_c - V_{c0}) \rightarrow \boldsymbol{I_C}(s) = \frac{C(sV_2 - V_{C0})}{(RCs+1)} \qquad [3]$$

$$I_t = \frac{Vcell - V_2}{R} \rightarrow \ \boldsymbol{V_2}(s) = Vcell - RI_t \qquad [4]$$

Substituting $V_2 = V_{cell} - RI_t$, we obtain the following equation for I_t:

$$I_t(s) = \frac{V_2 + LI_{L0}}{(R + Ls)} + \frac{C(sV_2 - V_{c0})}{(RCS + 1)} \ = \frac{V_{cell} - RI_t + LI_{L0}}{(R + Ls)} + \frac{VcellCs - RCsI_t - CV_{C0}}{(RCS + 1)} \qquad [5]$$

All the It terms are passed to one side and in turn the least common multiple is made:

$$I_t(s)(\frac{(R+Ls)(RCS+1)+R(RCS+1)+RCs(R+Ls)}{(R+Ls)(RCS+1)}) = \frac{(Vcell+LI_{L0})(RCS+1)+(R+Ls)(CsVcell-CV_{C0})}{(R+Ls)(RCS+1)} \qquad [6]$$

The denominator is eliminated in both terms and developing the numerator, we obtain:

$$I_t(s)(2RCLs^2 + (3R^2C + L)s + 2R) = LCV_{cell}s^2 + (2RCV_{cell} + RCLI_{L0} - LV_{C0})s + V_{cell} + LI_{L0} - CRV_{C0} \qquad [7]$$

Due to it is in the starting situation of the circuit, it can be assumed:

$$\boldsymbol{I_{L0} = 0} \qquad \boldsymbol{V_{C0} = 0} \qquad \boldsymbol{V_{cell} = cte}$$

Dividing all the terms by 2RCL, the general expression is obtained:

$$I_t(s) = \frac{\frac{V_{cell}}{2R}s^2 + \frac{V_{cell}}{L}s + \frac{V_{cell}}{2RCL}}{s^2 + \left(\frac{3R^2C+L}{2RCL}\right)s + \frac{1}{CL}} \qquad [8]$$

Initially V_{cell} has been defined as a constant value to simplify all the calculations that have been performed, but the cell voltages are changing throughout the simulation. Therefore, this voltage will be expressed as a step response (V_{cell}/s), leaving the expression of the total current:

$$I_t(s) = \frac{\frac{V_{cell}}{2Rs}s^2 + \frac{V_{cell}}{Ls}s + \frac{V_{cell}}{2RCLs}}{s^2 + \left(\frac{3R^2C+L}{2RCL}\right)s + \frac{1}{CL}} = \frac{\frac{V_{cell}}{2R}s + \frac{V_{cell}}{L} + \frac{V_{cell}}{2RCLs}}{s^2 + \left(\frac{3R^2C+L}{2RCL}\right)s + \frac{1}{CL}} \quad [9]$$

A second-order system made up of these parameters:

$$G(s) = \frac{{w_n}^2}{s^2 + 2\partial w_n s + \ {w_n}^2}$$

The natural frequency and the damping coefficient are obtained from the expression [9]:

$$\boldsymbol{w_n} = \sqrt{\frac{1}{LC}} \quad [10]$$

For a better analysis of the expression, the frequency and values of the circuit are set to unit values. Thus, w_n=1 and therefore *LC=1*

$$2\partial w_n = \frac{(3R^2C+L)}{2RCL} \rightarrow \boldsymbol{\partial} = \frac{(3R^2C+L)}{4R} \qquad [11]$$

Applying these changes results in this expression:

$$I_t(s) = \frac{\frac{V_{cell}}{2R}\boldsymbol{s}+\frac{V_{cell}}{L}+\frac{V_{cell}}{2Rs}}{\boldsymbol{s}^2+\left(\frac{3R^2C+L}{2R}\right)\boldsymbol{s}+1} \quad [12]$$

Once an expression of the total intensity from time has been obtained. To optimize the circuit, two paths can be followed:

- Search for the parameters that allow the circuit to be faster at the time of charging.
- Search for the parameters that allow to introduce more power to the coils.

Minimize charging time.

To study the fastest system, the circuit will be studied in two different situations:

- **Assume critical damping, ∂=1:**

Equalizing the damping coefficient to 1 gives the value of L as a function of R at which the current equilibrium situation will be reached in the fastest way:

$$1 = \frac{(3R^2C+L)}{4R} \rightarrow \frac{3R^2}{L} - 4R + L = 0 \rightarrow R = \frac{4 \pm \sqrt{16 - \frac{12L}{L}}}{6/L} = \frac{4 \pm 2}{6/L} \qquad [13]$$

Two possible solutions are obtained:

$$\boldsymbol{L = R} \qquad\qquad \boldsymbol{L = 3R}$$

- **Find the minimum or maximum value of ∂ as a function of L:**

The first derivative equalled to 0 will be performed to see at what point a maximum or minimum is found in the delta function:

$$\frac{d\partial}{dL} = 0 \rightarrow \frac{1}{4}\frac{d}{dL}\left(\frac{3R}{L} + \frac{L}{R}\right) = 0 \rightarrow \left(\frac{-3R}{L^2} + \frac{1}{R}\right) = 0 \rightarrow 3R^2 = L^2 \rightarrow \qquad \boldsymbol{L = R\sqrt{3}} \qquad [14]$$

The second derivative is made including the value of L=R√3, if it is greater than 0 it will be a minimum and if it is less a maximum:

$$\frac{d^2\partial}{(dL)^2} = \frac{6R}{L^3} \rightarrow \frac{d^2\partial}{(dL)^2} > 0 \rightarrow \; MÍNIMUM \qquad [15]$$

It is substituted into delta equation 11 with L= R√3 to see what the smallest value delta is will be able to have:

$$\partial = \frac{\left(\frac{3R^2}{R\sqrt{3}}+R\sqrt{3}\right)}{4R} = \frac{\sqrt{3}}{2} \qquad [16]$$

That is, with this value of L an underdamped system is obtained. Before performing any power calculation, the option in which L= R√ 3 can be previously discarded, since, being an overdamped system, it is always going to have a slower behavior than the two other options that are critically damped.

Both situations (L=R and L=3R) will be studied to see where the maxima and minima of the intensity are obtained, and how quickly they are reached

Case L = 3R

Substituting in the expression [12] we obtain:

$$I_t(\mathrm{s}) = \frac{\frac{V_{cell}}{2R}\boldsymbol{s}+\frac{V_{cell}}{3R}+\frac{V_{cell}}{2R}}{\boldsymbol{s}^2+2\boldsymbol{s}+1} = \frac{\frac{V_{cell}}{R}(\frac{s}{2}+\frac{1}{3}+\frac{1}{2s})}{s^2+2s+1} = \frac{\frac{V_{cell}}{R}(\frac{6s^2+4s+6}{12s})}{s^2+2s+1} \qquad [17]$$

Applying Laplace's inverse:

$$I_t(t) = \frac{V_{cell}}{R} L^{-1}\left\{\frac{\frac{V_{cell}}{R}(\frac{6s^2+4s+6}{12s})}{s^2+2s+1}\right\} = \frac{V_{cell}}{R}(\frac{1}{2}\partial(t) - \frac{2}{3}e^{-t}t) \qquad [18]$$

To check which of all the solutions is the optimal one, it will be analysed when the derivative of the input current becomes zero, since it is an inflection point in the speed of the system:

$$\frac{dI_t\,(t)}{dt} = 0 \rightarrow -\frac{2V_{cell}}{3R}(e^{-t} - e^{-t}) = 0 \rightarrow e^{-t} = e^{-t}t \rightarrow t = 1 \qquad [19]$$

The second derivative is equalled to zero, substituting the value obtained in the first derivative (t=1):

$$\frac{d^2I_t(t)}{dt}(t = 1)> 0 \rightarrow -\frac{2Vcell}{3R}\ (t-2)e^{-t} > 0 \rightarrow \frac{2Vcell}{3Re} > 0 \rightarrow MINIMUM \quad [20]$$

To verify that what has been solved theoretically also happens in practice, the circuit will be simulated in PSIM with the data L=3R and we will see how the total current behaves:

R = 1Ω ***L***=*3Hr* ***C***= *1/L= 1/3 F* ***VDC***=*1 V*

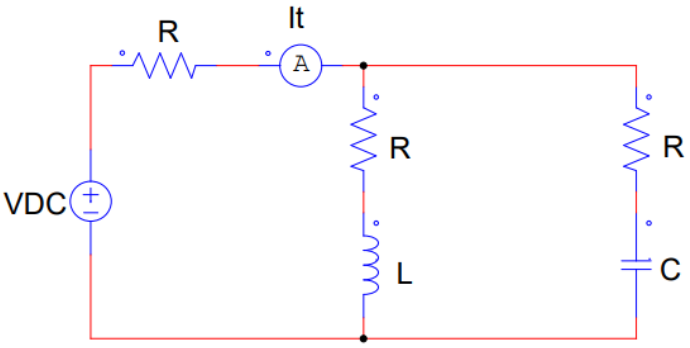

Figure 8:resulting circuit when the switches controlled by signal S1 are closed, situation L=3R

In Figure 9 one can see the I_t during the first three seconds during the simulation:

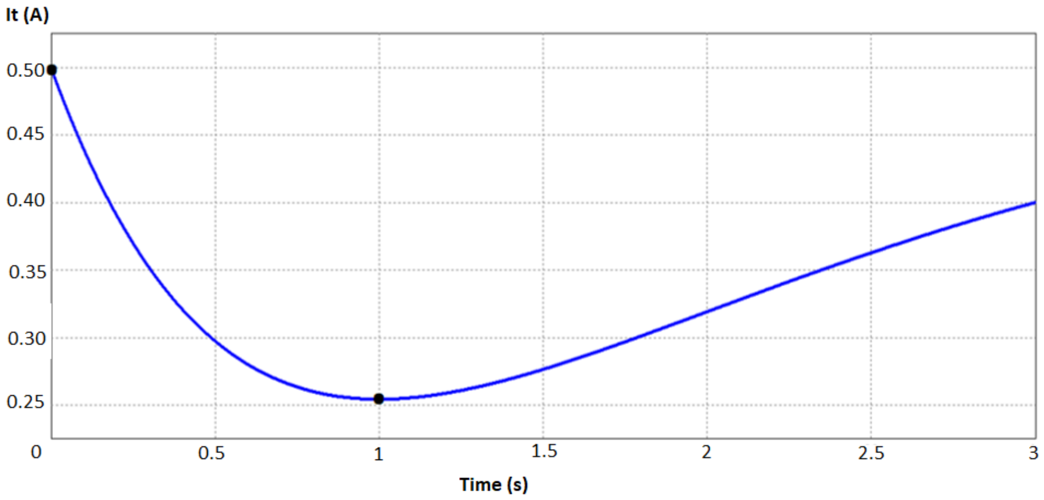

Figure 9:It graph when the switches controlled by signal S1 are closed, situation L=3R

Equation 18 will be studied in two situations (t=0 and t=1):

$$I_t(t=0)=\frac{V_{cell}}{R}\left(\frac{1}{2}\partial(t)-\frac{2}{3}e^{-0}0\right)=\frac{V_{cell}}{2R}=0.5A \quad [21]$$

$$I_t(t=1)=\frac{V_{cell}}{R}\left(\frac{1}{2}\partial(t)-\frac{2}{3}e^{-1}1\right)=\frac{V_{cell}}{2R}-\frac{2V_{cell}}{3R}=0.2547A \quad [22]$$

As can be seen, the results obtained theoretically coincide perfectly with the data obtained in the simulation (marked with a dot in the graphs), so it can be concluded that the simulation of the system has been developed in a correct way.

Case L = R

Substituting in the expression [12] we obtain:

$$I_t(s) = \frac{\frac{V_{cell}}{2R}\boldsymbol{s}+\frac{V_{cell}}{R}+\frac{V_{cell}}{2Rs}}{\boldsymbol{s}^2+\left(\frac{\frac{3R^2}{R}+R}{2R}\right)\boldsymbol{s}+1} = \frac{\frac{V_{cell}}{2R}\boldsymbol{s}+\frac{V_{cell}}{R}+\frac{V_{cell}}{2Rs}}{\boldsymbol{s}^2+2\boldsymbol{s}+1} = \frac{V_{cell}}{R}\left(\frac{\frac{2s^2+4s+2}{4s}}{\boldsymbol{s}^2+2\boldsymbol{s}+1}\right) = \frac{V_{cell}}{2Rs} \quad [23]$$

Applying the inverse of LaPlace we obtain:

$$I_t(t) = \frac{\boldsymbol{Vcell}}{\boldsymbol{2R}}\boldsymbol{\partial(t)} \quad [24]$$

The I_t plot will be observed in the circuit of Figure 8, this time with the L=R relationship:

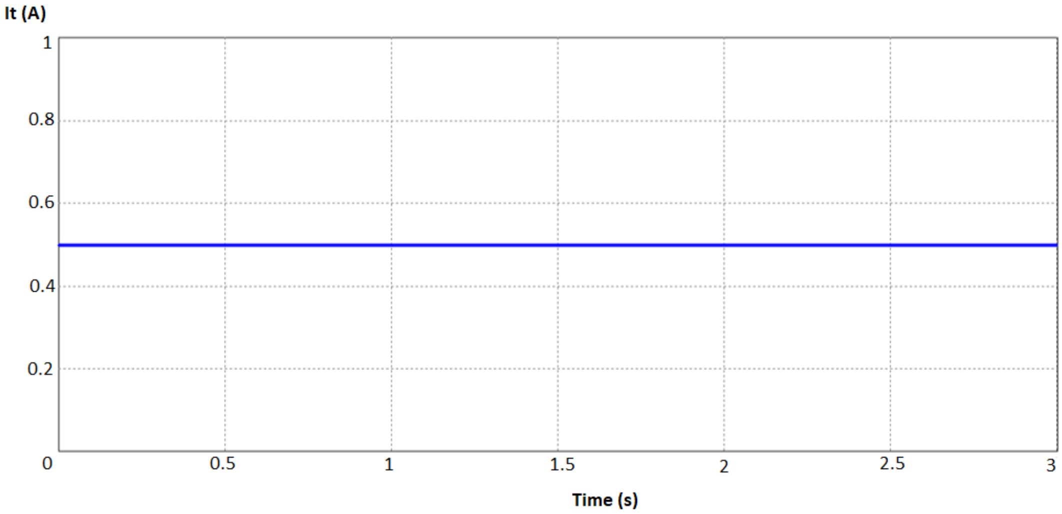

Figure 10:It graph when the switches controlled by signal S1 are closed, situation L=R

Studying equation 24 with the data L=R=C=1 we obtain: $I_t(t) = \frac{\boldsymbol{Vcell}}{\boldsymbol{2R}} = \boldsymbol{0.5A}$ [25]

Being a constant term, it is evident that the first and second derivatives will be zero. Only having studied the system in terms of speed it can be concluded that when L=R the system will behave in a faster way than with L=3R and therefore the system will be optimized. Even so, to corroborate that we are following the right path and procedure we will study the circuit in power.

Power study

In this section we will study which parameters for the elements are the best to achieve more power. To obtain the best system, the power expression will be obtained:

$$P(s) = V_2 \cdot I_t(s) = \frac{V_2 \cdot V_2}{(R+Ls)} + \frac{CsV_2 \cdot V_2}{(RCS+1)} = \frac{{V_{cell}}^2 - 2RI_t + R^2 I_t^2}{(R+Ls)} + \frac{Cs({V_{cell}}^2 - 2RI_t + R^2 I_t^2)}{(RCs+1)} \qquad [26]$$

It is the least common multiple:

$$P(s) = \frac{A}{RCLs^2 + (R^2C+L)s + R} = \frac{A}{s^2 + \left(\frac{R^2C+L}{RCL}\right)s + \frac{1}{CL}} \qquad [27]$$

The numerator is represented with a value of A because it is independent, since what is important is the denominator from which the natural frequency and the damping coefficient will be obtained:

$$\boldsymbol{w_n} = \sqrt{\frac{1}{LC}} \to w_n = 1 \to \quad LC = 1 \quad [28] \qquad\qquad 2\partial w_n = \frac{R^2C+L}{RCL} \to \ \partial = \frac{1}{2}\left(\frac{R}{L} + \frac{L}{R}\right) \quad [29]$$

In turn, as in the case of the time study, there are two ways:

- **Assume critical damping, ∂=1 :**

$$2 = \frac{R^2 + L^2}{RL} \to L^2 - 2RL + R^2 = 0 \to L = \frac{2R \pm \sqrt{4R^2 - 4R^2}}{2} \to \quad \boldsymbol{L = R} \qquad [30]$$

- **Find the minimum or maximum value of ∂ as a function of L:**

$$\frac{d\partial}{dL} = 0 \to \frac{1}{2}\frac{d}{dL}\left(\frac{R}{L} + \frac{L}{R}\right) = 0 \to \frac{1}{2}\left(-\frac{R}{L^2} + \frac{1}{R}\right) = 0 \to \frac{R}{L^2} = \frac{1}{R} \to \quad \boldsymbol{L = R} \qquad [31]$$

Studying how the power would be if we substitute L=R:

$$P(t) = {V_{cell}}^2 - 2RI_t + R^2 I_t^2 \to L^{-1}\{P\} = 2\left(\frac{V_{cell}^2}{R}\right)t \quad [32]$$

As it was known before carrying out the power study, the best option is L=R, since being a constant value it has a settling time equal to 0 and always delivers the maximum power.

Once the relationship between the parameters is obtained, these should be passed to the frequency at which the circuit is working, because if we implement in the PSIM circuit a frequency of 1Hz the balancing will be very slow, and it will never work. In this case a random frequency of 1000Hz has been chosen, with which the balancing will be done in a fast way and will not generate much noise.

Throughout the theoretical study an angular velocity of 1 rad/s has been assumed, with this value and that of the angular velocity, we obtain a parameter α that relates them:

$$\alpha = \frac{\omega_{circuit}}{\omega_{units}} = \frac{2\pi 10^3}{1} = 2\pi 10^3 \qquad [33]$$

By developing the expression of the angular velocity of the circuit, a relationship between the components obtained theoretically and those to be implemented in practice will be achieved.

$$\omega_{circuit} = \frac{1}{\sqrt{L'C'}} \rightarrow L'C' = \frac{1}{(\omega_{circuit})^2} = \frac{1}{\alpha^2 \omega_{units}^2} = \frac{1}{\alpha^2 \cdot \frac{1}{LC}} \rightarrow (\alpha L')(\alpha C') = LC \qquad [34]$$

Since with expression 29 there are two unknowns, to facilitate the resolution, a value for the inductance will be randomly assumed:

$$R = 0.2\Omega \qquad \boldsymbol{L' = L = 0.2Hr}$$

Knowing that L equals L', this value will be obtained for the circuit capacitor:

$$C' = \frac{C}{\alpha^2} = \frac{\frac{1}{L}}{\alpha^2} = \frac{1}{L\alpha^2} = \frac{1}{0.2 \cdot (2\pi 10^3)^2} \rightarrow \quad \boldsymbol{C' = 126nF} \qquad [35]$$

Once obtained these values of the components that form the circuit, it is known that with them the circuit will behave in the fastest way and obtaining the highest possible power. Now it only remains to carry out a programming (chapter: “Circuit programming”) that allows us to control the voltage of the cells and that its load is carried out in the most similar way to the one that really takes place in a battery of an electric car.

Sensibility study:

Sensitivity analysis is one of the most widely used tools to predict the expected results of a project. With them, decision making will be facilitated, and the values of the circuit elements will be assigned in a more appropriate way.
In figure 7 it has been assumed that all the resistances of the circuit are the same and have the value of R. But it is not quite true since the resistance of the cell depends on other parameters. That is why to study the sensitivity of our system we will study the system in this way.

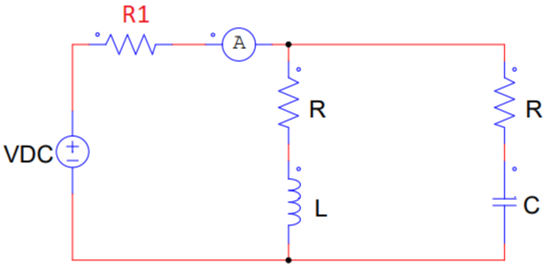

Figure 11:Resulting circuit when the switches controlled by signal S1 are closed, differentiating resistors.

The value of R1 will be:

R1=Rintern+Rwiring+ RMosfet

The Rwiring and RMosfet their value can be known, on the other hand of the Rintern is unknown, therefore the value of R1 will be expressed:

R1= R+∆R

The expression of the sensitivity will be studied:

$$\mathrm{Sensitivity} = \frac{\mathbf{I_t(R)-I_t(R+\Delta R)}}{\boldsymbol{R_1-R}} \quad [36]$$

Developing each expression of the numerator:

$$\mathrm{I_t(R)} = \frac{\mathrm{Vcell}}{\mathrm{2R}} \quad [37]$$

$$\mathrm{I_t(R+\Delta R)} = \frac{\mathrm{V_2+LI_{L0}}}{\mathrm{(R+Ls)}} + \frac{\mathrm{c(sV_2-V_{c0})}}{\mathrm{(RCS+1)}} = \frac{\mathrm{V_{cell}-R_1I_t+LI_{L0}}}{\mathrm{(R+Ls)}} + \frac{\mathrm{VcellCs-R_1CsI_t-CV_{C0}}}{\mathrm{(RCS+1)}} \quad [38]$$

$$\mathrm{I_t(R+\Delta R)}\big(\mathrm{(RCL+R_1CL)s^2+(2RCR_1+R^2C+L)s+(R+R_1)}\big) = \mathrm{LCV_{cell}s^2+2RCV_{cell}s+V_{cell}} \quad [39]$$

Substituting ,CL=1 R=L:

$$I_t(R+\Delta R)\left((R+R_1)s^2+(2R_1+R+R)s+(R+R_1)\right)=V_{cell}s^2+2V_{cell}s+V_{cell} \quad [40]$$

Substituting R1= $R+\Delta R$:

$$I_t(R+\Delta R)\left((2R+\Delta R)s^2+(4R+2\Delta R)s+(2R+\Delta R)\right)=V_{cell}s^2+2V_{cell}s+V_{cell} \quad [41]$$

Grouping terms:

$$I_t(R+\Delta R)=\frac{V_{cell}(s^2+2s+1)}{(2R+\Delta R)(s^2+2s+1)}=\frac{V_{cell}}{(2R+\Delta R)} \quad [42]$$

Finally, the expression is obtained:

$$\text{Sensitivity}=\frac{\frac{V_{cell}}{2R}-\frac{V_{cell}}{(2R+\Delta R)}}{(R+\Delta R)-R}=\frac{V_{cell}}{2R(2R+\Delta R)} \quad [43]$$

This increase in resistance is inversely proportional to the sensitivity, so that when the sensitivity increases the system will be less accurate and the balancing will be performed in a worse way. Figure 12 shows the cell voltages when R has a value of 5Ω,as one can see, no balancing is performed:

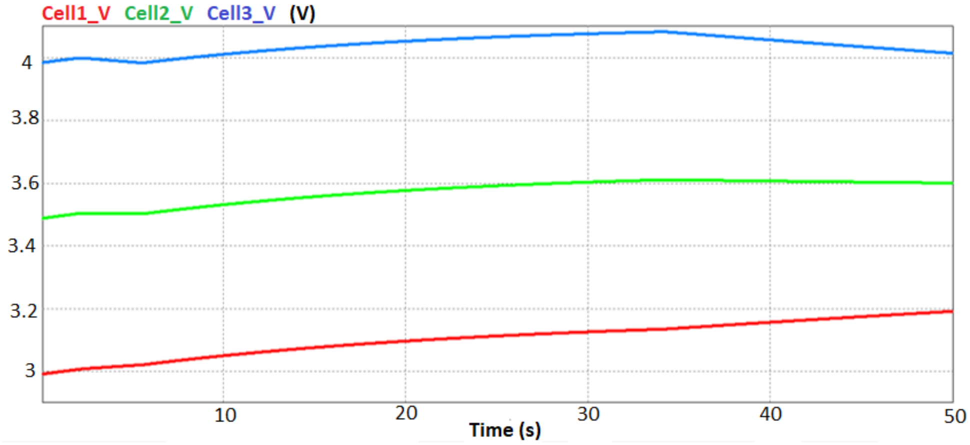

Figure 12: Cell voltages graphs when Vcell1>Vcell2> Vcell3, when $\Delta R = 5$

.

That is why in the section ("3.2 Theorethical Study”) we have assumed all the R of the circuit to be equal, because this means that ΔR=0 and thus the maximum possible sensitivity is obtained

3.1.3 Power supply circuit

Before explaining the programming that has been carried out, it is necessary to have clear how the process of load takes place in an electrical battery.
This process is carried out in 3 main phases [20][21]:

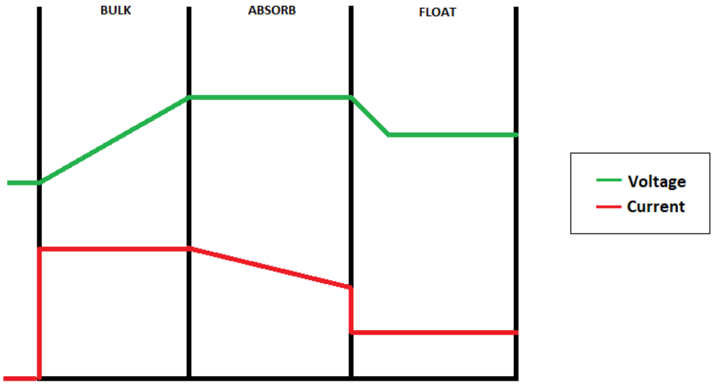

Figure 13:Stages of battery charging

Bulk: this is the first charging stage, in which, with constant current and a progressively increasing voltage, 90% of the battery charge is achieved. It is recommended by large companies (BMW, Tesla …) that the current of load in this stage is a tenth part of the total capacity of the battery. Knowing that in the circuit of PSIM this capacity is of 10Ah the current will be of 1A.

Absorb: in this stage the total charge of the battery is completed. Unlike the previous stage, in this one the voltage remains constant at its maximum value and the current will be decreasing little by little. The purpose of this stage is to recover the electrolyte (conductor used to transport the electric ions from the positive plate to the negative plate). The duration of this stage will increase, depending on how deteriorated the electrolyte is. The voltage provided should be higher than the total voltage of the battery. In this case the voltage is 10.95 V, since the 3.6 V of each cell make up 10.8 V.

Float: in this phase the battery is already 100% charged and only the necessary intensity is provided to compensate the self-discharge that can be realized. In the circuit to be implemented in PSIM this stage will not be considered, since the simulations and conclusions to be obtained are for very short times and this stage is a factor that needs a very long simulation time.

Once the 3 phases have been explained, we will proceed to the explanation of the programming thanks to a flowchart:

4.Circuit programming

In this section we will study the programming that has been carried out to obtain a correct cell balancing:

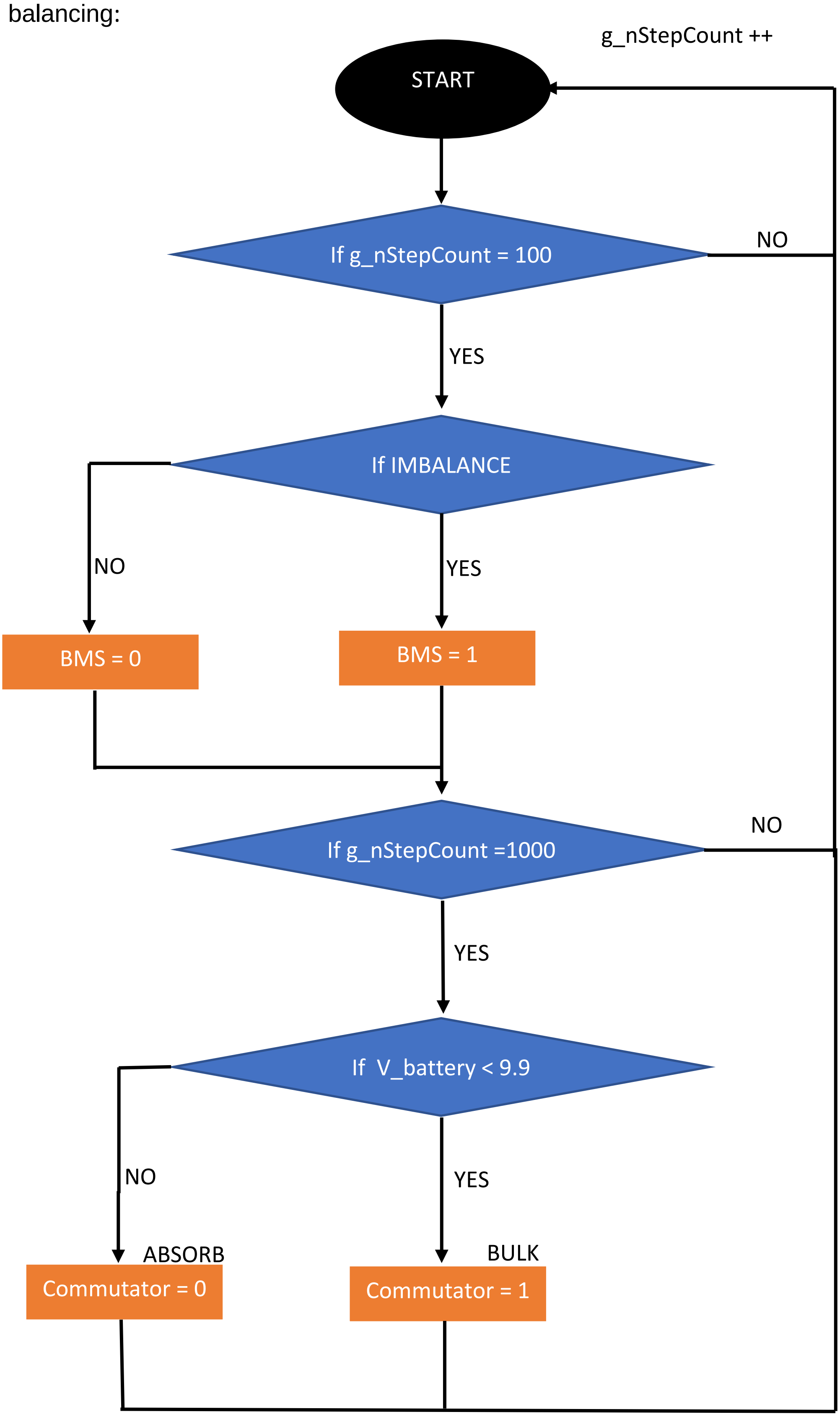

Figure 14:Flowchart for cell balancing programming.

Before starting the simulation, these parameters will be defined:

$$V_{Average} = (V_{cell1} + V_{cell2} + V_{cell3})/3$$

A variable will be defined with the name g_nStepCount which will act as a counter. Once it reaches a value of 100 (random value), it will be checked if the system is in balance or not. It will be understood that the system is not balanced if the subtraction between $V_{average}$ and any of the cells is greater than the variable defined as Imbalance.

As explained in the control circuit, the switches are regulated by two signals S1 and S2. These periodic signals are 180º out of phase and both have the same period and are multiplied by the BMS signal. In this way, when the BMS signal is equal to 1, balancing will be performed, while the BMS signal has a value equal to 0, no energy transfers will be performed, and all switches will be open.

When the variable g_nStepCount reaches the value of 1000 (random value), the state of charge of the battery will be checked. If the battery is less than 90% of its total charge (in this case 10.8*0.9= 9.72 V), a value of 9.9 V is set in the circuit to have a certain margin of operation, a constant current will be applied through the switch since it is in the bulk stage. Otherwise, if the battery voltage value is higher than 90%, a constant voltage will be applied since we are in the absorb stage.

Now the circuit will be simulated in different situations to check its correct operation.

5.Results and discussion

The circuit will be studied in three possible situations:

- Vcell1> Vcell2> Vcell3
- Vcell2> Vcell3> Vcell1
- Vcell3> Vcell 1> Vcell2

In each situation the maximum voltage has a different cell, in this way it will be possible to see if the circuit works in all possible operating situations.

5.1 Case 1: Vcell1> Vcell2> Vcell3

The following values will be chosen for the cell voltages: Vcell$_1$= 4V, V$_{cell2}$= 3.5V y V$_{cell3}$=3V.The cell voltages will be analysed through these two graphs (Figure 15 and Figure 16):

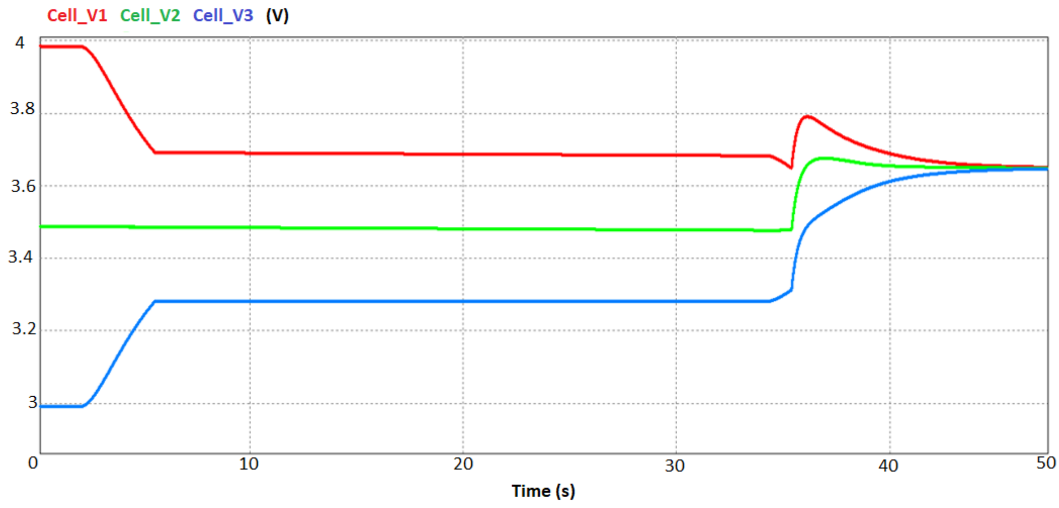

Figure 15:Cell voltages graphs when Vcell1>Vcell2> Vcell3

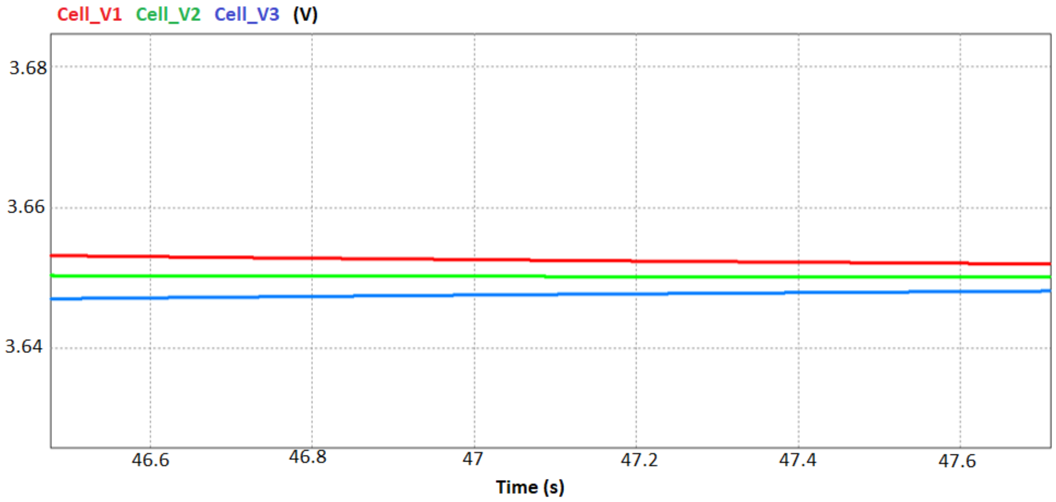

Figure 16:Zoom of cells voltages graphs display when Vcell1>Vcell2> Vcell3.

.

As can be seen in Figure 15 and 16, the three voltages behave as critically damped systems and in less than 50 seconds the balancing of the three cells is achieved, at a value close to 3.65V.

To know how the energy transfers have occurred, the power will be analysed. As it is known when the power is positive the cell will be delivering energy to the other two, on the other hand if it is negative, it will be receiving.

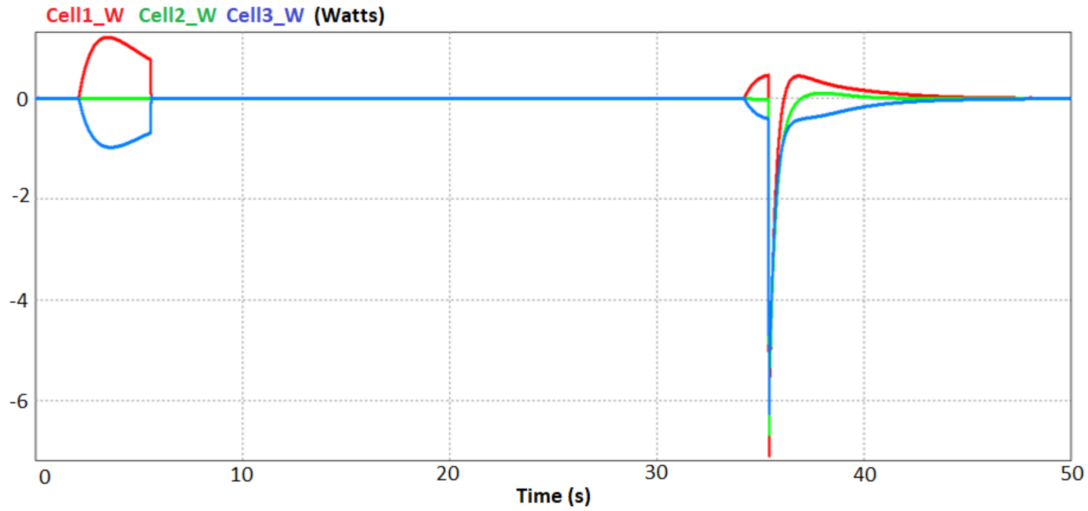

Figure 17:Cells power graphs when Vcell1>Vcell2> Vcell3

It is evident to think that since the one with the highest voltage of the three is the one located at the top of the scheme, the energy transfer will be carried out downwards to charge the third cell, which is the one with the lowest voltage. In Figure 17 it can be seen how in many moments of the simulation cell two is behaving as a communication nexus, being the first one the one that is giving energy to the third one.

Now it will be analysed through the graphs (Figure 18) of the battery voltage and the different charging stages (I_cte=Blunk and V_cte= Absorb) that the charging process is being done in a correct way.

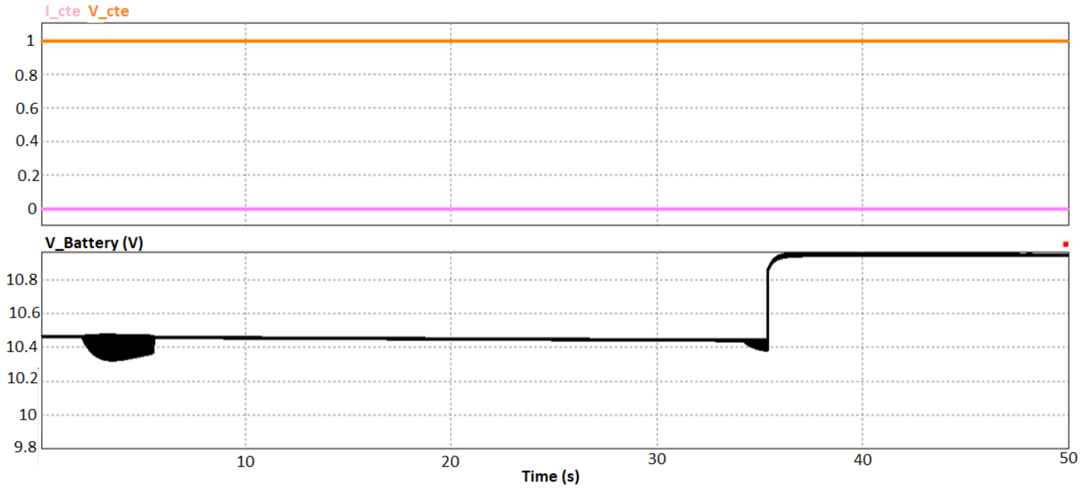

Figure 18:Cells (blunk, absorb and voltage battery) graphs when Vcell1>Vcell2> Vcell3.

As can be seen in the Figure 18, the simulation will be only in the absorb process, since the battery voltage is always higher than 90% (9.9V).

Now we will proceed to analyse what happens inside the control circuits of cell 1, where the inductors and capacitors are located.

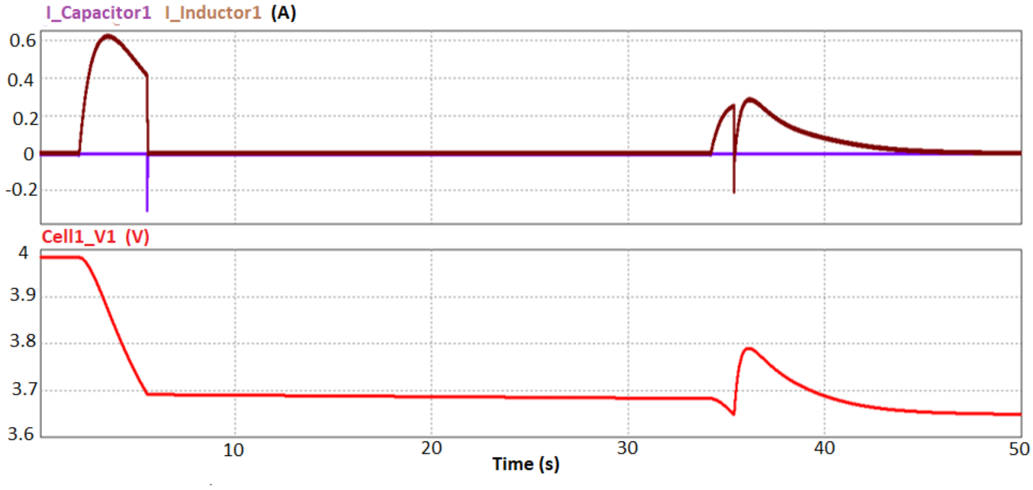

Figure 19:graphs of capacitor and inductor currents in cell 1 when Vcell1>Vcell2> Vcell3.

As it can be observed in Figure 19 when the voltage of cell 1 decreases the current through the coil increases, since through this the coil will oversee transferring that energy surplus to the rest of the cells that conform the battery. To obtain more conclusions, it will be extended in a part of the simulation:

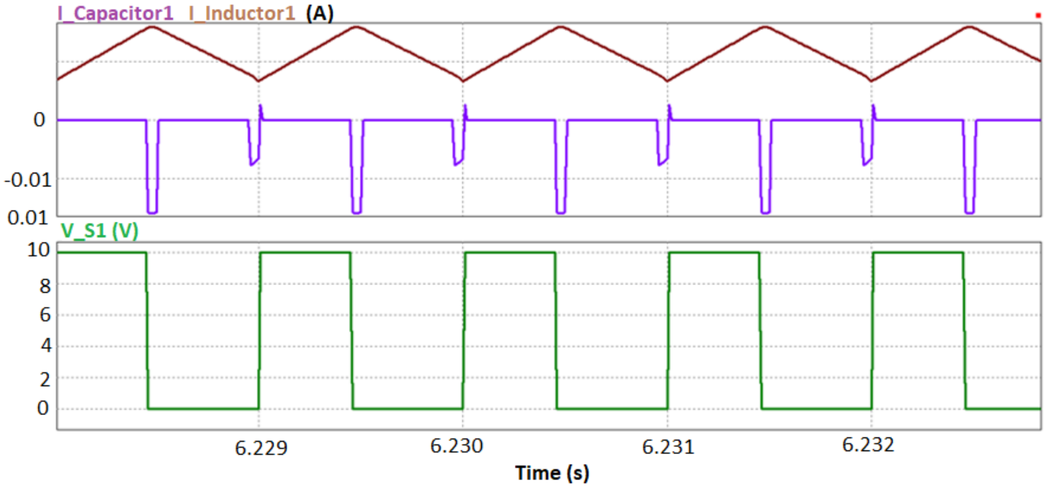

Figure 20:Zoom of graphs of capacitor and inductor currents in cell 1 when Vcell1>Vcell2> Vcell3.

As explained in chapter “3.1.2 Control Circuit”, it can be seen perfectly well that the function of the capacitor. It will be charged or discharged when the breaker opens or closes, so as not to burn the breaker.

5.2 Case 2: Vcell2> Vcell3> Vcell1

These random values will be chosen: Vcell$_2$= 4V, Vcell$_3$= 3.5V y V$_{cell1}$=3V

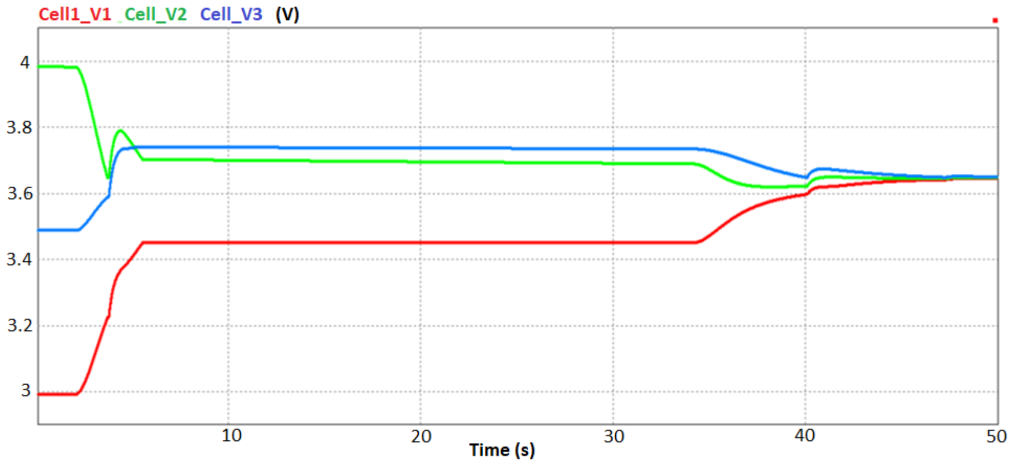

Figure 21:Cell voltages graphs when Vcell2>Vcell3> Vcell1

A perfect functioning of the simulation circuit can be observed in this situation since a balancing of the cells is performed before the 50 seconds of simulation.

5.3 Case 3: Vcell3> Vcell 1> Vcell2

These random values will be chosen: Vcell$_3$= 4V, Vcell$_1$= 3.5V y V$_{cell2}$=3V

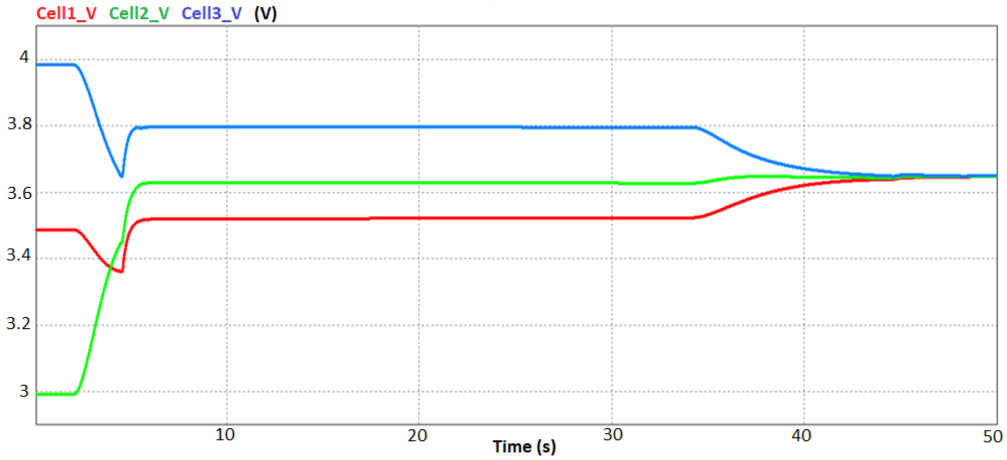

Figure 22:Cell voltages graphs when Vcell2>Vcell3> Vcell1

A perfect functioning of the simulation circuit can be observed in this situation, since a balancing of the cells is performed before the 50 seconds of simulation.

6. Conclusions

In this project a circuit has been designed and programmed through which the balancing of the cells is performed using inductors. This fulfils the main functions that were taken as the objective of the work, demonstration of the possible incorporation in the battery of an electric vehicle.

In addition, throughout the thesis numerous theoretical calculations have been performed to try to minimize the cell balancing time and improve the performance of the system, this has been achieved by parameterizing the circuit with L=R, thus achieving a critically damped response.

Although many companies continue to opt for the use of capacitors when making the BMS since they considerably reduce costs and achieve an acceptable balancing, with the completion of this thesis a new path is opened for the use of inductors, since it has been demonstrated an optimal performance in all possible situations. It is necessary to consider that the present project has only studied the battery in three single cells, which may differ from the results obtained in a complete battery.

As future projects, the possible incorporation of the circuit to a complete battery or the practical implementation of this same circuit is being considered.

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List of figures