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Battery Management Systems for Electric Vehicles using Lithium-Ion Batteries

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Abstract: ***A battery management system (BMS) is a system that manages a rechargeable battery (cell or battery pack), by protecting the battery to operate beyond its safe limits and monitoring. It is to investigate advanced battery management technologies for the estimation, monitoring, and control of battery states, associated modelling techniques, thermal and charging/discharging management for optimized life, performance, and range. To improve the quality of battery and safe operation, battery management system is employed. The main objective of this work is to design and optimize the Battery Management System including a lithium-ion battery model.***

Keywords: State Machine, State of Charge, Cell Balancing, Extended Kalman Filter, Unscented Kalman Filter

1. Introduction

The battery includes all the management and monitoring systems that compose the Battery Management System (BMS). Batteries have demanding requirements regarding safety, power density (acceleration), energy density (autonomy), high efficiency, deep discharge cycles or low self-discharge rates.

EVs demand the use of high-performance batteries that can deliver the required power and energy. Lithium-Ion based batteries are one of the most promising technologies.

Lithium is the lightest metal and the largest energy density per weight of all metals found in nature. Using lithium as the anode, rechargeable batteries could provide high voltage, excellent capacity and high-energy density. It is capable of storing up to three times more energy per unit weight and volume than the conventional lead-acid and NiMH batteries because of the high-energy characteristics.

Lithium is unstable, especially during charging. So, lithium ions have replaced with lithium metals because they are safer than lithium metals with only slightly lower energy density. It requires almost no maintenance during its lifecycle and it is well suited for electric vehicles because its self-discharge rate is less.

2. BMS Closed-Loop Harness Dashboard

1) The BMS closed-loop harness dashboard consists of
    a) Test sequence variant
    b) BMS closed-loop
    c) BMS state request
    d) Fault alarm sensors.
2) The test sequence will talk about the sequence in which the BMS model is running and state requests will talk about the state in which the BMS model is present.
3) The fault sensors will give the mall functioning of the model in different states such as charging, discharging, driving.
4) It is used to run all the possible conditions that are used to run the battery model without any damage absorbed by the battery.
5) The BMS model has different types of fault sensors such as system, high temperature, over-voltage, under-voltage, charger or inverter connected, voltage sensor.
6) The BMS closed-loop model is mainly consisting of 2 important parts such as BMS ECU and PLANT.
7) The BMS ECU which controls over the state machine, SOC calculations, balancing logic and current and power limitations block.

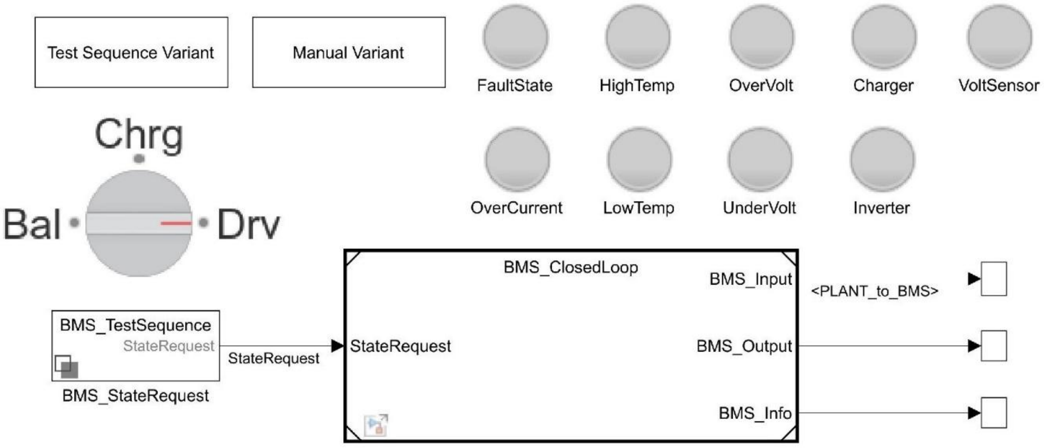

Figure 1: BMS closed-loop harness dashboard

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This model is used to perform various tasks as per user-defined:

1) State of Charge estimation using Extended Kalman Filter, Unscented Kalman Filter
2) Passive Battery Cell Balancing
3) State Machine for Pre-charging and Contactor Management
4) Fault Management - Over/Under Voltage, Over Current, Over Temperature, etc.
5) Charge and Discharge Current Limit Calculations

To design and test these algorithms, the project also includes files for

1) Li-ion Battery Cell Parameter Estimation
2) Battery Pack with 6 cells in series and 96 cells in series
3) Simulink Test files with test cases to test State Machine Logic
4) Linking requirements to Models

3. Closed-loop Battery Management System

Here will have two main blocks.

a) BMS_ECU
b) PLANT

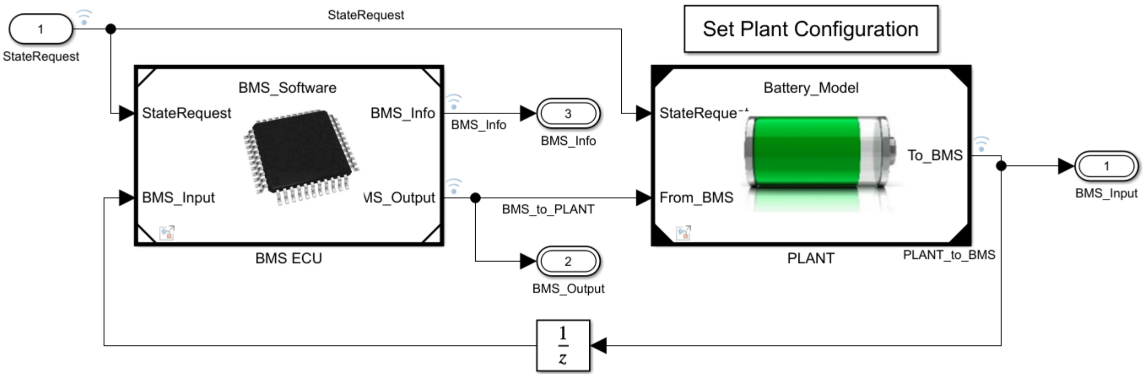

Figure 2: Closed-loop Battery Management System

- The BMS Closed-Loop consist of interlinking of the BMS_ECU and the Plant(Battery Pack)
- The plant is actually the battery, and the BMS_ECU is a battery management system mainly implemented as a software in a simulation environment in the MATLAB.

a) BMS ECU:

The BMS ECU block is used to control the battery by using logics and algorithm which are present in the microcontroller or microprocessor. The BMS ECU has 4 sub-blocks

- Current power limitation block.
- State machine block.
- Soc estimation block.
- Balancing logic block.

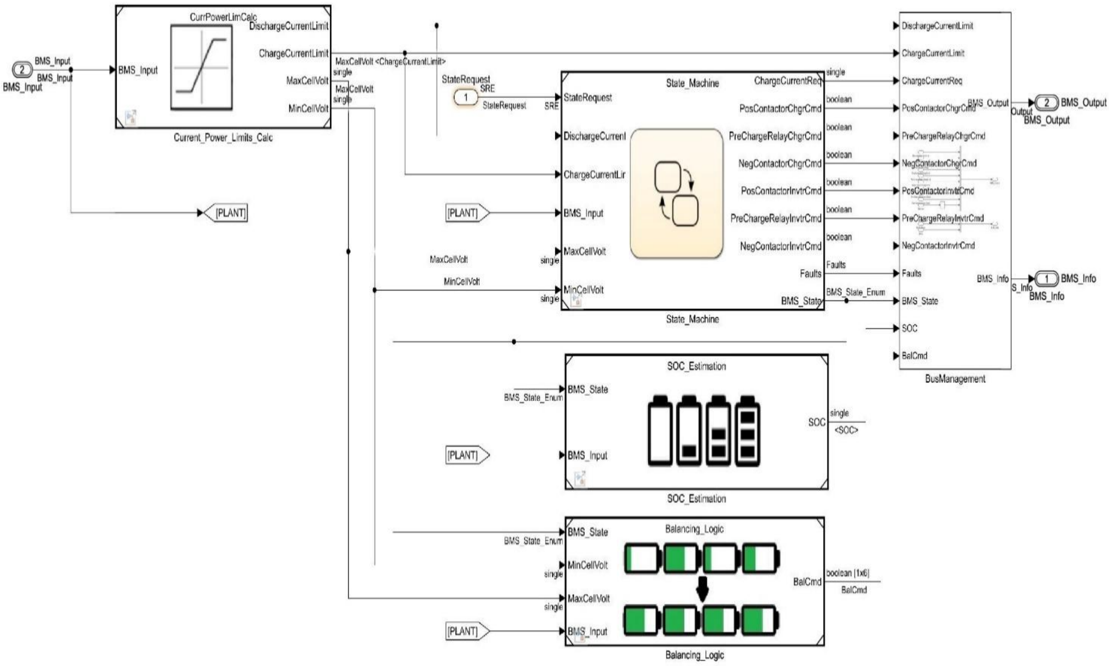

Figure 3: Subsystem of BMS ECU block

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1) Current Power Limitation Block:

- This block is mainly used to limit the current and power to be flown inside and out of the battery pack.
- The function of the block is to calculate the charge current limit and discharge current limit.
- These limits are based upon the battery lower and upper voltage of the cell.

2) State Machine Block:

- The state machine block is called as the heart of the BMS ECU where all the algorithms are present in this block.
- Depending on the state the subsystems inside the block are used to operate.
- The state machine having different subsystems which are operated by the test sequence and limit control block.
- The state machine can have the access of discharge current limit, charge current limit, cell voltage, pack voltage, cell temperature, voltage charger, voltage inverter, pack current, state request, maximum cell voltage, minimum cell voltage.
- They are used to sense the changes, according to the state and testing sequence, the state machine block will activate the subsystems such as BMS state, charge current regulator, positive contact charge mode, pre-charge relay charge command, negative contactor charge command, positive charge invertor command, pre-charge invertor command, negative charge invertor command, faults.

3) Soc Estimation Block

- The SOC estimation block comprises of coulomb counting, UKF-EKF, state transition function, and measurement function.
- The coulomb counting is the integration of the current over some time.
- The UKF-EKF block which estimates the state of charge by considering all the disturbances.

4) Balance Logic Block:

- Balancing block is used to balance the voltage of the cell.
- It is also having the state machine algorithm which is used to operate the system whenever the voltage of the cell fluctuates.
- The block is used to require in BMS because it takes care of the cell voltage or the pack voltages.
- When the fault state is achieved by the model, the battery pack is disconnected from the load by BMS.

b) PLANT:

1) The blocks inside the plant consist of a battery pack and a pre-charge circuit and charger load.
2) The blocks are connected with the charge positive line and negative charge line throughout the plant.
3) There are two types of battery pack system:
    - 6 cell series 1 modules.
    - 96 cell series of 16 modules.

1) 6 Cell Series of 1 Module:

- In these 6 cells 1 module battery pack, the cells are connected in series and the positive line is connected to the positive terminal of battery.
- The negative line is connected to the negative terminal of the battery.
- The battery pack is parallelly connected with the temperature sensor and is used to regulate the temperature of the cell in the module respectively.
- These temperature sensors are used to indicate the faulty cell when the cell is thermally running out.
- Each module is connected with a cell management in which each cell is monitored and is equipped with a balancing circuit.
- A current regulator block and voltage regulator blocks are attached in series and parallel where the current and voltage are measured for every module.
- simulation is stopped when the SOC of the cell drops below 0.001.

2) 96 Cell Series of 16 Module:

- In this type, the 16 modules consist of 6 cells are connected in series.
- Each module of the negative terminal is connected with the positive terminal of the next module.
- The signal output from each block is monitored by the cell management system The signal output from each block is monitored by the cell management system.

4. Simulation Result

Test hardness Dashboard:

The test hardness dashboard is the model which is used to test the BMS model outputs by changing the values of the given input to the BMS. By changing the values of the test conditions, we can observe the results in the form of the graph in the scope.

Test Sequence

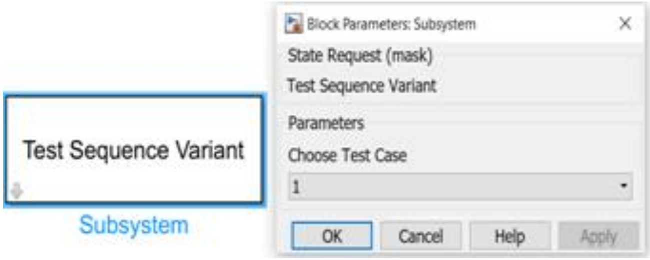
We ran Simulation for three Test Sequences and Configuration selected for Simulation is 1 module battery Pack (With 6 Cells in Series).

Test Sequence has Different Conditions like for Balancing, Charging and Driving

- TEST SEQUENCE 1 includes Driving Condition, Balancing Condition and Charging Conditions with Transition Occurring at Specific Time Intervals.
- TEST SEQUENCE 2 includes Driving and Charging Condition
- TEST SEQUENCE 3 includes only Charging

1) Test Sequence 1

Now we have selected case 1 as per in the image.



Choose Test Case: 1

Figure 4: Test sequence Variant for test case 1

Test cases can be selected from this subsystem block.

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After selecting a certain test number, we can see whether it is the correct one selected for testing and also the Steps in that testing. This can be done with the help of the BMS_StateRequest block used in the model. On opening this BMS_StateRequest model we get

Going further into the BMS_TestSequence block inside this block, we can see whether it is properly selected. From the following figure we can see which Test sequence is selected.

Here from the above test sequence, it was set as,

- Driving for first 3000 secs.
- After 3000sec starts balancing operations occurs for next 1000 Secs.
- Then charging and balancing occurs for next 5000 secs.
- After that sequences post charge balancing operation occurs till end of the simulation period.

Results:
Run the simulation and results are shown as,

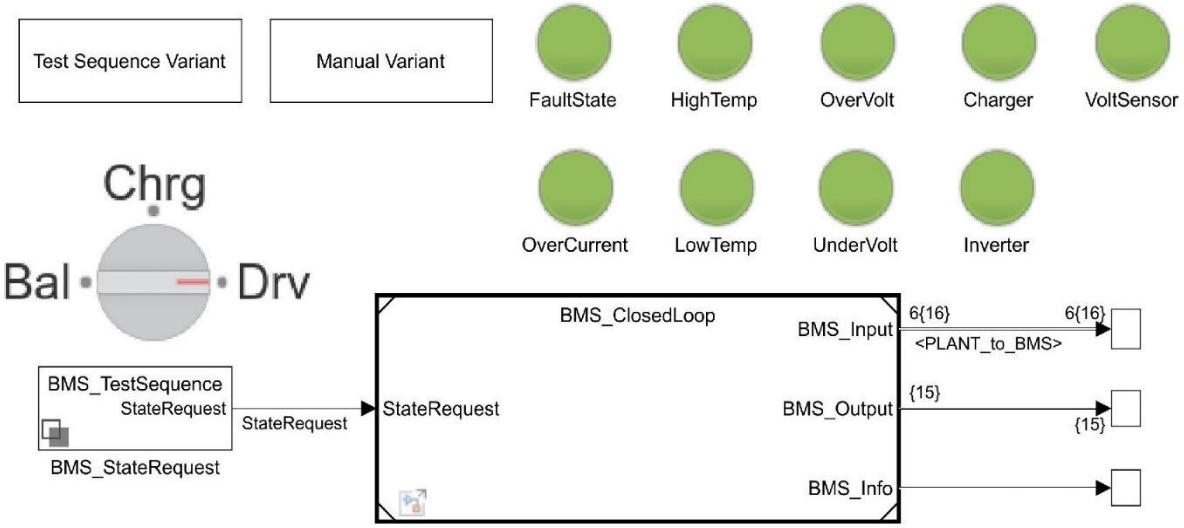


Figure 5: Output of BMS closed-loop for test sequence1

The lamp indications are showing green for overall simulation period showing that there are no faults occurs during the sequences.

The scope result plotted as,

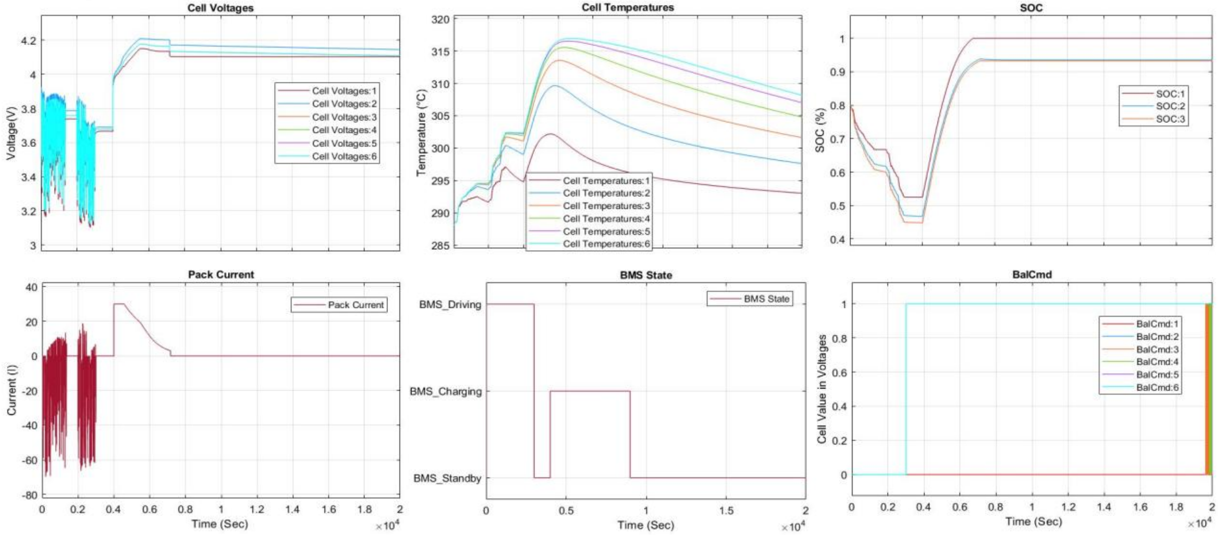


Figure 6: Output waveforms of Test sequence 1

Cell voltages: -

- For first 3000secs all 6 cells are in drive mode where discharging occurs majorly and in standby mode for lesser duration at approximately 1000 to 2000 secs.
- The voltages vary from 3.1V (min) to 3.9V(max) in this range.
- From 3000 secs to 4000secs cell balancing occurs and in this stage the module in standby mode and voltage is constant at nearly 3.7V.
- After 4000secs charging occurs, voltage raised from 3.7V to 4V. At 4V to 4.2V at constant current as nearly 30 A and after 4.2 V as constant voltage, current reduces from 30A to 2.6A at end of the charging and cell balancing occurs up to 9000Secs.

- After 9000 secs post charge cell balancing starts. All cell voltages are balancing to a voltage with respect to cell 1 to 4.1 V as shown below, in this stage the pack is in standby mode.

Pack current:
- Explained pack current graph as well in the cell voltage.
- This is also varied as per the driving till 3000 secs where accelerating and deaccelerating both occurs.
- current from 20amps to -75amps as per the driving. then again between its standstill condition, then after 3000 secs charging for 1000 secs. then again charging and balancing occur.

Cell temperature:
- Initially during driving till 3000 secs the temperature is gradually increasing. the maximum temp is of cell 6 which is 288K to 302K in this region.
- From 3000 secs to 4000 secs balancing region so temperature is at constant range.
- After 4000 secs temperature start increasing till current constant mode. then decreases till 9000 secs.

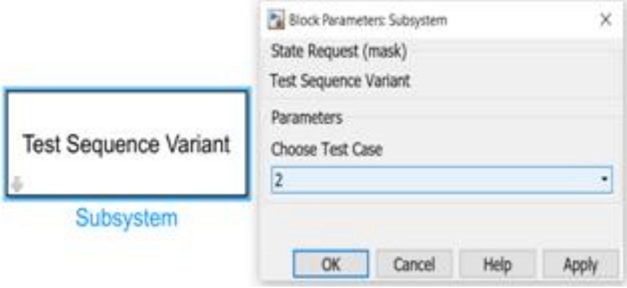
BMS State:
- For 3000 secs battery is in driving mode or call it as discharging mode.
- From 3000-4000 secs for 1000 secs, it is in balancing standby mode.
- From 4000-9000 secs for 5000 secs, it is in charging and balancing mode.
- After 9000 secs only post charging balancing will occur till simulation end.

SOC:
- Initially we can see battery SOC is 80 %. And there are three different colours of battery represents which indicates three different techniques to find SOC.
- Light Red colour plot SOC estimation represents coulomb counting technique. Blue colour plot SOC estimation represents unscented Kalman filter technique.
- Red colour plot SOC estimation represent Extended Kalman filter technique. For driving till 3000 secs SOC got decreases till 45% approx.
- After 3000 secs for 1000 secs till 4000 secs it is in constant mode of 45% because of cell balancing occurred.
- After 4000-9000 secs it is in charging and balancing mode.
- from 4000-7000 secs it is in CC mode charging and from 7000- 9000 secs it is in CV mode charging.
- After 9000 secs SOC become constant at approx. 95%.

Balancing cell:
- Till 3000 secs during driving mode no cell balancing occurred.
- Between 3000-4000 secs cell balancing occurred. And cell 2 and cell 6 raised to 1.
- After 4000-9000 secs its value will be still 1 till end of the simulation.
- And cell 1 has low voltage which is at 0 state till end of the simulation.
- At the end of the simulation all 6 cells is at equal stage.

1) Test Sequence 2

Now we have selected case 2 as per in the image.



Choose Test Case: 2

Figure 7: Test sequence Variant for test case 2

As we can see in the BMS test sequence case 2 has been selected

In this test case we have 10000 secs for driving and after that charging occurs till end of the simulation.

Results

The dashboard results are shown as without any faults occurred

The scope result plotted as,

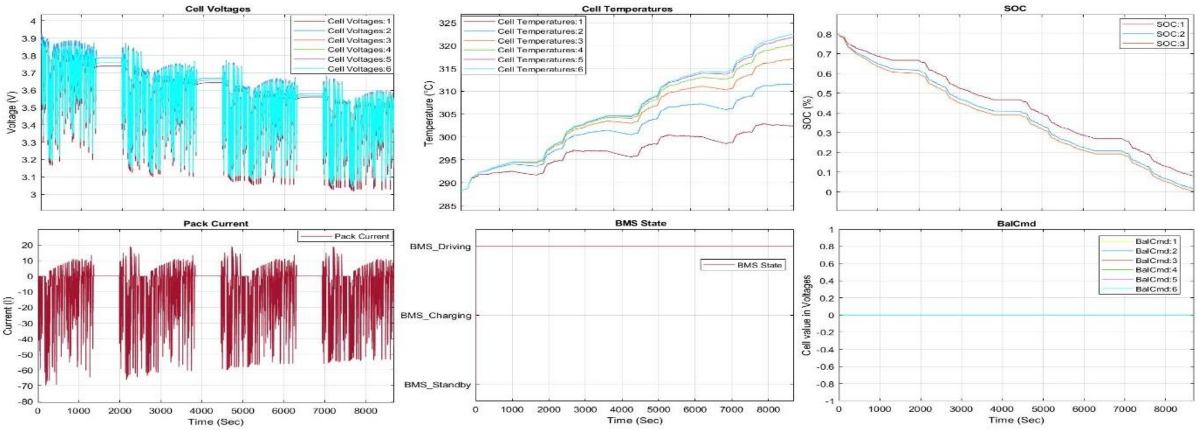


Figure 8: Output waveforms of Test sequence 2

Cell voltage and pack current:

- Cell voltage range from 3.9V- 3.05V approx. The pack current varies from -70Amps - 20Amps. Some negative current also occurs because of Drive cycle which works in regenerative mode.
- Both current and voltage works according to drive cycle and works as accelerated and deaccelerated mode. Entire capacity drained at 9000 secs.
- For 10000 secs its driving then charging occurred.

Cell temperature:

- As per this image cell 1 has least temperature rise and cell 6 has high temperature rise.
- Cell 1 temp is from 288K to 303K.
- Cell 6 temp is from 288K to 322.5K.
- These cells temperature is increasing decreasing as per the driving and charging period.

BMS:

- Entire sequence is performing in drive mode as shown from the above plot.
- Small duration of standby modes is not plotted in this plot as simulation upto 10000secs command is given as drive mode.
- But in actual practical situation standby modes are not present as battery current drains by other small auxiliaries of EV's.

SOC:

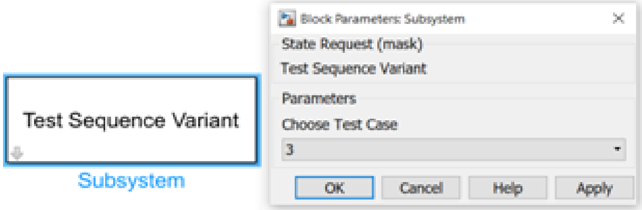
- Initially SOC started from 80%. From 80% to 0%
- During the entire cycle which includes driving and charging.
- During standby mode its value will be constant.

Cell balancing:

- Balancing of cells are not performed in the entire cycle.

2) Test Sequence 3

Now we have selected case 3 as per in the image.



Choose Test Case
3

Figure 9: Test sequence Variant for test case 3

As we can see in the BMS test sequence case 3 has been selected.

This shows the procedure that how much operation mentioned as per time limit. In this test only charging occurred.

Results

The dashboard results are shown as without any faults occurred

The scope result plotted as,

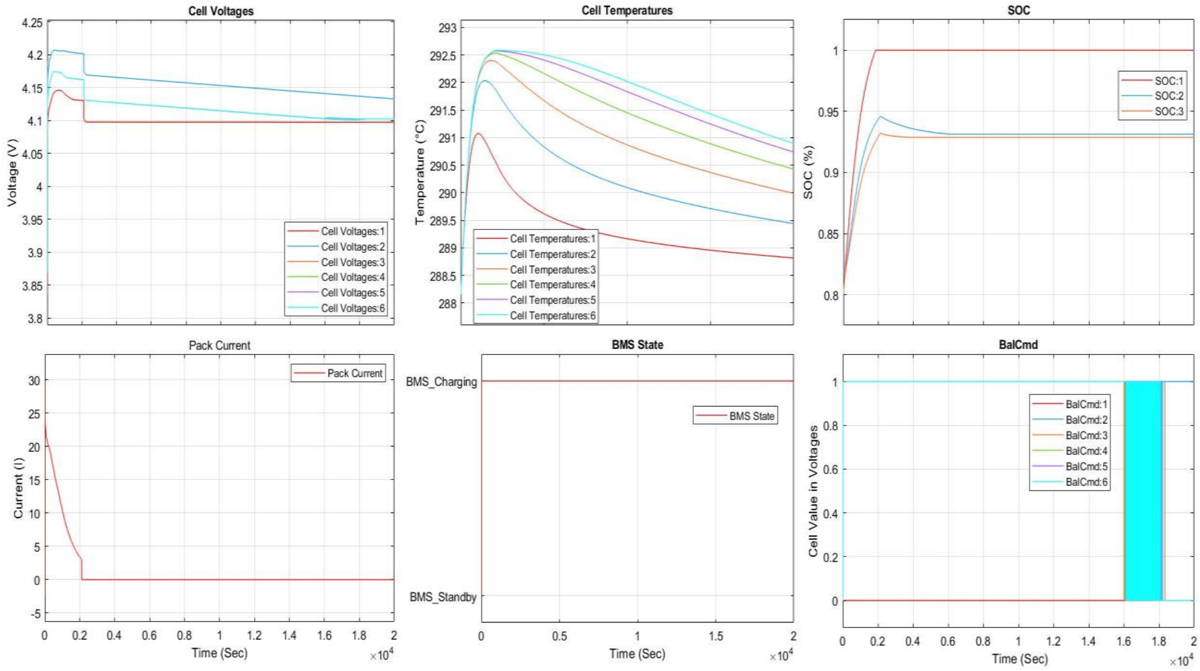


Figure 10: Output waveforms of Test sequence 3

Cell voltages:

- By combine we can see the graph of cell voltage and pack current where this case has totally charging state so all cell voltage drastically increases at some point to achieve max voltage.
- By example our cell no 2 voltage is higher from 4.1-4.2V approx. then it gets stable at 4.1V.
- All cell voltages getting higher initially at some point then stable region.

Pack Current:

- The battery pack current raising from 0-24Amps approx. initially then comes to 2.5Amps approx. at the end of 2000 secs of charging state.
- At 2000 secs battery is fully charged.
- At full charging condition current flow will be cut-off.

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Cell temperatures:

- The cell temperatures continue to increase heat upto full charge and after that the temperatures get started to reduces to ambient temperature.
- As shown from result plot the temperatures start decreases after full charge (at 2000 secs).

BMS state:

- Entire battery pack sequence is operating in charging mode.

SOC:

- Again, these SOC with three colour plotting shows three different techniques of charging. All three techniques getting charged
- After 2000 secs but the Light red colour shows the coulomb technique which calculate 100% SOC in this image.
- Another two mode which is UKF & EKF SOC is 93% approx. which is the true SOC of the cells.

Cell Balancing:

Here again cell 6 and cell 2 starts to balance with respect to cell 1 and all cells trying to balance at the end of the simulation.

5. Conclusion

The purpose was to design and develop a battery management system for lithium-ion cells.

This model is used to perform various tasks like State of Charge estimation, Cell Balancing, State Machine for Pre-charging and Contactor Management, Fault Management, Charge and Discharge Current Limit Calculations.

To design and test these algorithms, the Li-ion Battery Cell Parameter Estimation, Battery Pack with 6 cells in series and 96 cells in series, Simulink Test files with test cases to test State Machine Logic and Linking requirements to Models are included in the simulation model

Here we have discussed all three tests of BMS over the model. Analysed the result with individual parameters.

We have analysed pack voltage, pack current, cell temperature, BMS, cell balancing and SOC model.

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