Modeling of Cell Balancing, Battery Aging and Temperature Monitoring for Battery Management Systems

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Abstract - ***The sub-systems and characteristics of a battery management system (BMS) for electric vehicles are presented. A BMS is accountable for safe operation, performance, and battery life under diverse charge-discharge and environmental conditions and it is a necessity for Lithium-ion battery packs. A detailed survey of the Indian two-wheeler market was performed to understand the market share of parameters such as battery rating, battery type, etc. The paper focuses on the systems such as cell balancing and temperature monitoring. It also demonstrates the simulation explaining characteristics of a lithium-ion cell such as battery aging. The sub-systems designed, are giving good results but also providing substantial data for research and a better understanding of the behavior of Lithium-Ion cells.***

Key Words**:** ***BMS, Cell balancing, Temperature monitoring, Battery aging, Lithium -on Cell***

1.INTRODUCTION

The Indian Automobile Industry is currently ranked at number 5 globally and is one of the largest industries which is additionally estimated to be the 3rd largest by the year 2030. There is going to be a drastic change in Indian mobility within the coming years to cater to the needs of a large population. The traditional modes of transport and infrastructure will not be adequate in the coming years. Taking into consideration this aspect, the Government of India is functioning towards developing a mobility option which is 'Shared, Connected and Electric'. To achieve this objective, Lithium-Ion cells will play a major role.

Lithium cells are the building blocks of rechargeable Lithium-ion battery packs which are the predominant energy storage systems in aircraft, electric vehicles, portable devices, and other equipment requiring a reliable, high-energy-density, low-weight power source.

However, the Li-ion battery manufacturing industry in India is at a nascent stage at present. Similarly, there is a dearth of manufacturers of battery management systems in India. The majority of the battery pack manufacturers in India give their customers battery packs that use a BMS imported from China, Taiwan, the US, etc. The Indian market is dominated by BMS imported from China and also the US namely Daly, China Aviation, Deligreen, Link Sun, Orion, etc. In the upcoming years, as the EV market grows, developing technology for in-house production for efficient BMS would be a necessity. This necessity proves to be the motivation for this project of BMS.

Due to the paucity of indigenous manufacturers of BMS, expansion of this work on a larger scale will prove to be beneficial so as to promote in-house production and utilize unexplored technology for battery packs in India.

2. REVIEW OF LITERATURE

Lithium-ion chemistry is very sensitive to overcharge and deep discharge, which can damage the battery, shorten its lifetime and even cause hazardous situations. This requires the adoption of a proper BMS to keep each cell of the battery well within its safe and tested operating range.

In [1], the definition of a flexible hierarchical platform for BMS implementation and an overview of the main techniques for charge balancing and State of Charge (SoC) estimation has been discussed. There is potential to improve the modeling of the systems related to cell lifetime prediction. The emphasis laid on the initial design considerations for a battery pack has proved to be substantial [2].

Battery technology has been widely developed and applied in the past decade, however, the development of BMS for EVs has been slow and insufficient. This inefficiency is being caused because of the complexities such as battery state evaluation, battery modeling, and cell balancing [3]. BMS can be developed using a variety of functional blocks and innovative design techniques. Considering battery requirements and battery life goals will lead to determining the right architecture, functional blocks, and related ICs to develop a BMS and charging scheme to optimize battery life [4].

Most BMS algorithms and software are developed by performing system-level simulations with Simulink. Model-Based Design with Simulink facilitates in gaining insights into the dynamic behavior of the cells in the battery pack, exploring architectures of the software, testing operational cases, and beginning hardware testing early which eventually helps in reducing design errors [5]. Most of the cell balancing schemes which are based on voltage as their main parameter, lead to a pack being more unbalanced than without them. It is important to implement cell balancing algorithms more efficiently considering the current growth in the use of Li-ion battery packs and the criticality of their use [6]. Battery Management Systems: Design by Modelling describes the design of BMS with the aid of simulation methods. [7]

3. SURVEY OF BATTERIES

The types of batteries used in electric vehicles may be of the type Lithium Ion, VRLA (Valve Regulated Lead-Acid), Lead Acid, etc. The classification shown in Fig.1 gives us a clear idea that Lithium-Ion batteries have a greater market share of 56% compared to the other batteries.

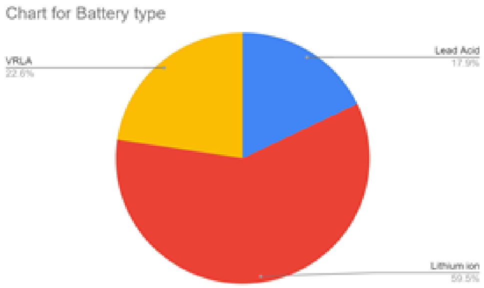

Fig. 1: Battery Type

Considering our area of focus that is BMS for Lithium-Ion batteries, with the help of the Fig. 1, we observe that 38.8% of Lithium-Ion batteries used in electric two-wheelers in the market have a battery capacity of 48V and 44.9% have a battery capacity of 60V.

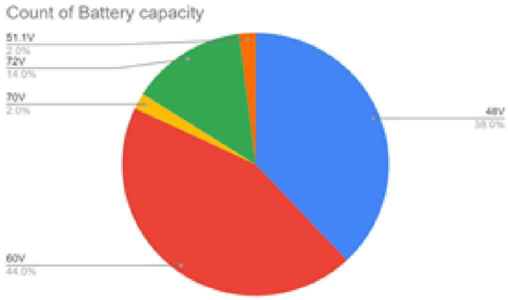

Fig. 2: Battery Capacity Segmentation of Vehicles

Lithium-Ion batteries dominate the market due to parameters such as energy density, weight, number of cycles (battery life), maintenance frequency, efficiency and cost. Considering Lithium-ion batteries, the use of 48V and 60V battery pack ratings gets an almost equal share in the market as shown in Fig. 2.

4. FLOWCHART

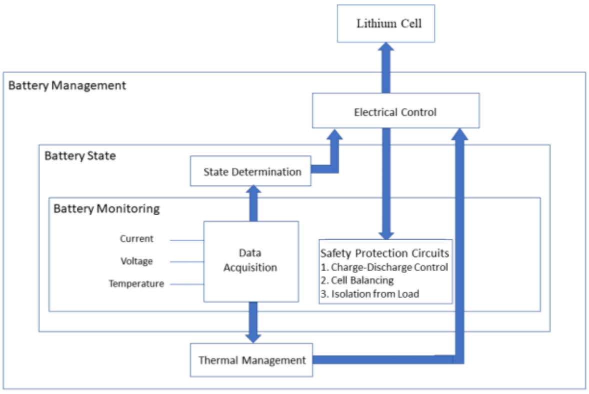

Fig. 3: Flow Chart of BMS

For the design of the BMS, the design flow began with finalizing the basic specifications of the battery pack. The design in MATLAB began with battery modeling.

The first step that we followed in the development of an accurate battery model was to build an equivalent circuit that would demonstrate the battery's behavior and dependencies on temperature, (SoC), State of Health (SoH) and current.

SoC is defined as the ratio between the amount of charge extractable from the cell at a particular point of time and its total capacity. It is basically a relative measure of the amount of energy stored in a battery. Accurate SoC estimation is important because battery management systems use the SoC estimate to inform the user of the expected usage until the next recharge, keep the battery within the safe operating window and ultimately improve battery life.

5. MODEL SIMULATIONS

5.1 Cell Balancing Model

Figure 4 represents a passive cell balancing circuit. Passive balancing makes the battery stack look like every cell has the same capacity as the weakest cell. It uses a comparatively low current and drains a small amount of energy from cells having high SoC during the charging cycle. Because of this, all cells charge to their maximum SoC. This is accomplished by using an Insulated Gate Bipolar Transistor (IGBT) as a switch and bleed resistor in parallel with each battery cell.

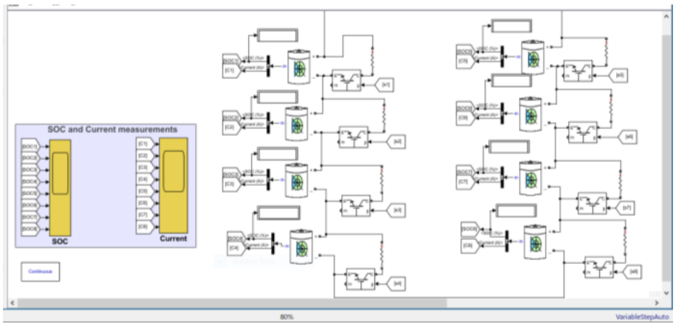

Fig. 4: Passive Cell Balancing Layout

Fig. 4 shows the cell balancing circuit implemented in MATLAB where 4 cells are in series and there are two such sets connected in parallel which means that this is a 4s2p combination of cells in a battery pack. Each cell has one transistor and a resistor connected to the collector terminal of the IGBT. Unequal distribution of charge or large differences in SoC of the cells of a lithium-ion battery pack is one of the significant reasons which will contribute to the reduced quality of life of a lithium-ion cell. This problem can be minimized by using efficient devices like IGBT which help in achieving good voltage balancing using minimum components.

If the input at the gate terminal of the IGBT is high it is going to be conducting in the direction of the collector to emitter as it is a unidirectional device. The gate input (S1) goes high only when the SoC of any of the other cells is less than that of the first cell. Once S1 becomes high, the IGBT will switch on and transfer the excess charge from this cell to the other cells. Also, the resistor which is connected is a bleeder resistor that is used for discharging the excess charge in the circuit as soon as IGBT switches off.

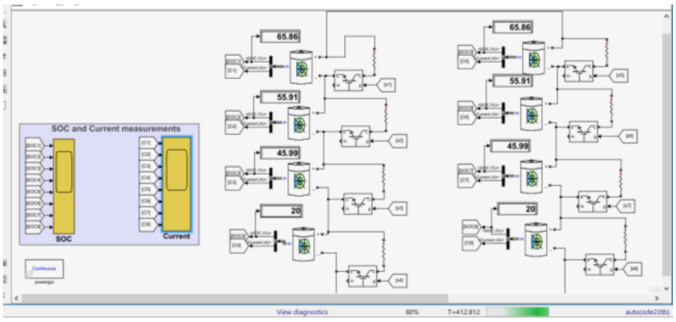

Fig. 5: Initial stage of Cell balancing

Figure 5 shows the initial stage of passive cell balancing circuit simulation in MATLAB where the SoC of all the cells is different. That means the distribution of charge in all cells is unequal and not balanced.

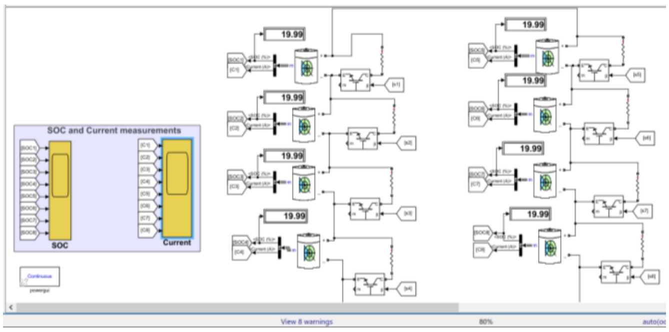

Fig. 6: Final stage of Cell Balancing

After the simulation is run in MATLAB, in the final stage which is shown in Fig. 6, the SoC of all the cells is equal and balanced which is 20%. The passive cell balancing circuit efficiently redistributes the excess charge from the other cells and drains out the excess charge such that all the cells are now balanced and have SoC 20%. In Fig. 7, a graphical representation of the same is shown.

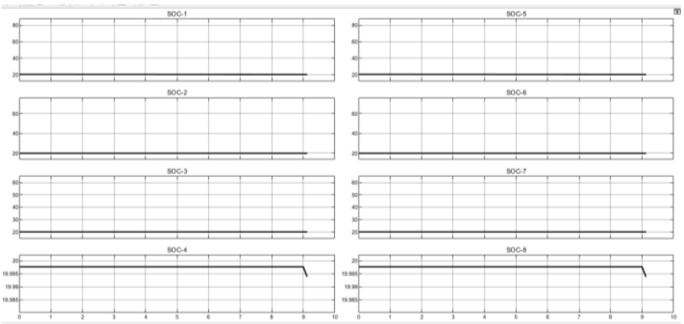

Fig. 7: Graphical Representation of Final SoC%

5.2 Battery Temperature Behavioral Model

Figure 8 represents a comparative model between a cell with temperature effect and without temperature effect. Battery A is subjected to a variable ambient temperature during the discharging and charging process. Battery B is where the impact of temperature is neglected. The performance of both these is compared through the measurements block and the output is given on the scope where we can understand the temperature variation with time and its effect on voltage, SoC, and current.

The internal or ambient temperature of a cell increases or decreases due to charging or discharging, heat losses, ambient temperature variations, and output voltage. The capacity also increases or decreases and it is necessary to take into consideration these effects because that takes analyzing the cell behavior closer to practicality.

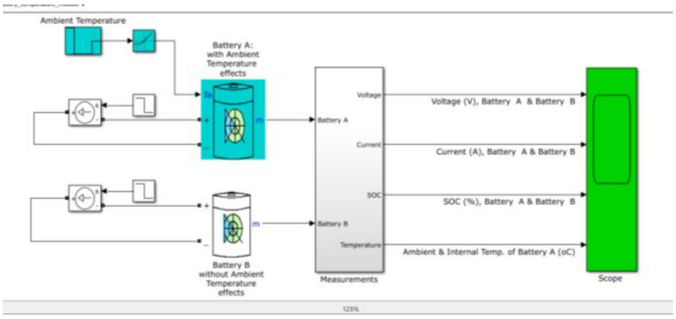

Fig. 8: Battery Temperature Monitoring Model

The prime difference between Battery A and B is that temperature variation block has been added to Battery A to add ambient temperature effect where we have specified the time interval and the amplitude i.e., temperature is set as 20 to -20 degree Celsius which will help us realize the discharging process and then -20 to 0 degree Celsius during the charging process.

In the sub-block (Fig. 9), Bus Selector ports are used to select and use the several inputs coming from Battery A and Battery B discretely. As we can see here, voltage, current, SoC from A and B both along with the extra element of the temperature of A are obtained and hence we obtain the comparative output of Battery A and B in terms of Voltage, SoC, and Current.

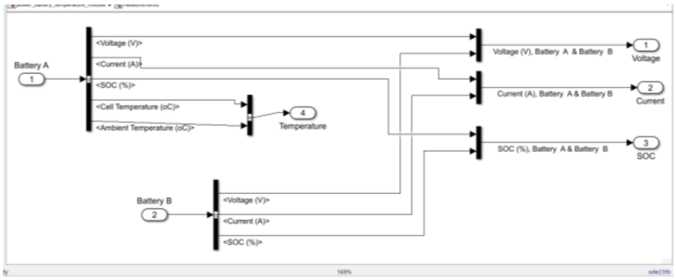

Fig. 9: Sub-block of Battery Temperature Monitoring Model

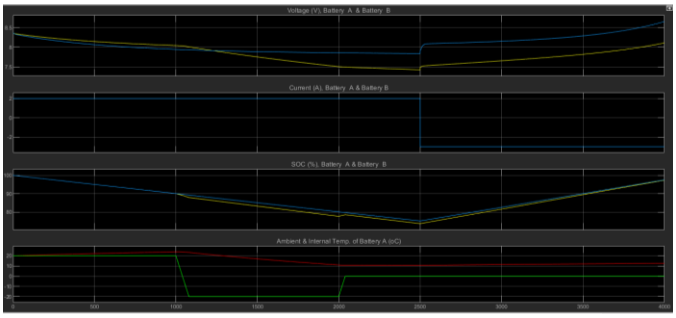

Fig. 10: Battery Temperature Monitoring Model Output

In Fig. 10, At t = 0 s, Battery A and B are discharged with 2A and in graph 4, the ambient temperature is 20 degrees C. The internal temperature is increasing to its steady-state value due to heat losses from the discharge process in the form of the red line in graph 4. This causes the output voltage of Battery A which is the yellow line in graph 1 to slightly increase, while battery B output voltage continues to decrease.

At t = 1000 s, the green line which is ambient temperature is decreased to -20 degrees C. This causes the output voltage of Battery A to greatly decrease as the internal temperature decreases rapidly shown as a yellow line in graph 1. The reduction in SoC is due to a decrease in the battery capacity. The output voltage of battery B continues to reduce slowly to its steady-state voltage.

At t = 2000 s, the ambient temperature which is the green line in graph 4 is increased from -20 degrees C to 0 degrees C. As the internal temperature increases, the output voltage of Battery A also increases and we can see it in graph 1 with the help of the yellow line. Also, as the capacity increases, the SoC of Battery A increases and we can see that in graph 3. The output voltage of Battery B remains constant to its steady-state value.

At t = 2500 s, Battery A and B are charged with 3 A at an ambient temperature of 0 degrees C. And this causes the internal temperature to increase due to heat losses during the charging process, which increases the charging voltage of Battery A.

5.3 Battery Aging Model

Figure 11 depicts the aging model of a Lithium-Ion battery and with the help of this model, the relationship between several parameters of a lithium-ion battery pack i.e., voltage, current, SoC, cell temperature, age, and maximum capacity is shown.

It is a model which shows the effect of aging due to charge-discharge cycles on a Lithium-ion battery pack.
Basic parameters like Initial SoC as 100% and initial cell temperature are set as 25 degrees C. 25 degrees C is the ambient temperature and the block in the center is being used for generating charge-discharge cycles.
The idea is that some parameters are taken directly from the battery and others are given as separate inputs so that ideal charge-discharge cycles are generated to simulate the effect of aging on these cells. The output contains parameters like Voltage, Current, SoC, etc. The battery is subjected for 1000 hours to several charge-discharge cycles at various Depths of Discharge (DoD) and discharge rates.

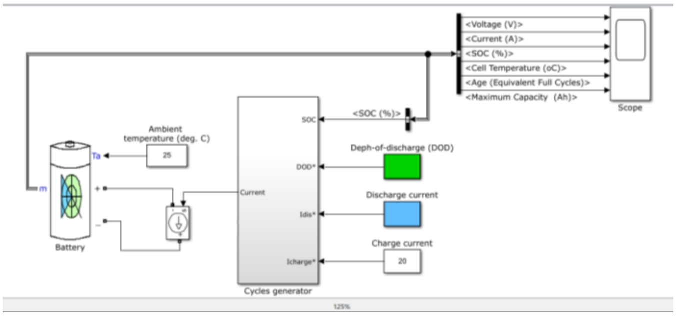

Fig. 11: Battery Aging Model

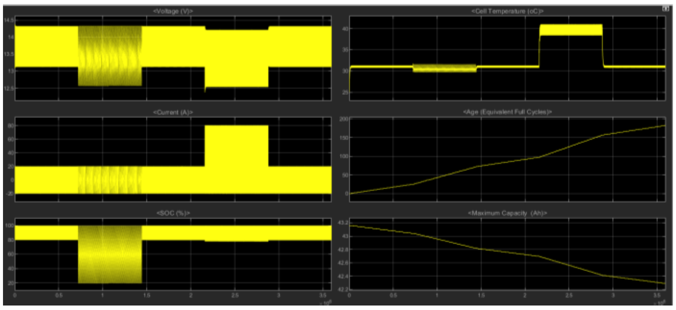

Fig. 12: Battery Aging Model Output

In the graphs shown in Fig.12, at first, the battery is cycled to a DoD of 20% at a 0.5C discharge rate. Afterward, the DoD and discharge rate are increased to 80% and 2C, respectively.

At t = 0 s, the battery cycling starts with a discharge current of 20A i.e., at a 0.5C discharge rate. At an ambient temperature of 25 degrees C. The initial SoC is 100 % where the discharge goes on until the SoC reaches 80% or DoD of 20%. Afterward, the battery is charged to 100% SoC with a charge current of 20A. As this cycle continues, the battery capacity decreases and its aging continues. There is a rise in the internal cell temperature from 25 degrees C to 33 degrees C.

At t = 200 h, the battery is discharged to 20% SoC i.e. DoD of 80%, and charged to 100% SoC again. This cycle is repeated for another 200 hours and the battery age starts to increase rapidly.

At t = 400 h, the cycling DoD is brought back to 20% for another 200 hours. And it results in slowing down the aging process of the battery.

At t = 600 h, the discharge current is increased to 80A i.e. 2C discharge rate. There is a rise in the internal cell temperature from 33 degrees Celsius to 43 degrees Celsius. As this cycle goes on, the age of the battery increases rapidly, which in turn reduces the battery capacity.

And at t = 800 h, the discharge current is brought back to 0.5C rate again i.e. 20A for another 200 hours which in turn slowed down the aging process of the battery.

6. CONCLUSION

We performed a detailed market analysis of electric two-wheelers which includes specifications of Lithium-ion battery packs such as current rating, system voltage, and battery types. In this paper, we have demonstrated the design of important subsystems in a BMS like cell balancing and battery temperature monitoring along with an important battery characteristic of aging. We have simulated the aging model for a time period of 1000 hours and hence it has been studied for most of the possible cases of functioning resulting in better reliability. These models are applicable for implementation in a BMS for a Lithium-Ion Battery pack in suitable applications such as electric vehicles, energy storage systems, etc.

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