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Passive Cell Balancing of Li-Ion batteries used for Automotive Applications

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Abstract. Due to the increasing demand of Li-ion batteries in automobiles and home applications due to their high volumetric energy density, high gravimetric energy density, low self-discharge and high efficiency. However, due to their high energy carrying capability, they tend to be more unstable compared to other batteries like lead acid batteries and hence need extensive monitoring to make sure they are operating within their specified safe operating limits; failing to do so may result in fire hazards and explosions. Hence this creates a demand for sophisticated Battery Management System (BMS) which will not only optimize power draw from the batteries but also keep them operating within safe limits, thus not putting the users at risk. This research paper begins with battery modelling using passive components and discusses the major factors which are important while designing an effective BMS. It also provides simulation to help better understand the functioning of a BMS.

1. Introduction

Li-ion batteries are most widely used battery in the Electric Vehicle (EV) due to its high performance [10]. Li-ion batteries are very fragile due to their high energy density (Wh/L) and specific energy (Wh/kg). Hence sophisticated electronics are required to make sure no cell in the pack is going outside their safe operating area (SOA) [7]. A typical Li-ion cell has a nominal voltage of 3.7V, maximum voltage of 4.2V and minimum voltage of 2.7V. If the extreme limits of the battery are violated, i.e. the any cell is charged more than 4.2V or discharged less than 2.7V, it can lead to unstable cell conditions and even cause fire hazards [8].

The functions of a BMS is to keep all the cells within their pre-set safe operational limits by voltage, current, temperature measurement and communicating with the master controller if any cell is out of bounds so that necessary steps can be taken to bring the cell to its SOA or deploy contingencies to prevent fire hazards. A complete BMS will have controlled charging using Constant Current Constant Voltage (CCCV) to ensure all cells are charged to their 100% State of Charge (SoC), cell balancing techniques so that all the cells are at the same voltage after charging and necessary failsafe and protections circuits so that the user or the vehicle is not damaged in case of unwanted operations of the battery pack [2],[4]. The objective of this paper is to develop and design a passive balancing using Constant Current Constant Voltage (CCCV) charging. This paper is organized as follows. Section 2 presents the basic functions of Battery management systems; Section 3 presents cell balancing techniques, section 4 presents the design approach, section 5 presents the simulation results and section 6 presents the conclusion.

2. Basic functions of BMS

The Li-ion cell BMS ensures that the cells in the battery remain within the safe operating limits and it takes action when the cell goes out of the operating limits. A BMS will disconnect loads if the voltage goes too low, and disconnect chargers if the voltage goes too high. It will also check that the voltage of each cell in the pack is the same, and bring down the voltage of any cell that is higher than the others. If the voltage (nominal voltage of 3.7V) of the lithium cell goes beyond 4.0V to 4.5V or below 3V then two things can happen [i] they can burst [ii] their life reduces. A BMS also monitors the temperature and regulates it. Cell balancing, i.e. equalizing the voltages of all batteries in the pack, is done by cell balancing which is broadly classified into 2 categories: passive cell balancing and active cell balancing [4].

From the charge and discharge cycles of Li-ion cell distinct drops and spikes in voltages can be observed. To understand the nature of these charging and discharging cycles the electrical equivalent circuit of the battery has to be modelled correctly. In equivalent circuit model shown in figure 1 passive components (resistors and capacitors) are used to model the behaviour of the battery during charging and discharging durations. From the charging and discharging intervals, sharp increase and decrease in terminal voltages of the Li-ion cell can be observed [1].

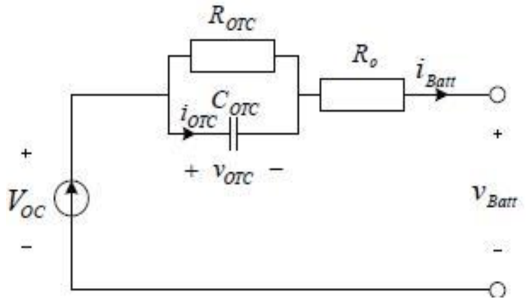

Figure 1. Equivalent Circuit model of a cell with Passive Components

This is the drop due to the internal resistance which can be modelled using a resistor. Internal resistance arises due to the electrochemical reactions inside the battery which resists charge or discharge. The cell voltage drop follows an exponential pattern as observed in [1].To account for the exponential discharge of the cell a parallel RC network is connected in series with internal resistance of the cell.

When the charging current is removed, the battery voltage becomes a function of the capacitor voltage whose charge is decaying through the resistor and it follows an exponential pattern. Hence the battery can be modeled using an open circuit dependent voltage source (V_{OC}), in series with an internal resistance (r) and parallel RC network (R_{OTC} and C_{OTC}). [1].

3. Cell balancing techniques

Cell balancing is the method by which after each charging cycle, the voltages of all the cells in the battery pack are equalized by using passive components. This is either done by discharging the most charged cell or transferring the charge from one cell/pack to another cell. This is very important as any irregularities in the cell voltages after the charging is complete will cause the pack voltage to differ from the nominal value and it will give an inaccurate sense of the SoC of the whole pack [9]. Moreover, if during the charging cycle, cell voltages are not monitored and balanced, it may cause few cells to be overcharged and that may prove to be hazardous.

3.1 Passive cell balancing.

This method uses a resistor to dissipate the energy of the cell with the highest voltage in a series pack. Generally the weakest cell reaches maximum voltage threshold faster for the same current through the rest of the other cells in the pack. When the cell voltage exceeds the SOA (safe operational area), the switch is turned on and cell is allowed to discharge through the resistor also called bleeding resistor as shown in Figure 2, so that the cell voltage and SoC comes down to a safe level. This process is repeated until all the cells have reached the same voltage. The voltage is monitored using voltage monitoring ICs which convert the voltage from analog to digital using A/D converters.

Passive cell balancing, although it is a dissipative method, it is more commercially implemented due to its easier control. Charge and discharge rates of a battery are governed by C-rates. The capacity of a battery is commonly rated at 1C, meaning that a fully charged battery rated at 1Ah should provide 1A for one hour. The same battery discharging at 0.5C should provide 500mA for two hours, and at 2C it delivers 2A for 30 minutes. Losses at fast discharges reduce the discharge time and these losses also affect charge times [5 & 6].

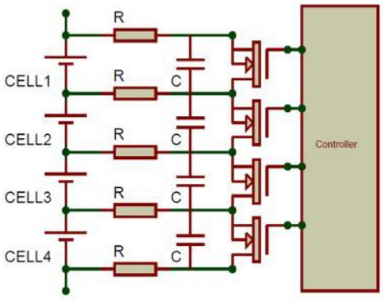

Figure 2. Passive balancing circuit using resistors and capacitors

3.2 Active cell balancing

Unlike passive balancing, active balancing does not dissipate the energy through a resistor; rather it stores or transfers the energy from one cell to other as shown in Figure 3. Switched capacitors do that by storing the energy from a higher voltage cell in a capacitor and then transferring it to another lower voltage cell. In the Flyback topology, as shown in Figure 4, the energy transfer happens by a transformer in which the pack is connected to the primary side of the transformer and each cell is connected individually to the secondary side, which is divided into many parts so as to provide the required voltage to the cells. Now, transformers do not work on DC, hence switches are used to convert constant DC into pulsated DC which activated the transformers.

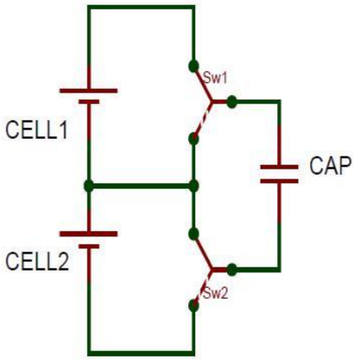

Figure 3. Switched capacitors

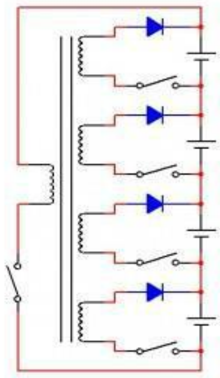

Figure 4. Flyback Topology

4. Design approach

The BMS is implemented using passive balancing approach due to its simplicity and ease of control. Passive balancing uses a resistor, also called bleeding resistor, across every cell to dissipate the charge after the cell is fully charged. This prevents the overcharging of the cell and lets the other cells in the pack (the weaker cells) to get charged to 4.2V. Li-ion batteries are charged using a method called CCCV charging (Constant Current Constant Voltage Charging). This method supplies constant current to the cell until the cell reaches 4.2V, after which the constant voltage mode starts which maintains 4.2V across the cell and current reduces exponentially. This method makes sure that the cell is fully charged (100% SoC). [5]

4.1 Realistic constraints

The following factors limit the functionality of the battery management system designed.

- Faulty voltage measurements of cell (lower accuracy and resolution of the voltage measurement IC, 10mV accuracy is preferred for Li-ion cells).
- Floating ground in the vehicle (ground terminal's voltage can vary from 0V to 24V in worst cases), where it becomes difficult to measure the accurate pack voltage, leading to faulty measurements.
- Inaccurate SoC (State of Charge) measurement algorithms, which do not take into account the degrading cell capacity with life cycle. This can lead to overcharging or over discharging, thereby causing sub-optimal usage of the pack and potential fire hazards.
- Preventing EMI (electromagnetic interference – influence of the magnetic field of one current carrying conductor on an adjacent current carrying conductor and introducing noise in the signals).
- Detecting short circuit or open circuit faults.
- Li-ion cells tend to degrade in terms of charge holding capacity/SoC with age. On an average Li-ion cells function optimally for 3-4 years, but sophisticated BMS can extend that up to 8-10 years.
- Redundancy in BMS is a very important feature which ensures essential functioning even when a system fails, but this also increases the complexity and size of the circuit.

4.2 Alternatives and Tradeoffs

The alternative to passive balancing could be active balancing or Flyback topology. Alternative 1: Active Balancing

- Charge from higher voltage/higher SoC cells is stored inside a capacitor and transferred to a low voltage/low SoC cell.
- Charge can only be transferred from adjacent cells.
- Experimental method, not very commonly implemented.

Trade off: Expensive to implement, more complex control.

Alternative 2: Flyback Topology

- Charge is transferred from the pack to the weaker cells using a transformer.
- The pack transformer is the primary side, and the transformer attached to each cell is the secondary side.
- By switching MOSFETs at high frequencies, the transformers are activated and the energy from the pack is transferred to the weak cells.

Trade off: Complex control, circuit bulky due to the use of transformers.

4.3 Design specifications

The design specifications such as cell type, number of cells considered, capacity of each cell, nominal voltage, charging current, balancing technique and charging method of the Lithium ion Cell are given in the Table 1. The BMS for the specification listed in Table 1 is developed in the MATLAB/Simulink environment.

Table 1: Design Specifications of Lithium ion cell.

Parameter	Detail
Type of cell	Lithium Ion cell
Number of cells	1/4
Capacity of each cell	1300mAh
Nominal voltage	3.7V
Charging current	1.3A (1C)
Balancing technique	Passive balancing
Charging method	Constant current Constant voltage

4.4 Analytical Calculations

Capacity of battery = 1300 mAh = 1.3Ah (1000 mAh = 1 Ah)

Charging current = 1.3A (according to datasheet charging current should be 1 C (c-rating), hence in this case I_{charge} = 1C*1300mAh = 1.3A)

Time taken to charge = Capacity/charging current = 1.3/1.3 = 1h

In reality, charging time is almost double due to constant voltage mode of CCCV charging (discussed in chapter 4).

Bleeding resistor value = 30 ohms (generally in the range of 25-40 ohms)

Bleeding current = Voltage of cell/bleeding resistor = 4.2/30 = 0.14 A

Power dissipated in the resistor over one cycle = I^2 R=(0.14)*(0.14)*30 = 0.588 W

This power loss in each resistor is compensated by the charging current, hence for a large battery pack, passive balancing can prove to be a highly dissipative.

5. Simulation results

This section presents the simulation results of passive balancing circuit in detail using simulink

5.1 Passive Balancing of single cell circuit

As seen in Figure 5, a single cell is connected to a 4.2V DC voltage source. First it is checked if the cell is above 2.7V. If it is lower than 2.7V, it is initially charged by a method called trickle charge, which is supplying a very low current (0.5C) to bring up the voltage of the cell. Once the voltage of the cell reaches 2.7V, it can be charged using the rated charging current (usually 1C). A passive balancing bleeding resistor is placed in series with the cell. If the cell voltage goes beyond 4.2V, the charging switch is turned off and the balancing will turn on. This way the charging will stop and the cell will start discharging through the resistor till the voltage reaches a safe voltage. The sudden voltage drop, as observed in Figure 6, when the balancing switch is turned on is due to drop across the internal resistance which appears as –IR, hence the terminal voltage becomes $V_{terminal} = V_{OCV} - I_{charge}*R$ [1]. (Note: CCCV mode has not been implemented in this circuit.)

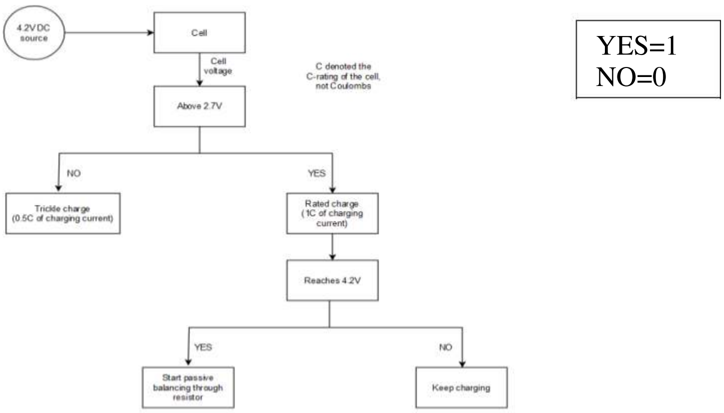

Figure 5. Flowchart of passive balancing of single cell

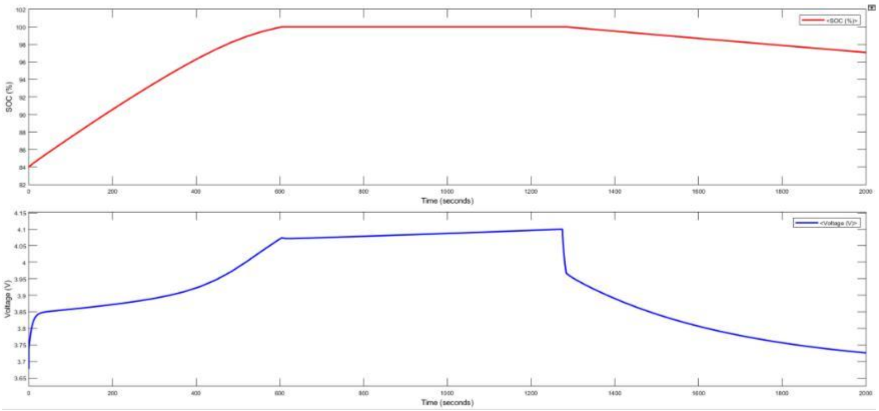

Figure 6. SoC and Voltage graphs of passive balancing of single cell

5.2 Passive balancing of 4 cells in series

As seen in Figure 7, the voltages of all the 4 cells are checked to see if they cross 4.2V. The output of the cell voltages blocks is given to an OR gate, which gives output 1 if anyone of the voltages exceeds 4.2V. Output of the OR gate will be 1 if any one of the cell is crossing 4.2V. As soon as that happens, the charging switch S is turned off and that particular cell's energy is dissipated through a resistor. Figure 8 shows the circuit, where the 4 cells are connected to individual resistors for passive balancing.

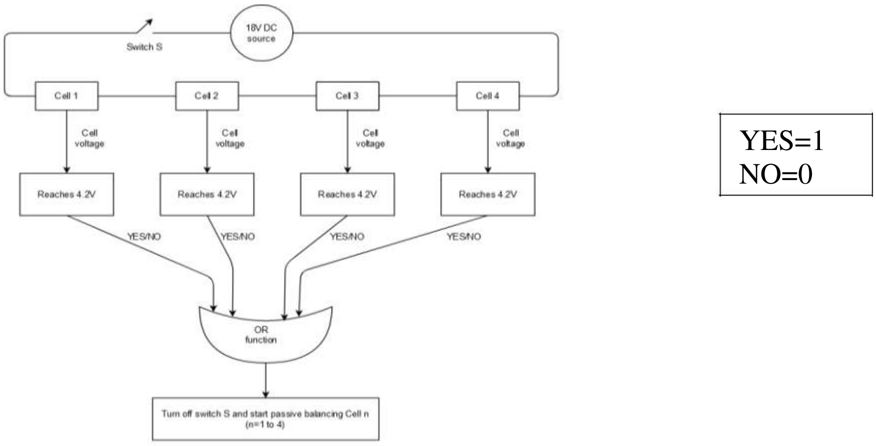

Figure 7. Flowchart showing the logic of passive balancing 4 cells in series

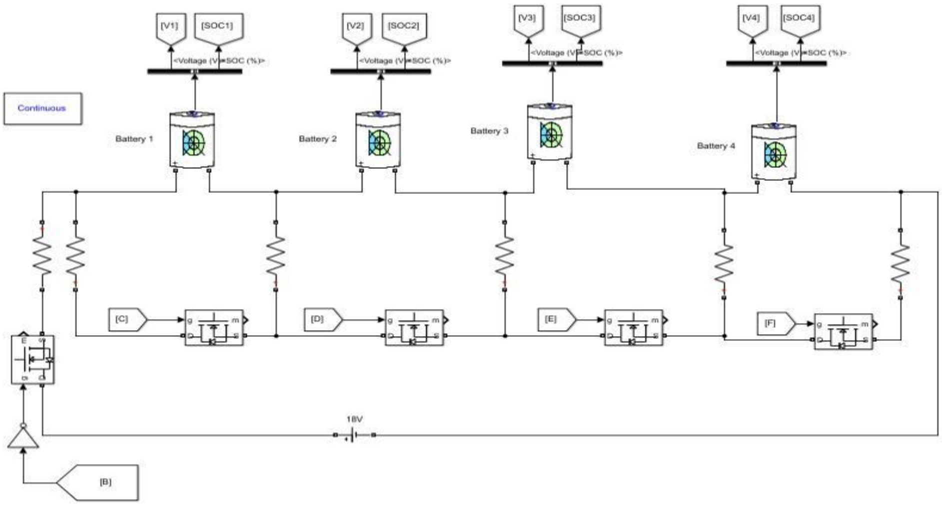

Figure 8. Circuit of passive balancing 4 cells in series using SIMULINK

Figure 9 and Figure 10 present the voltage and SoC graphs of the 4 cells, with the break point being the turning off of the charging switch. Similar approach is implemented in battery management integrated chips in which the voltages are measured and compared using comparators and appropriate action is taken.

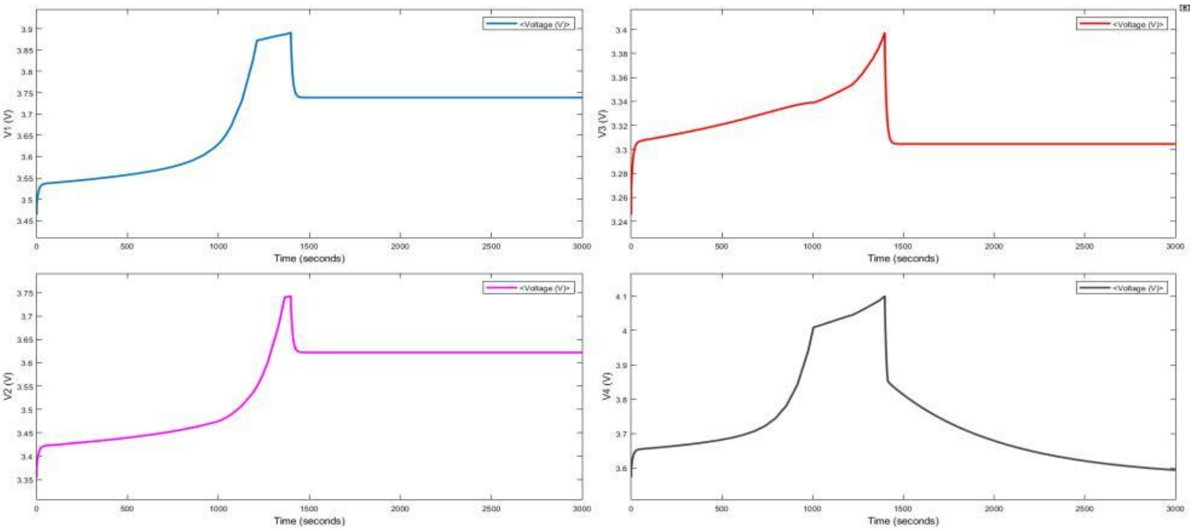

Figure 9. Voltage graph of passive balancing of 4 cells

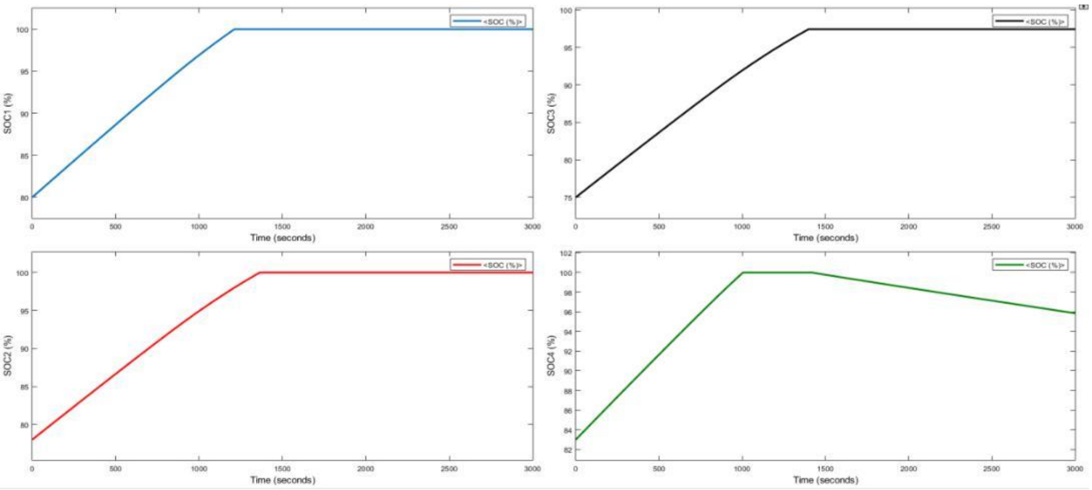

Figure 10. SoC graph of passive balancing of single cell

5.3 Constant current constant voltage (CCCV) charging

In Figure 11, cell is connected to a constant current source which supplies 1C of current to the cell and the cell voltage rises. Once the voltage reaches 4.2V, it is switched to constant voltage mode as the current is exponentially reduced to 0. This ensures that the cell is fully charged. Figure 12 shows the voltage, SoC, charging current and switch graph of the circuit, in which the break point shows the point of switching over to constant voltage mode. [3]

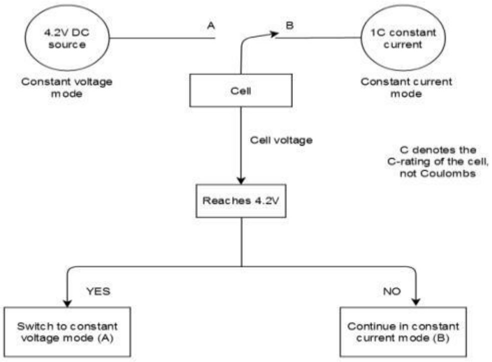

Figure 11. Circuit for CCCV charge with constant voltage source and constant current source

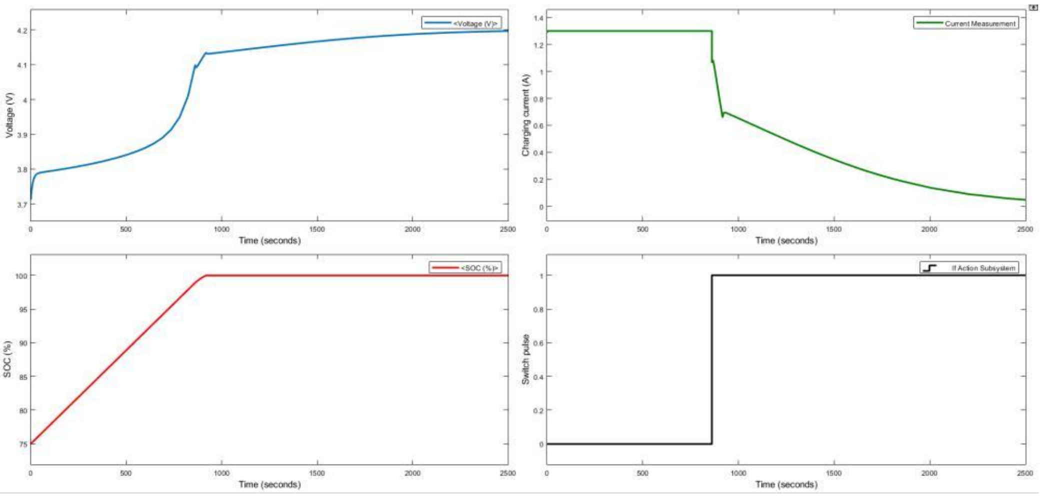

Figure 12. Simulation of CCCV charge

6. Conclusion

This paper presented the basics and importance of battery management systems in a Li-ion battery pack. This is followed by battery modelling using equivalent circuit and the charge and discharge graph, which is explained with the help of the equivalent circuit model. Then the cell balancing techniques are discussed with major focus on passive balancing (switched resistor). The trade-offs of using active balancing are discussed so as to give a clear understanding of why passive balancing is chosen. MATLAB/Simulink modelling of single cell and four cells, with their charge and discharge graphs are discussed after balancing techniques. Finally, the charging method for Li-ion battery packs is discussed and it is highlighted as to why this method is the required to charge Li-ion battery packs.

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