Battery Management Integrated Circuits to improve the runtime for Li-ion Batteries and predictive battery degradation circuit.

Vemparala Sai Kumar
Department of EEE
Birla Institute of Technology and Science
Pilani, India
BITS ID: H2021H1400155P
h20210155@pilani.bits-pilani.ac.in

Mayank
Department of EEE
Birla Institute of Technology and Science
Pilani, India
BITS ID: H2021H1400154P
h20210154@pilani.bits-pilani.ac.in

Mukul Kant
Department of EEE
Birla Institute of Technology and Science
Pilani, India
BITS ID: H2021H1240095P
h20210095@pilani.bits-pilani.ac.in

Dakshita Gupta
Department of EEE
Birla Institute of Technology and Science
Pilani, India
BITS ID: H2021H1240096P
h20210096@pilani.bits-pilani.ac.in

***Abstract*— - Because of the high demand of the Li-ion batteries for different purposes, it is being required to maintain their performance and safety by considering the size of the management system as a constraint. For that purpose, a Battery Management System is explicitly required. In this paper, a BMS is discussed that has both cell monitoring and balancing in which a modularized charge equalizer that uses monitoring IC is shown. Modularization is done to make a master and slave part wherein the master has the central equalization converter which is further shared with the battery cells through the cell switches in the slave module. Monitoring IC, this is there in the slave module do the individual cell monitoring. In this paper a model of 88 Li-ion batteries is proposed, results of which are shown at the end and show a good performance. This report analyses the conventional approaches to increase the runtime of Li-ion batteries through the use of Battery Management ICs and predictive battery degradation circuits.**

***Keywords*— Li-ion batteries, Battery Management System, Charge Equalization, State-of-Charge Estimation, equivalent circuit model**

I. Introduction

With the coming of the electronic revolution resulting in widespread use of electronic gadgets, the battery technology holds the key to furthering the use of electronics into unprecedented domains. The Li-ion batteries have been a path-breaking innovation that has been around for some years now and is being increasingly relied upon because of their ability to deliver power equivalent to the previous generation batteries while being smaller in size and lighter in weight. Parallel, there has been much higher progress in the complexity and hence the energy consumption by the electronic packages which has placed demands of increasing the runtime of such complex packages powered by smaller power packs. This is the focus of the given report wherein we analyze different approaches used to monitor the remaining runtime and possibilities of increasing the overall runtime of a given Li-ion battery through the use of Battery Management ICs and predictive Battery degradation circuits.

A Battery Management System is any electronic system that manages to protect a rechargeable battery from operating outside its safe operating area, monitors its state, calculates and reports secondary data, ultimately controlling its environment, authenticating it and / or balancing it. Thus, the goal of a Battery Management System may include increasing the runtime, optimizing battery usage, increasing overall battery life or simply reporting on the battery charge/discharge data.

Based on complexity and performance, the Battery Management Systems may be classified as: Passive Regulators, Active Regulators, Hybrid or Complete BMS.

The passive regulators increase battery lifetime by achieving balance across batteries or cells via bypassing of charging current when the cell's voltage reaches a certain level. Active Regulators intelligently turn on/off a load to achieve balancing. A complete BMS, in addition to protecting the battery, also reports the state of the battery to a display.

A Battery Management System may be implemented in any of three topologies:

- Centralized: a single controller is connected to the battery cells through multiple wires
- Distributed: a BMS board is installed at each cell, with just a single communication cable between the battery and a controller
- Modular: a few controllers, each handling a certain number of cells, with communication between the controllers

II. Methods For Charge Equalization

There are different methods for charge equalization that were initially proposed. Some of them are discussed below:

A. *Resistive method of charge balancing-*

In this method, a fixed resistor (selected based on the required balancing currents) in series with an active switch is connected in shunt to each cell. The cell properties are monitored continuously by monitoring ICs, and based on the difference in SoC of each cell, the controller controls the switches. The overcharged cells are made to discharge through their respective resistors. The major disadvantage is the wastage in energy dissipation in resistors, and their heating.

B. *Switched capacitors method of charge balancing-*

In this method, capacitors are connected across the individual cells, as capacitors can maintain constant voltage across the cells. The cell properties are monitored continuously by monitoring ICs, and based on the difference in SoC of each cell, the controller controls the switches. The undercharged cells can be charged the average value of the module, by capacitors discharging through it. The major disadvantage of this is, the more cells in series in a module, the more capacitors are needed, thus, this method is expensive. It also takes a long time to achieve charge equalization.

C. *Charge balancing using multiple winding transformer-*

In this method, the primary winding is connected to an AC source and the secondary winding is divided into multiple windings which are connected to individual cells through AC/DC converters. The controlling of charging of cells is simple and has high efficiency. But it requires a special multiple winding transformer, and cannot be used in applications where there is a high chance of future expansion of battery packs.

D. *Quasi-resonant-zero-current-switching (QRZCS) buck- boost converter-based charge balancing-*

In this method, cell voltage is balanced by continuously switching of individual cell equalizer modules (ICE), controlled by a BMS controller which follows an equalization algorithm. QRZSE technology is used in buck-boost converters to reduce switching loss of MOSFETs, which can increase the efficiency of the equalizer module. But the major problem is each cell requires a separate ICE module, which increases the circuit size and implementation cost.

To overcome all these challenges in the different methods discussed above this paper proposes an efficient BMS. By this method the equalization energy is shared between all the batteries and the target cell with the help of Monitoring IC (LTC6802). The proposed charge equalizer is split in two parts, one master and multiple slaves wherein each slave module has a monitoring ICs, battery modules, cell switches and module switches. This design takes a centralized equalizer circuit that is shared by all the battery cells instead of having the equalizers for each cell individually. The extra advantage of such a design is that it is easy to implement and extensible. At the end the results are shown from the experiments conducted by the authors by taking a pack of 88 Li-ion batteries, revealing that a good cell balancing performance is achieved.

III. A Modified monitoring IC for Li-ION Cell

As discussed in the reference [], in their work they have presented an architecture of an IC which is capable of monitoring 6 cells each set stacked above another, with a total of 192 cells. The architecture consists of 6 parallel 12-bit ΣΔ modulators which can measure voltages of 6 cells. There are a total of 13 ADC in the IC architecture. Each A/D converter is a 12 - bit having 5mV accuracy, run in parallel to synchronize the whole battery voltage. Other 6 ADC's are used for individual cell temperature. The last ADC is multiplexed to measure the whole die temperature. The single IC is used for a measuring of 6 cells. For measuring multiple series-connected cells, the IC must also be stacked. For each ADC , the output is connected to the parallel decimators. Thus in total 13 parallel decimators are also used. UART or SPI protocol is used for the transfer of cell parameter/information to the microcontroller.

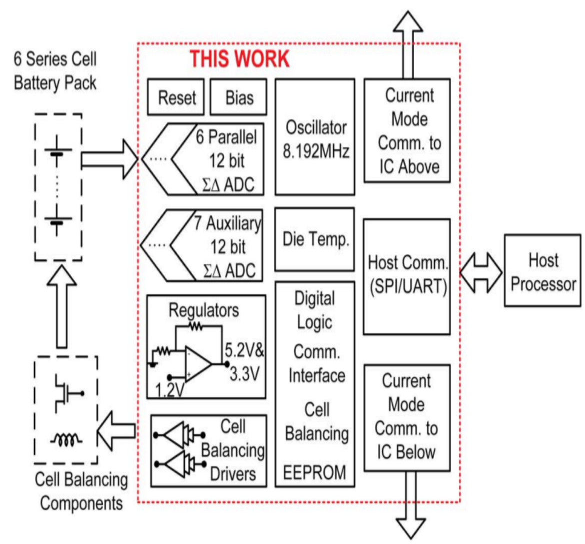

Figure 1. Block diagram of the IC and chip micrograph showing various blocks

IV. Features And Circuit Design

The battery cells connected in series are modularized into M modules such that each module has K cells. As stated above the equalizer is split into two parts i) one master and ii) multiple slaves. The master module consists of a microcontroller and a bi directional dc-dc converter. The complete arrangement and design can be viewed in Figure1.

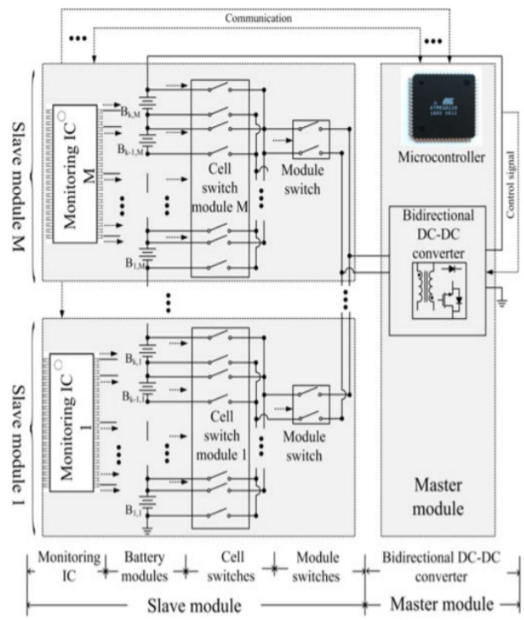

Figure 2. Proposed Charge Equalizer

Slave modules get signals from the microcontroller and dc-dc converter performs the charge equalization by equalization current between the unbalanced battery cell and the complete battery. The monitoring IC is monitoring for the charge in all the cells of its own slave module and then controls the switch matrix to make a direct path from dc-dc converter to the selected battery cell (where the charge is not equal). The monitoring IC used in this design is LTC6802 which is manufactured by Linear Technology consisting of a 12-bit ADC (Analog to Digital Converter), high precision voltage reference, and a high voltage multiplexer with serial data communication interface. Each IC can simultaneously monitor up to a maximum of 12 series connected battery cells with a common mode voltage of 60V. Multiple such ICs are used here to monitor longer strings of batteries, with a small time-delay of 13ms. Thus, this IC continuously monitors the cell voltage and tells the same to the microcontroller. In the IC an n-MOSFET switch is there which does the balancing of the battery cell. The switch turn-on and turn-off mechanism is controlled with the opto-coupler as shown in Figure 2.

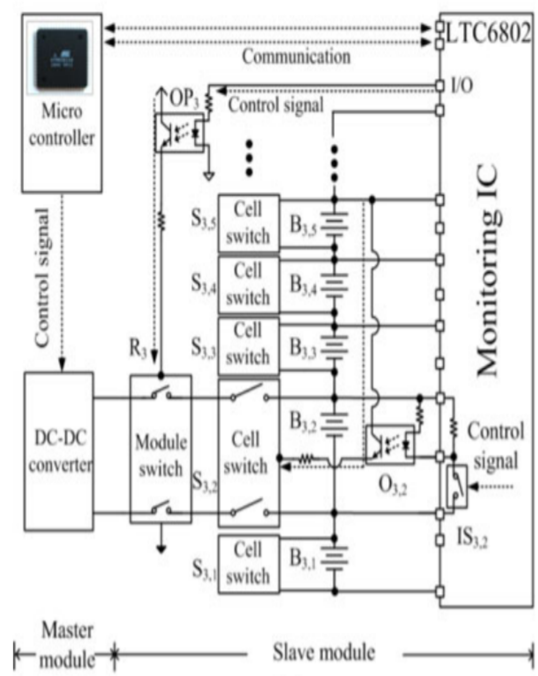

Figure 3. Cell switch, Module switch, Monitoring IC circuit for cell parameters measuring

To summarize the features of complete scheme we can say that it is an easy to implement BMS design with the monitoring IC that significantly reduces size, cost and increases the performance as compared to the resistive balancing techniques with energy dissipation. The control method is also very simple in this design.

V. Operating Principle

The difference in the % of SOC of the cells is taken as the main condition for cell balancing operation. In the proposed work, a special BMS algorithm is followed by the microcontroller in the master module. Monitoring IC (LTC6802) is used continuously to transfer the current state of cells in real time to the master. Average SOC of all cells are calculated and individual cell SOCs are compared with the average value. The cells with value less than average are undercharged cells, and those with values more than average are overcharged cells. Based on the information, the master communicates with the slave modules for charge equalization. Based on the algorithm the master microcontroller sends controlling signals to the module switches and cell switches. The following steps depict the battery management system algorithm.

Step.1) When the master module is initialized then, the monitoring ICs checks the current condition of all slave modules. If there is any abnormal operation of any cell, warning signals are generated and the cell is cut-off from the system, and states of all the cells are again checked.

Step.2) The mode of operation of the battery is checked. There are three modes, charging mode, discharging mode, idle state. Charge unbalancing is not affected by the mode of operation as SOC variation is the same in any mode. In charging mode, each cell is monitored for overcharging. In discharging mode, each cell is monitored for undercharging. In idle mode, the states of every should not change.

Step.3) The cells which have SOC more/less than average value, the proposed charge equalization method is applied. The monitoring ICs again check for states of all cells and start from step 1.

CASE 1) In case of an overcharged cell…

Overcharging of a cell occurs during the charging of the battery. During this mode of operation, all slave module switches and cell switches are turned ON.

Step.1) If the monitor IC detects an overcharged cell, the corresponding cell switch is turned OFF making the cell cut-off / open circuit. The cell stops charging, while other cells are charging.

Step.2) From monitoring IC, the average of SOC of all cells is calculated continuously.

Step.3) Once the average value reaches the SOC of the overcharged cell, the corresponding cell switch is turned back ON.

Step.4) Now all cells continue to charge together, maintaining individual SOCs equal to the average value.

CASE 2) In case of an undercharged cell…

Undercharging of a cell occurs during the discharging of the battery. During discharging mode of operation, all slave module switches and cell switches are turned ON.

Step.1) If the monitor IC detects an undercharged cell, the corresponding cell switch is turned ON making the cell connected directly to supply. During this time all other cell switches are turned off.

Step.2) From monitoring IC, the average of SOC of all cells is calculated.

Step.3) Once the SOC of the cell reaches the average value, the corresponding cell switch is turned OFF, and other cell switches are turned ON.

Step.4) Now all cells continue to charge together, maintaining individual SOCs equal to the average value.

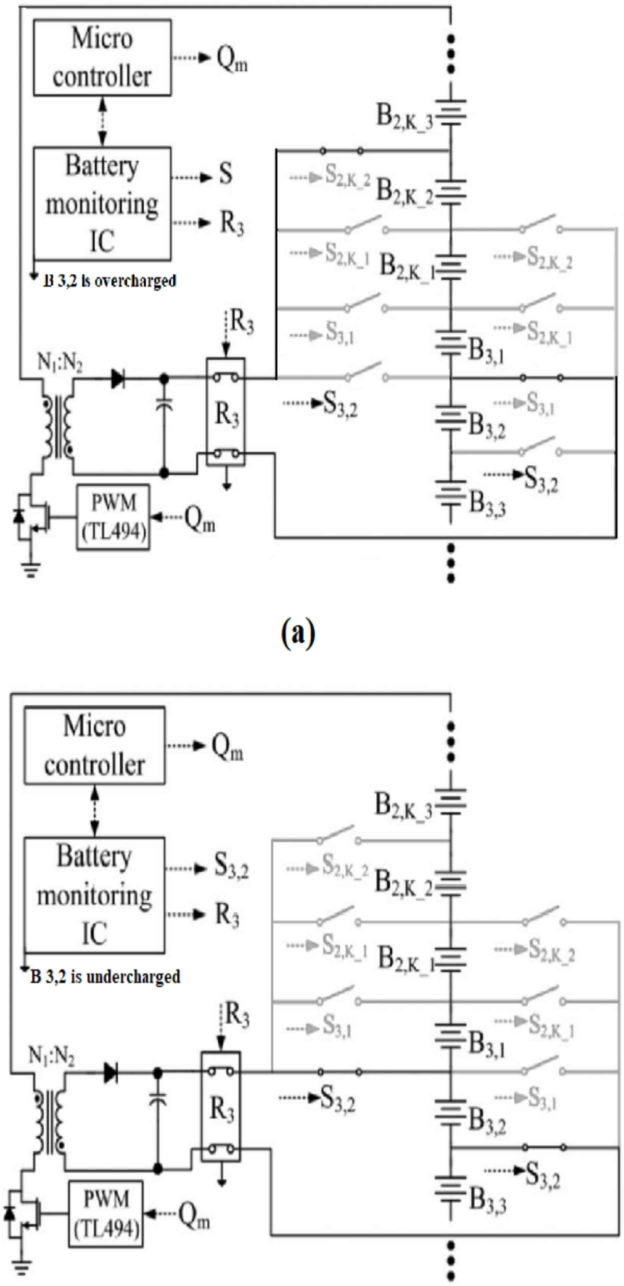

Figure 4. Proposed charge equalization method. (a) If $B_{3,2}$ is overcharged. (b) If $B_{3,2}$ is undercharged.

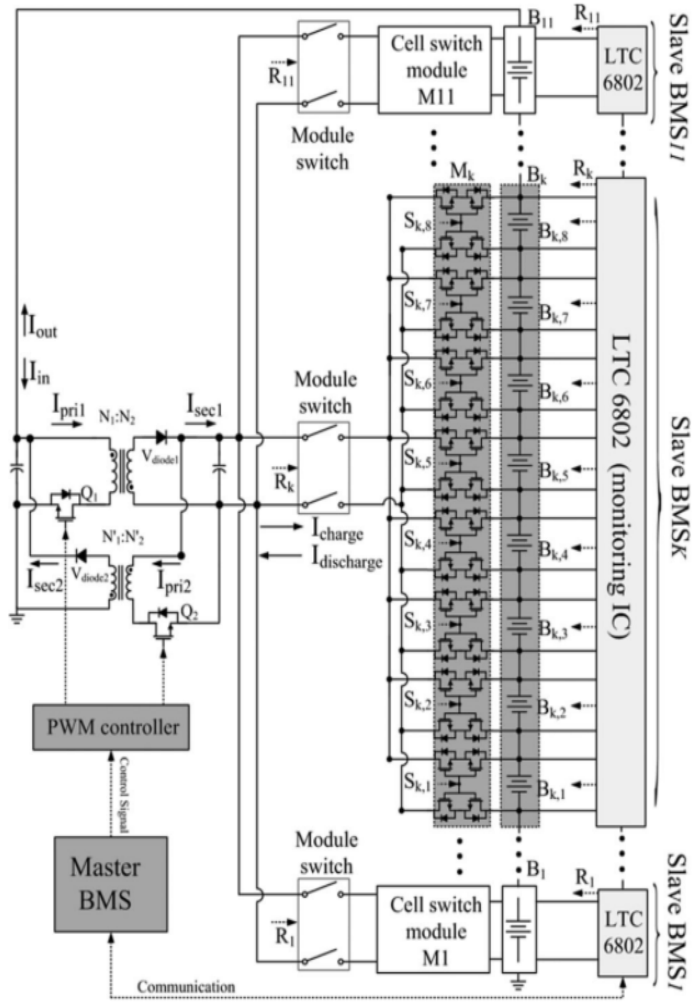

Figure 5. Proposed design for 88 cells.

VI. Experimental Results

A. *Proposed Design-*

Prototype circuit in the proposed work, consists of 88 Li-ion cells, with a master module and slave modules. Master module is composed of bi-directional DC-DC buck-boost converter for both charging and discharging modes, and a microcontroller following BMS algorithm. There are 11 slave modules, each slave module is connected to 8 cells. A slave module consists of a single module switch, and 16 unidirectional cell switches, 2 cell switches connected to each individual cell, allowing bidirectional controlled power transfer. Buck-boost converter is designed to give a maximum of 2A. Each slave module is designed in a single board. Such 11 boards are stacked on top of another in a modular fashion.

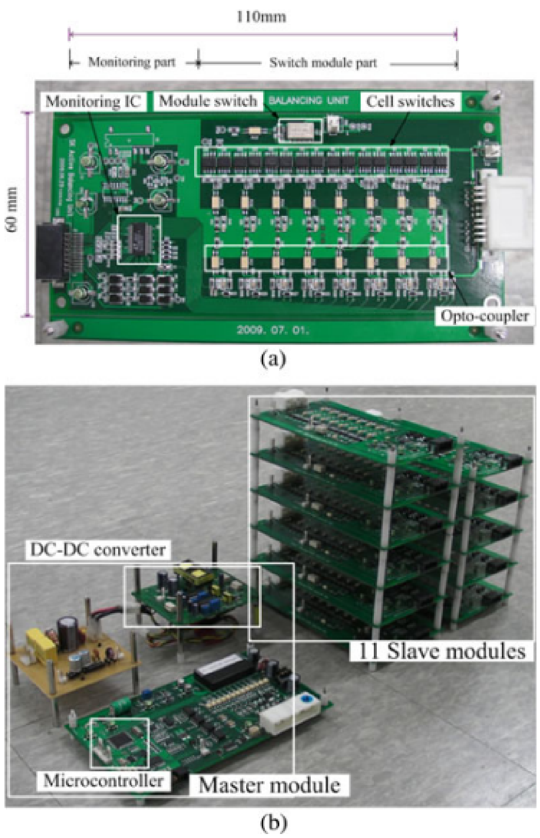

Figure 6. (a) Slave module prototype, (b) BMS prototype for 88 cells

B. *Equalization Time Calculation-*

Equalization time is the time taken by the algorithm to bring SOC of the overcharged/ undercharged cell to the average value of all the cells. This time depends on the equalization current and the difference of the SOC from the average value. Higher the equalization current and lower the SOC difference lesser the equalization time. SOC can be estimated from the datasheet using the run-time voltage of the cell, and equalization current, measured by the monitoring IC connected to the respective cell. To find the difference in SOC (ΔSOC) from difference in voltages (ΔV) between respective overcharged/ undercharged cells with average voltage of all cells. If $Q_{available}$ and Q_{total} are the available and total charge of the cell used in the prototype, and C is the capacitance of the cell. Then equalizing time (Δt_{eq}) is given by,

$$\Delta SOC = \frac{Q_{available}}{Q_{total}} = \frac{C \,.\, \Delta V}{Q_{total}}$$

$$C = \frac{Q_{available}}{\Delta V} = \frac{I_{eq} \,.\, \Delta t_{eq}}{\Delta V}$$

$$\Delta t_{eq} = \frac{C}{I_{eq}} \Delta V = \frac{Q_{total}}{I_{out}} \,.\, \Delta SOC$$

C. *Experimental Results of Cell Charge Balancing-*

The proposed BMS algorithm can predict equalizing time for a single cell, as the authors have calculated. At SOC difference of 10%, to get a charge equalization in 1hr, the DC-DC converter must give an output of 1.56A.

When all 88 cells are connected as in the proposed work, the authors have tested keeping one of the cells as undercharged by ΔSOC of 14.3% and another cell overcharged by ΔSOC of 5.7%. The master module brought the SOC of the overcharged cell to average value in 60min at 2A. After the first cell charge equalization, the BMS has a 10-min halt time before the next cell balancing. During this time, the master module checks for any protective warnings. Then the master module brought the SOC of the undercharged cell to average value in 43min at 2A. Thus, the BMS can bring the ΔSOC of 20% to ΔSOC of 1.3% in 1hr 53min. From this demonstration, by using a single buck-boost converter and no capacitor they have achieved a high performance and efficient, fast charge equalizer for high-capacity cells of an electric vehicle battery pack.

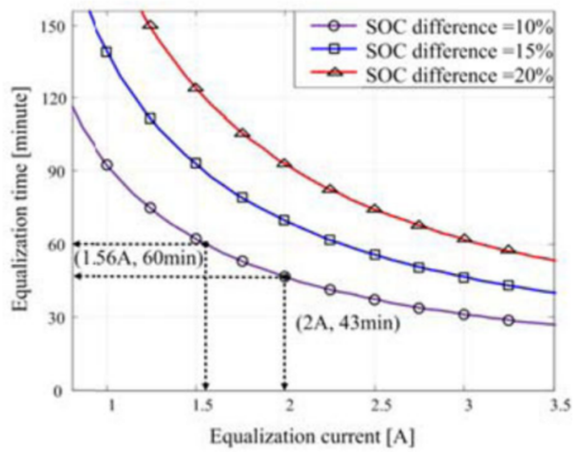

Figure 7. Simulation results of the equalizing time at different SOC and different equalizing currents of a single cell.

VII. Battery Modelling for predictive analysis

The Battery source can be modelled in various ways, namely: i). Electrochemical, ii). Data Driven, iii). Electrical models.

We are interested particularly in the equivalent electrical model of the Li ion battery.

The common equivalent circuit models mainly include the following:

i). Rint Model

ii). Thevenin Model

iii). Second order RC Model

iv). PNGV Model

A. *Rint Model-*

It is also known as the internal resistance model. It has a constant voltage source with a resistor in series. Open Circuit Voltage (V_{OC}) is the ideal voltage source. V_L is the terminal voltage across the terminals of the battery. R_0 is the internal resistance of the battery. The current in the circuit is i(t). The Rint model is shown in Figure 6.

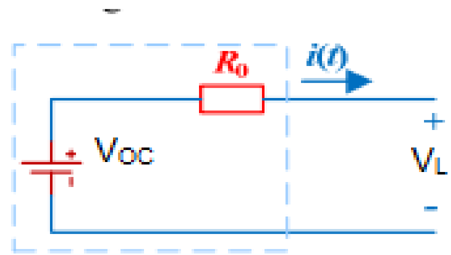

Figure 8. Rint Model

This model is not only simple in structure but also sets a basis for other circuit models and hence it is often known as the ideal model.

However, it has a limitation that it does not consider the load transfer polarization and diffusion polarization and so, has a small range of applications and is not very accurate.

During the charging and discharging process, a part of electrical energy is converted to heat energy.

Using KVL in the circuit given in Figure 6:

$$V_{OC} – V_L = R_0 . i(t)$$

B. *Thevenin's Model-*

It is based on the Rint model which also considers the internal polarization effect of the battery along with its heat consumption content. RC network is added to simulate the nonlinear charge-discharge process. R_P is the non-linear contact resistance between electrolyte and plate also known as polarization resistance, C_P is the equivalent capacitance of electrode plate known as polarization capacitance and other parameters are the same as that in the Rint model.

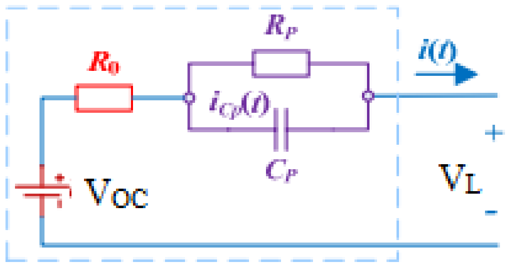

Figure 9. Thevenin’s Equivalent Model

This model is also known as First Order RC Model which takes into consideration the ohmic polarization and electrochemical polarization of Li ion batteries. However, as the battery ages, the SoC estimation accuracy based on this model decreases.

$$V_L = V_{OC} - (i(t) \,.\, R_0) - V_P$$

$$dV_P \, dV_P = -\frac{V_P}{R_P C_P} - \frac{V_P}{R_P C_P} + \frac{i(t)}{C_P} \frac{i(t)}{C_P}$$

C. *Second Order RC Model-*

In this model, an extra circuitry of RC network is added to the Thevenin’s model in order to represent the concentration polarization inside the battery, RC is the concentration impedance and CC is the concentration capacitance.

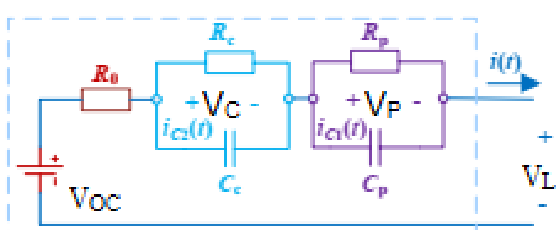

Figure 10. Second Order RC Model

Compared to the previously discussed two models, the second order RC model has a relatively complex structure that requires a higher computing energy of existing processors. However, this model can better describe the internal ohmic polarization, electrochemical polarization and concentration polarization. Also, its simulation results are closer to that of the ideal operational characteristics of the battery.

$$V_L = V_{OC} - (i(t) \,.\, R_0) - V_P - V_C$$

$$dV_P \, dV_P = -\frac{V_P}{R_P C_P} - \frac{V_P}{R_P C_P} + \frac{i(t)}{C_P} \frac{i(t)}{C_P}$$

$$dV_C \, dV_C = -\frac{V_C}{R_C C_C} - \frac{V_C}{R_C C_C} + \frac{i(t)}{C_C} \frac{i(t)}{C_C}$$

D. *PNGV Model-*

In addition to Thevenin’s model, a large capacitance C_b is added to characterize the change of battery Open Circuit Voltage, which is mainly caused by the accumulation of the load current. The other parameters are the same as defined in Thevenin's model.

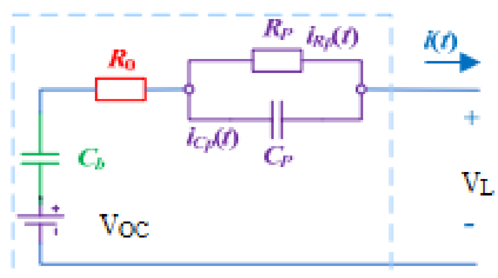

Figure 11. PNGV Model

The PNGV model describes the integral change of open circuit voltage with current-time by using large capacitance C_b . It shows the relationship between the battery capacity and open circuit voltage and also characterizes the DC response of the battery.

$$V_L = V_{OC} - (i(t) \,.\, R_0) - V_P - V_b$$

$$dV_P \, dV_P = -\frac{V_P}{R_P C_P} - \frac{V_P}{R_P C_P} + \frac{i(t)}{C_P} \frac{i(t)}{C_P}$$

$$V_b = C_b \int \quad i(t)dt \int \quad i(t)dt$$

VIII. Conclusion

The prototype taken in the paper with 88 Li-ion batteries with the proposed model of battery equalizer circuit has shown good performance which is used for enhancing the battery lifetime and runtime. Cell balancing and charge equalization is done effectively with the help of monitoring IC which is a much simpler yet effective method that reduces the overall size and complexity of the cell balancing circuit. This proposed model can be used in applications like EVs where stacking of Li-ion batteries are required.

As per the results mentioned in the reference paper for Equivalent Circuit Models for Predictive analysis of BMS, and from the empirically derived relations between V_L and V_{OC} , we conclude that PNGV model has higher accuracy under practical conditions and hence can be used for reference in the predictive battery degradation circuit.

IX. References

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