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Battery Management System of Electric Vehicles

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Abstract: *Electric cars have developed a game-changing technology in earlier years. A Battery Management System (BMS) is the most important feature of an Electric Vehicle (EV). Lithium-ion batteries have a large capacity to store energy. The BMS controls the battery packs in electric vehicles. The major function of the BMS is to monitor the battery's position accurately, which assures proper operation and extends the battery performance. The BMS' measure job is to keep check up on operational parameters, evaluate and balance the battery pack's cells. The major aim of this work is to keep track of battery characteristics, calculate SOC using Coulomb Counting method, and balance cells. Current is used as an input parameter to apply the coulomb counting method. Together with SOC calculation Terminal Voltage of the battery is also estimated with the help of relationship between OCV and SOC. In difference with current and temperature, the charging and discharging resistances is bear in mind to calculate the Terminal Voltage. Results of all the algorithms will be approximately analysed. MATLAB R2020a software is used for the simulation of different algorithms and SOC estimation. Two phases of BMS are considered which are discharging phase and the Charging phase. After SOC Estimation, Cell balancing is also performed over 3 cells of the battery pack.*

Keywords: *Electric Vehicles, Lithium-ion batteries, BMS, SOC, Cell balancing.*

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I. INTRODUCTION

Nowadays, with the rise in global warming and observing at the current situation of rates and accessibility of fossil fuels, there is an increasing importance on development of electric vehicles. Other energy sources are aggressively being examined and developed. Norway has become the first country to ban fuel-based cars by 2025 by pushing the development of electric vehicles (EVs).Programs such as Advanced Research Projects Agency – Energy (ARPA-E) sponsored by the U.S. Department of Energy (US-DOE) and the recent announcement of a $50M grant for the Battery500 initiative, the U.S. government is also encouraging the commercialization of electric vehicles (EVs).

Electrification in the vehicle is the easiest way to achieve clean and efficient transportation that is critical to the sustainable development of the entire world. The key and the enabling technology to this revolutionary change is battery. Electric vehicles are generated by large number of battery cells, needs an effective BMS to take decisions on charge/discharge of battery and cell balancing on the basis of load demand, cell voltage, current, temperature measurement and estimated battery SOC.

Electric vehicles works on rechargeable battery packs that are made of multiple cell packs placed in a series and parallel. These battery packs generate several hundred volts of electricity. Various features inside the car are dependent on the electricity produced before. Because of which it becomes a crucial part of the vehicle that needs constant monitoring and control.

This requires Battery Management System (BMS), an embedded system that monitors the components closer to the battery cell. No avoid voltage fluctuations and imbalance in voltage conditions for which each cell needs to be monitored properly.It consists of different parts that make sure the battery runs effectively without chances of possible failures.

The main function of Battery Management System is to protect the battery and to prevents its safety limit during operations. It not only estimates the state of charge (SOC) of the battery but also calculate the health of battery.

Along with it also manages the battery optimization through cell balancing which improves the life of the battery for the long term. The BMS will also calculate voltage, temperature and the colling system of the vehicle.

Lithium-ion batteries charge faster, last longer and have higher power density for more battery life in a lighter package. These batteries are currently used in most electric vehicles because they have high energy per unit mass relative to other electrical storage systems. These battery packs are not even very big in size and they can be highly unstable. To avoid such problem these batteries shouldnot overcharged. The condition in which temperature of the cell is increase due to current flowing through battery during charging or overcharging is known as Thermal Runaway. Such problems can harm the life span of the battery. To avoid such situations, we need a BMS to monitor the voltage and current. BMS keeps the battery safe and prevents it for long term.

Cell balancing is another safety feature of the BMS. In the battery, each cell cannot be operated equally within the battery pack. All cells can have different capabilities, one may be stronger than another. Because of which,during charging or discharging, they charge at different levels. They can degrade the health of the whole battery pack. If any cell in battery is gets short circuited or fails, it can damage the whole pack. Equalisation of the charge between individual cells is done during cell balancing. Without disturbing the SOC of the system, BMS monitors and control the charge required by each cell in the chain.

This process is quite difficult to balance each cell individually for safety and proper operation as it contains many cells placed together in the battery pack. These problems requires a special devoted system known as the Battery Management System (BMS).

II. BATTERY MANAGEMENT SYSTEM

2.1 Understanding BMS

As in pure Electric Vehicles, the only source of energy is battery.Therefore BMS, which stands for Battery Management System is one of the crucial part for electric vehicles, to ataining battery performance and extending battery life. Some factors that prevents electric vehicles to commonly used vehicle are its driving range, high price, battery difficulties, and inconsistent charging. Lithium- ion batteries were introduced to solve this problem. Battery packs have been adopted for various electronic gadgets and electric cars, because of its high efficient energy densities. This become more popular in a variety of applications, including small mobility vehicles, trucks/buses, and industrial gear. But at the same time inappropriate utilization of battery leads to electric shock and fire. A Battery Management System (BMS) is necessary to use battery packs effectively and safely.

We can say that, a BMS is just anologous to the brain of a battery pack, as it monitors pack current, cell voltage, cell temperatures, and determines available energy throughout the cells, state of charge (SOC), and status of health (SOH) in order to maintain cells within safe operating limits and thus extending battery life. Fromthe above discussion the, battery management systems (BMS) is used to assure optimal performance, reliable handling, and long lifespan under a variety of chargedischarge and atmospheric circumstances across sectors. In a vehicle, the BMS is part of a complex and fast-acting power management system. In addition, it must interface with other on-board systems such as the motor controller, the climate controller, the communications bus, the safety system and the vehicle controller.

2.2 Functions of BMS

1. Discharging Control: The primary function of a BMS is to maintain the lithium cells within the safe operating region. For example a typical Lithium 18650 cell will have an under voltage rating of around 3V. It is the responsibility of the BMS to make sure that none of the cells in the pack get discharged below 3V.

2. Charging Control: Apart from the discharging the charging process should also be monitored by the BMS. Inappropriate charging of battery may lead to damage or lifespanmay get reduced. For lithium battery charger a 2-stage charger is used. The first stage is called the Constant Current (CC) during which the charger outputs a constant current to charge the battery. When the battery gets nearly full the second stage called the Constant Voltage (CV) stage is used during which a constant voltage is supplied to the battery at a very low current. The BMS should make sure both the voltage and current during charging does not exceed permeable limits so as to not over charge or fast charge the batteries. The maximum permissible charging voltage and charging current can be found in the datasheet of the battery.

3. State-of-Charge (SOC) Determination: You can think of SOC as the fuel indicator of the EV. It actually tells us the battery capacity of the pack in percentage. Just like the one in our mobile phone. But it is not as easy as it sounds. The voltage and charge/discharge current of the pack should always be monitored to predict the capacity of the battery. Once the voltage and current is measured there are a lot of algorithms that can be used to calculate the SOC of the Battery pack. The most commonly used method is the coulomb counting method; we will discuss more in the next part. Measuring the values and calculating the SOC is also the responsibility of a BMS.

4. State-of-Health (SOC) Determination: The capacity of the battery not only depends on its voltage and current profile but also on its age and operating temperature. The SOH measurement tells us about the age and expected life cycle of the battery based on its usage history. This way we can know how much the mileage, that is the

distance covered after full charge, of the EV reduces as the battery ages and also we can know when the battery pack should be replaced. The SOH should also be calculated and kept in track by the BMS.

5. Cell Balancing: Another vital function of a BMS is to maintain cell balancing. For example, in a pack of 4 cells connected in series the voltage of all the four cells should always have equal. If one cell is less or high voltage than the other it will affect the entire pack, say if one cell is at 3.5V while the other three is at 4V. During charging these three cells will attain 4.2V while the other one would have just reached 3.7V similarly this cell will be the first to discharge to 3V before the other three. This way, because of this single cell all the other cells in the pack cannot be used to its maximum potential thus compromising the efficiency. To deal with this problem the BMS has to implement something called cell balancing.

There are many types of cell balancing techniques, but the commonly used ones are the active and passive type cell balancing. We will learn more about cell balancing later in this paper.

6. Thermal Control: Temperature also affect the life and efficiency of a Lithium battery pack and also the operating boundaries. The battery tends to discharge faster in hot climates compared with normal room temperatures. Adding to this the consumption of high current would further increase the temperature. This calls for a Thermal system (mostly oil) in a battery pack. This thermal system should only be able to decrease the temperature but should also be able to increase the temperature in cold climates if needed. The BMS is responsible for measuring the individual cell temperature and control the thermal system accordingly to maintain the overall temperature of the battery pack. Powered from the Battery itself: The only power source available in the EV is the battery itself. So a BMS should be designed to be powered by the same battery which it is supposed to protect and maintain. This might sound simple but it does increase the difficulty of the design of the BMS.

7. Logbook Function: Because the SOH is relative to the condition of a new battery, the measurement system must hold a record of the initial conditions or a set of standard conditions for comparison. An alternative method of determining the SOH is to estimate the SOH value based on the usage history of the battery rather than on certain measured parameters, such as the number of charge-discharge cycles completed by the battery. Therefore, the logbook function of the BMS would record such important data to the memory system.

8. Communications: The communications function of a BMS may be provided though a data link used to monitor performance, log data, provide diagnostics or set system parameters. The function may also be provided by a communications channel carrying system control signals. The choice of the communications protocol is not determined by the battery; instead, it is determined by the application of the battery. The BMS used in electric vehicles must communicate with the upper vehicle controller and the motor controller to ensure the proper operation of the vehicle.

III. ESTIMATION OF SOC

The SOC is an essential factor for batteries. Generally, the State of Charge of a battery is defined as the ratio of its current capacity to the nominal capacity. Nominal capacity of a battery represents the maximum amount of charge that can be stored in the battery which is provided by the manufacturer.

3.1 Direct measurement methods:

Physical battery properties, such as the impedance and voltages of the battery are utilized in this type.

(i) Impedance method – Measurements of impedance provide data of various parameters whose magnitudes may depend on the SOC of the battery. Although the impedance parameters and their variations with SOC are common for all battery systems, it turns out to be appropriate to perform a wide range of impedance experiments for identification and use of impedance parameters for SOC estimation of a given battery.

(ii) Impedance spectroscopy method – Measuring battery impedances over a wide range of ac frequencies at different charge and discharge currents is performed in this method. By least-squares fitting, we can find discharge currents to measured impedance values. SOC may be indirectly concluded by measuring current battery impedances then comparing them with known impedances at various SOC levels.

(iii) Terminal voltage method – The terminal voltage method refers to the terminal voltage drops due to internal impedances while battery is discharging. Thus, the electromotive force (EMF) of battery becomes proportional to the terminal voltage. Since the EMF of battery is linearly proportional to the SOC, the terminal voltage of battery is approximately linear proportional to the SOC. This method has been employed at various temperatures and discharge currents.

(iv) Open circuit voltage method - A linear relationship between the state of charge (SOC) and its open circuit voltage (OCV).

$$V_{OC}(t) = a_1 \times SOC(t) + a_0 \quad (1)$$

Where *SOC (t)* is the SOC of the battery at time *t*, a_0 is the battery terminal voltage when SOC = 0%, and a_1 is obtained from knowing the value of a_0 and at SOC = 100%.

By equation (1), the estimation of the SOC is equivalent to the estimation of its OCV. In this method, OCV of batteries is directly proportional to the SOC when they are disconnected from the loads for longer duration more than 2 hours. Hence, such a long disconnection time may be inappropriate for battery. Apart from the lead-acid battery, in Li-ion battery, there is no linear relationship between the OCV and SOC. A generic relationship of Li-ion battery between SOC and OCV is shown in figure.

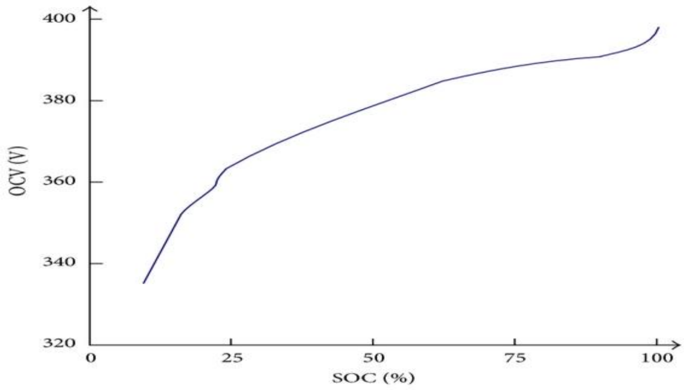

Figure 1: Relationship between SOC and OCV

3.2 Hybrid methods:

Hybrid method of SOC estimation can extend the available data, integrate individual model data, and make the best use of the merits of multiple estimating methods thus improving the accuracy of estimation. Hybrid methods normally produce good estimation results compared to individual ones. This method is a combination of different views such as direct measurement method and book-keeping estimation method.

(i) Per-unit system and EKF combination_- The combination of PU system to the identification of suitable battery model parameters for the high accuracy SOC estimation of a Li-ion battery. By implementing the battery parameters differed by the aging effect, in the basis of PU system, the accurate values in the equivalent circuit model in addition to the terminal voltage and current are converted into dimensionless values to a set of base value. Dynamic and measurement models in the EKF algorithm are supplied by these converted values.

(ii) Coulomb counting and Kalman filter combination - By using Kalman filter, this method improve the initial value used in the Coulomb counting method. Kalman filter method make the approximate initial value convert to its real value and Coulomb counting method estimate the SOC for the long working time. The SOC estimation error is 2.39% when compared with the real SOC obtained from a discharge test. This method reduces favourably with an estimation error of 11.0% when using Coulomb counting method.

(iii) Coulomb counting and EMF combination - This method is a combination of direct measurement method and book-keeping estimation with Coulomb counting method during the discharging phase. It is implemented in a real-time estimation system. In order to calculate SOC and remaining run-time (RRT) effectively and to enhance the SOC estimation, system's ability to withstand with the aging effect, a simple adaptation algorithm is implemented. In this algorithm, under the name of adapting Qmax with aging, the stable conditions of the charge state are exploited.

3.3 Adaptive systems:

These are self-designing ones which automatically adjust in different systems. Currently, various new adaptive systems for SOC estimation have been produced with the development of artificial intelligence.

(i) Fuzzy neural network (FNN) - FNN is especially employed in unknown systems identification. In nonlinear system identification, FNN can efficiently match the nonlinear system by doing calculations of optimized coefficients of the learning mechanism. There was an investigation of soft computing technique for SOC estimation of individual batteries in a battery string. It referred to a fusion of FNN with B-spline membership a function that is the reduced-form genetic algorithm.

(ii) Kalman filter - Kalman filters are used to estimate states based on linear dynamical systems in state space format. The process model defines the evolution of the state from time. It's suitable for linear systems, unfortunately Li-ion batteries show obvious nonlinear dynamic characteristics. For example, the SOC-OCV characteristics of a Li-ion battery have obvious nonlinearity; some important parameters in the equivalent

model, such as polarization resistance, capacitance, show some time-varying characteristics because of the changing working conditions.
(iii) Support vector machine (SVM) - SVM is utilized in various sectors of pattern recognition, regression problem, though the regression problem inherently tougher than classification problem. The SVM used as a nonlinear estimation system is more robust than a least-squares estimation system because it is insensitive to small changes. The estimator based on SVM removes the drawbacks of the Coulomb counting SOC estimator and forms précised SOC estimates.
(iv) BP neural network - The most well-known method in artificial neural networks is BP neural network. Due to their good ability of nonlinear mapping, self-organization, and self-learning, this type is utilized. It is defined as the relationship between the source and target is nonlinear and very complex in SOC estimation. SOC indicator based on artificial neural networks predicts the current SOC by making use of the recent history of voltage, current, and the ambient temperature of a battery.
(v) RBF neural network_- The most useful methodology with incomplete information is RBF neural network. It analyzes the relationships between reference sequence and the comparative ones in a given set. It uses the input data of the discharging current, temperature, and voltage at terminal of battery to estimate the SOC.

3.4 Book-keeping estimation method:

In this method, discharging current is used as the input and integrates the discharging current over time for estimation of the SOC. These methods include some internal battery effects such as self-discharge, capacity-loss, and discharging efficiency.

(i) Coulomb counting method - A technique used to trace the State of Charge of a battery pack. It integrates the active current flowing over time to define the complete addition of energy which is entering or leaving the battery pack. This generates a battery capacity (measured in Amp-hours). Furthermore, different parameters such as, application of battery, fluctuation of voltage in battery, temperature, life Cycle of battery, etc, have to be recognized along with the coulomb counting method to perceive a more precise SOC calculation.
(ii) Modified Coulomb counting method - The improved current of the battery is taken into consideration to improve the precision of estimation.

The improved current is the function of discharging current. There is a quadratic relationship between the improved current and discharging current of battery. By practice of experimental data, corrected current is calculated by the following form:

$$Ic(t) = K_2 I(t)^2 + K_1 I(t) + K_0 \tag{2}$$

where, K_2, K_1 and K_0 are constant values obtained from the practice experimental data.
In modified Coulomb counting method, SOC is calculated by the following equation:

$$SOC(t) = SOC(t-1) + \frac{Ic(t)}{Qn}.\Delta t \tag{3}$$

The experimental results show that the accuracy of the modified Coulomb counting method is superior to the conventional Coulomb counting method.

IV. METHODS FOR CELL BALANCING

In modern devices like laptops or even smart phones we will have battery which consists of many different cells. Let's consider battery of 5 cells having different SOC, here there is maximum voltage which battery will charge upto and also minimum voltage, i.e point battery will discharge upto. Cell balancing is the process of equalising voltage among individual cells so after cell balancing there will be battery pack with almost same SOC. If among 5 cell 1 cell is fully discharged and other 4 cell still have charge we cannot discharge it further as we cannot discharge it lower than its minimum voltage value.To prevent this from happening and in order to fix this situation cell balancing is the solution.

In Electric vehicle cells charge and discharge at same rate. Also in Electric vehicle discharging must stop when any cell runs out of charge though other cell still holds charge and charging must stop when any cell reaches it's maximum charging voltage otherwise it will lead to Thermal runaway
There are two methods of cell balancing:

4.1 Active cell balancing

In an active cell balancer, energy transfers from a higher voltage to a lower voltage cell within the battery. In other words, the cell with higher SOC transfers energy to a lower SOC cell. For example, consider 3 cells of SOC 70, 80 and 60 respectively. Energy is transferred from cell 2 to cell 3 through capacitor or inductor and cells are balanced having nearly same SOC.

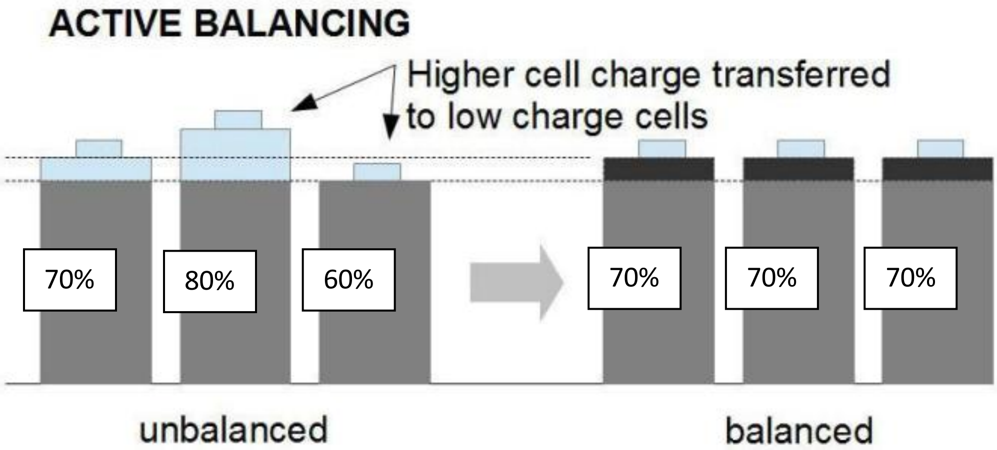

Figure 2: Active Cell Balancing

PROS:
a) Energy is transferred from one cell to another hence less energy is wasted
b) Soc of pack is equal to average of all individual cell SOC

CONS:
a) Complex architecture
b) Only one-way flow of energy from higher to lower
c) Additional cost of electronics .

4.2 Passive cell balancing

In the Passive Cell Balancing technique, there is a burn-off of excess energy from the higher energy cells till it matches or equals the lower voltage cell. There can be either fixed shunting or switching shunting resistor method for passive cell balancers. For example, consider 3 cells of SOC 80, 50 and 60 respectively. Here connect the cell with resistor in order to drain excess of energy from cell in the form of heat. Energy from cell 1 and cell 2 is drained in order to bring them in balanced condition.

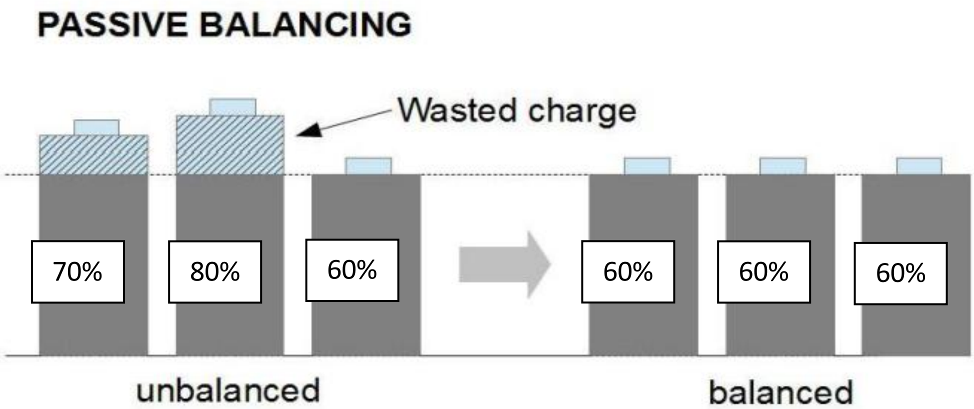

Figure 3: Passive Cell Balancing

PROS:
a) Simple architecture
b) Offers self-discharging current and corrects long-term mismatch
c) Cost effective method

CONS:
a) Capacity of cell is limited by weakest cell i.e least SOC
b) Energy is spent as heat which is inherently wastful
c) This technique only balances the top 95% of each cell because it burns off excess energy
d) Due to heat additional coolent is required

V. EXPERIMENTAL PROCEDURE

4.1 SOC – Coulomb's Counting Method

From the various methods, as discussed previously, we have worked on Coulombs Counting method as this algorithm is simple and work efficiently on software model.

The coulomb counting method is also known as the battery current integration method. In this method, a discharging or charging current $\mathrm{I(t)}$ is measured and integrated over time to calculate amount of energy remaining inside the battery.

$$SOC = SOCo - \frac{1}{Cn}\int_0^{\mathrm{t}} \mathrm{I(t)} \quad (4)$$

where $SOCo$ is the initial State of Charge and Cn is Capacity of Battery.

Also, there is a relationship between the Open Circuit Voltage (OCV) of battery and State of Charge (SOC). This relationship can be used to monitor the terminal voltage of battery and it is shown by,

$$Vt = OCV(SOC) - I \times R(T, SOC)\ , \quad (5)$$

where R is charging or discharging resistance at given temperature.

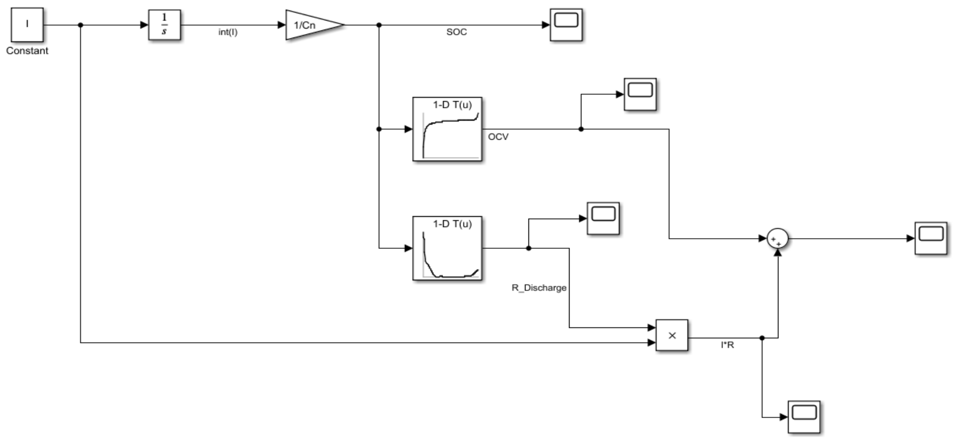

Figure 4: Simulation – SOC estimation by using Coulomb's counting method.

The battery parameter like Voltage, Current and temperature of each cell is extracted using appropriate sensors and this data is recorded in the form of look-up tables. These look-up tables are used to calculate SOC accurately and reduce the chances for junk value. Coulomb Counting method basically deals with the current flowing out of the cells to calculate SOC. This could be illustrated with the expression given in equation (4). And the terminal voltage of battery is monitored by using the relation between the OCV and SOC of battery as expressed in equation (5).

4.2 Cell Balancing- Passive Cell Balancing

Passive balancing approaches work by removing charge from the highest cells until the charge of the lowest cells is equal. This is accomplished by discharging the extra charge through resistors that are switched by transistors in their active state. Methods for passive balancing can be used in two ways. The first method is to use a fixed shunt resistor, and the second method is to use a controllable shunt resistor. Although it does not appear to be as elegant as active balancing since energy is spent in heat, there are number of reasons why this technique has become the preferred method of most BMS, including: Simple design, low-cost parts, simple installation, and expandable design. Passive balancing can be used with a cooling system to maintain the battery pack temperature under control.

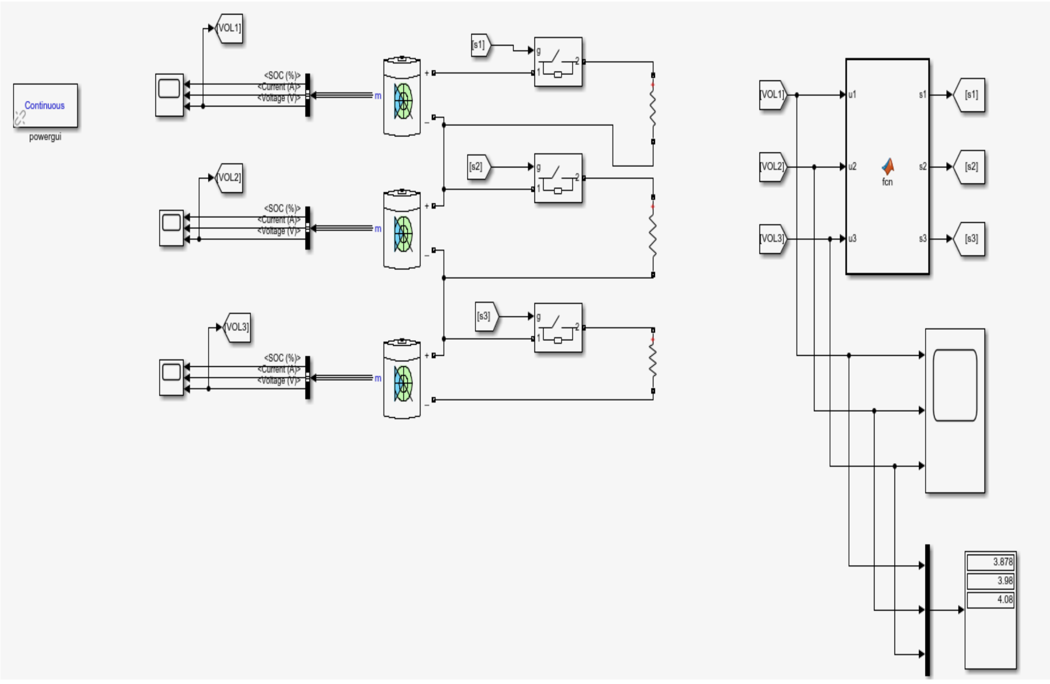

Figure 7: Simulation – Passive cell balancing.

In this section, simulation of SOC cell balancing is discussed. A battery pack of 3 lithium cells is considered for the process. This model shows a single battery module. A single battery module consists of three individual cells connected in series. The reason for making these modules is to increase the efficiency of the system and to simulate different configurations. It can be observed that each cell is equipped with an individual voltage monitoring element that gives out the voltage of the individual cells. These monitored voltages are fed as input to the function block, whose output is used to trigger the switch, as in figure. Hence, according to the variations in voltage level, excess amount of charge is dissipated in the form of heat, via resistor.

VI. RESULTS AND DISCUSSIONS

The battery pack monitored in the experiment was the Lithium-ion battery. After Simulating the BMS model, the battery parameters such as SOC, terminal voltage, and balanced voltage after cell balancing.

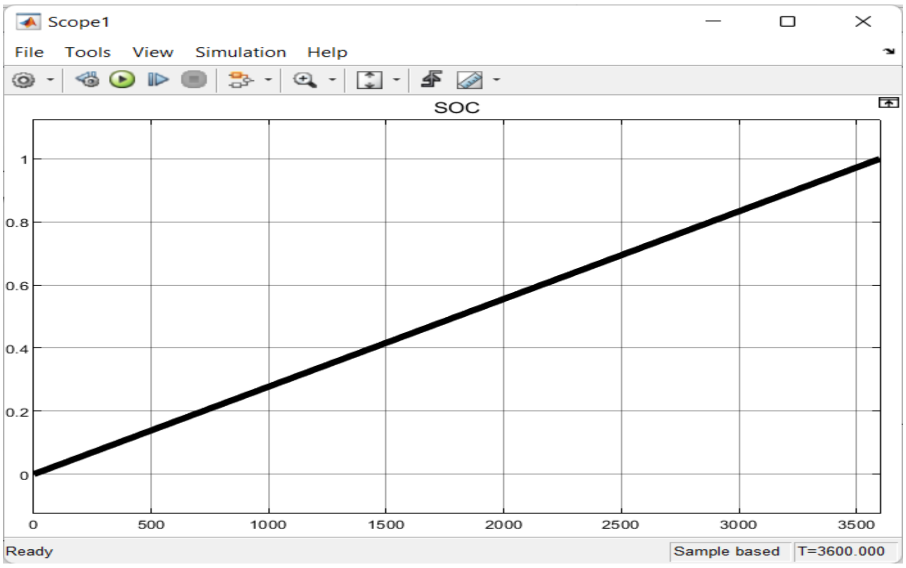

Figure 8: Result1 – Estimated SOC.

In Figure 8, the graph represents the track SOC that is estimated by using the Coulomb Counting method. These values of SOC were monitored during the charging state, initially from 0% to completely charged state, i.e. 100%. This result is obtained from simulation of Coulombs Counting method, the accuracy of these can be improved by considering many other factors like temperature, life cycle of battery, fluctuation of battery voltage, etc.

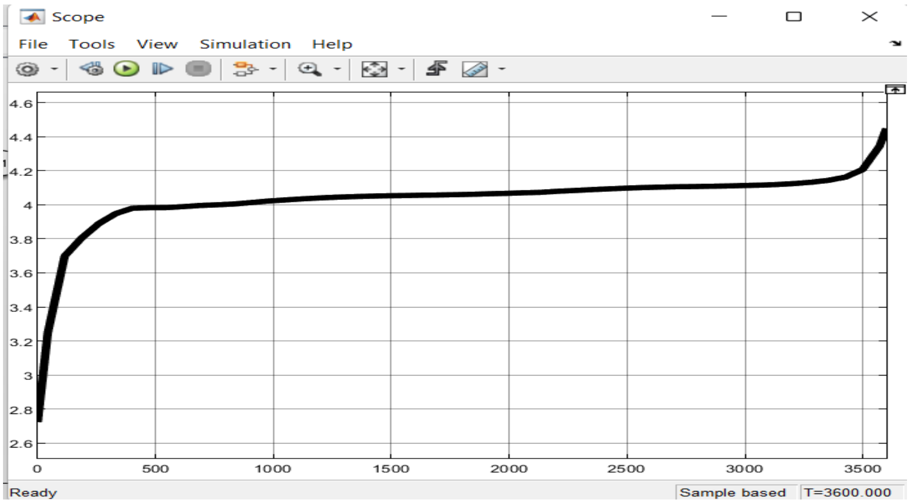

Figure 9: Result2 – Monitored Terminal Voltage.

In Figure 9, the graph shows the monitored voltage of the battery, during charging. Comparing this with plot of SOC (Figure 8), the terminal voltage of battery increases rapidly till the battery is approximately 10% charged and then maintains a constant voltage around 4.2V till it is at 90% of its total charge. This result can be clearly observed in figure 9.

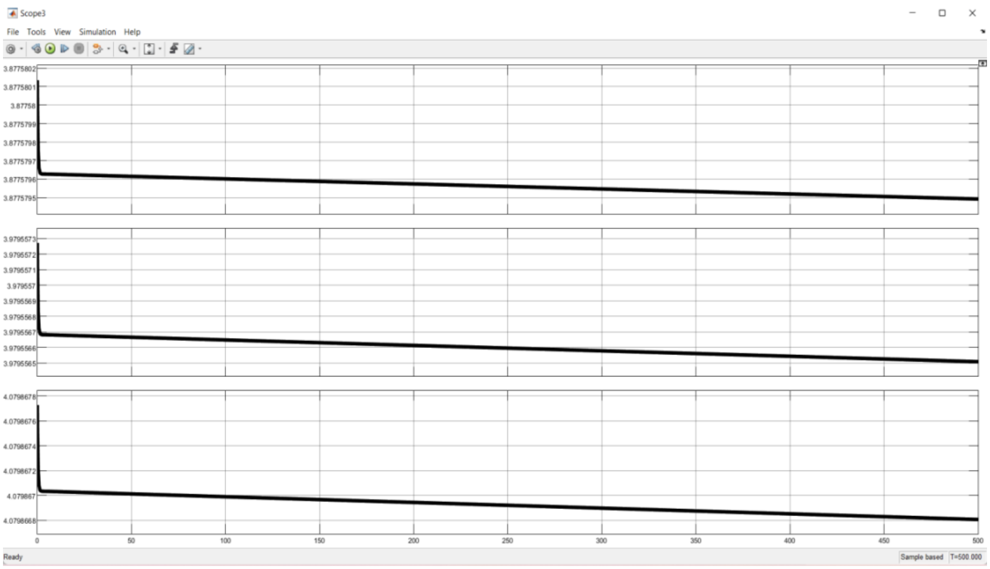

Figure 10: Result3 – Cell Balancing.

Cell balancing is a very important factor in BMS. Figure 10 depicts the cell balancing function of the BMS. Three of the cells in the battery pack were monitored for this experiment. These cells were initially unbalanced. However, cells with higher voltages discharged themselves over time until all the cells were balanced. The balanced voltages of 3 cells are shown in the graph that is around 4V.

VII. CONCLUSION

The BMS SOC estimation, Terminal voltage monitoring and Cell balancing are performed using MATLAB. In this way we have developed the simplest system model for battery management in electric vehicle by controlling the crucial parameters such as voltage, current, state of charge, temperature and also maintaining cell-balancing. It is every important that the BMS should be well maintained with battery reliability and safety. This report focuses on the study of BMS, along with simplification and optimizes the power performances of electric vehicles. Moreover, the target of reducing the greenhouse gases can greatly be achieved by using battery management system.

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