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An Integrated Approach to Lithium-Ion Battery Cell Management through Accurate Voltage Measurement and Cell Balancing

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***Abstract*—Battery packs have become a critical component in various applications from portable electronics to electric vehicles. Accurate voltage measurement is essential for effective battery management, ensuring safety and reliability, which is especially important in high-power battery packs that consist of multiple cells connected in series or parallel configurations, such as Electric Vehicles (EVs). This paper explores the voltage measurement topologies, pack configuration principles, and implementation of cell balancing in a lithium-ion battery pack. We review the various types of faults that can occur in lithium-ion batteries, different voltage sensor placement strategies, and their impact on the accuracy and robustness of voltage measurement. Our results show that proper cell balancing can improve battery performance, reduce the risk of safety incidents, and extend the battery lifespan.**

***Index Terms*—Lithium ion, battery cell, balancing, fault, State of charge, charging, discharging**

I. INTRODUCTION

Lithium-ion batteries are a popular and widely used energy storage option for a variety of applications, such as powering portable electronic devices and powering electric vehicles. They are arguably the first choice of Electric Vehicle (EV) batteries available on the market owing to their outstanding advantages in terms of low self-discharge rate, energy density,long life, and low maintenance. However, their promising potential cannot conceal the safety issues that have slowed the rapid growth of electric vehicles. Their broad adoption is typically constrained by: i) Maintaining performance and reliability under adverse conditions and over an extended period; ii) Developing cells and battery systems that meet safety criteria; iii) Handling the complexities of large battery packs; iv) Accounting for weight due to Battery Management System (BMS), packaging, cooling, and sensing; v) Charge rate constraints, particularly when using high energy density cells; and vi) Cost considerations.

Lithium Ion batteries can be prone to faults that can lead to reduced performance, shorter lifespan, and even safety hazards. Reference [1] reports that most fire-related electric vehicle accidents result from thermal runaway of Lithium-Ion Batteries (LIBs), and the safety threat has become a significant problem that should urgently be addressed. The Netherlands Institute of Public Security (NIPV) reported 221 incidents involving Alternative Fuel Vehicles (AFVs) in 2021. 80.7% of these incidents involved passenger cars, 54.7% of which were Battery Electric Vehicles (BEV), while 38.7% were Plug-in Hybrid Vehicles (PHEVs) as shown in Fig. 1 [2].

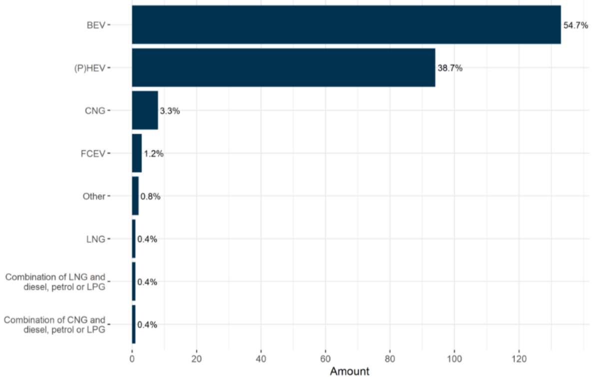

Fig. 1. Breakdown of the incidents by vehicle technology. A large portion concerned Battery Electric Vehicle (BEV) with 54.7% and the second largest number involved Plug-In Hybrid Electric Vehicle (PHEV) with 38.7%. The other 6.6% is shared among other vehicle technologies: Compressed Natural Gas (CNG), Fuel Cell Electric Vehicle (FCEV), Liquified Natural Gas(LNG) etc. [2]

Recently, a number of excellent review papers on faults and safety of batteries have been produced [3]–[6]. Compared to other safety reviews, This section aims to provide a broad audience with a comprehensive overview that focuses on the factors of safety events, methods to improve safety at various levels, and a structured introduction to various safety standards and test requirements. In Lithium-ion battery technology, several factors affect the safety performance during operation. Thermal abuse, mechanical abuse, and elec-

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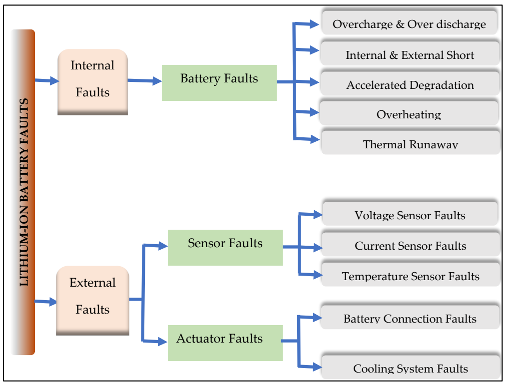


Fig. 2. Lithium-Ion Battery Faults Classified into Internal faults and External Faults with the later further categorized into Sensor faults and Actuator faults.

trical abuse are the three main types of abuse. The scope of this part is limited to electrical abuse and will not go into detail about physical abuse, such as nail penetration, crushing, and dropping. There are different types of electrical faults, and the most common are classified into battery faults, actuator faults, and sensor faults, as illustrated in Fig.2. The battery faults category is referred to as internal faults, while actuator and sensor faults are known as external faults.

Any of these faults can inherently trigger abnormal heat up, resulting in temperature spikes which could lead to thermal runaway if not efficiently and rapidly handled. The faults within the cell are the most severe in Lithium-Ion Batteries (LIBS), including overcharge, over-discharge, excessive heat, short circuits, electrolyte leakage, battery swelling, rapid degradation, and thermal runaway [7]. These faults are also interlinked as one usually leads to one or multiple other faults. as illustrated in Fig.3.

Overcharging and discharging batteries can result in a various adverse battery chemical reactions, leading to rapid degradation. During thermal runaway (TR), these side reactions and the gases produced by the chemical reactions could start causing the battery to swell. This swelling, combined with mechanical damage, could result in electrolyte leakage. The most common causes of the Internal Short Circuit are production errors, excessive heat, physical collisions, or penetration by metal dendrites or physical punctures.In Various situations, such as chemical reactions during overcharge and over-discharge, External short Circuit (ESC), Internal short Circuit (ISC), or a connection loose of the cell connector, cause abnormal heat generation, which raises battery temperature. On top of internal battery faults, external faults in terms of sensor failures can cause severe safety hazards to Lithium-Ion Batteries. The three primary sensors, voltage, current, and temperature, play a defining role in the battery management system. The sensor measurements are critical for all feedback-based algorithms in the BMS. The accuracy of multi-state and all state estimate is influenced by the current sensor measurements. To make a high-accuracy prediction, the battery model parameters are updated in real-time using the estimated SOC and temperature measurements. Therefore, any error in sensor readings can accumulate and lead to inaccurate estimation, leading to battery abuse.

Cell connection is liable to poor contact in a complex environment of significant temperature differences and vibration. Actuator faults can lead to an increase in resistance and abnormal heat generation, mainly in large battery packs where a slight increase in connection resistance can induce localized overheating. This can be very detrimental to the battery and may lead to thermal runaway.These faults have a greater impact on system control and effectiveness than battery and sensor failures.

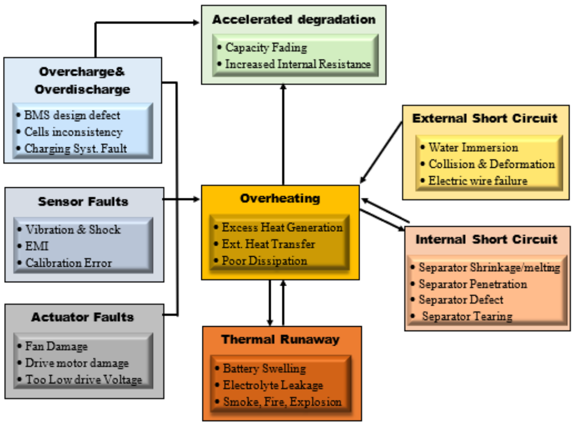


Fig. 3. Different Battery Faults Interconnection and their causes. the colors from light green to Strong orange depict the different faults severity while the different arrows direction show how the occurrence of one fault lead to the other

II. MODELING OF LITHIUM-ION BATTERY:EQUIVALENT CIRCUIT MODEL

The need for high-performing, efficient, and safe energy storage solutions fora diverse spectrum of applications has driven the advancement of Lithium-Ion batteries and safe energy storage solutions for a wide range of applications, from consumer electronics to electric vehicles. One of the critical factors in this advancement is the development of the Equivalent Circuit Model (ECM), a mathematical model that provides a framework for predicting the behavior of Li-Ion batteries under various conditions of operation.The typical Li-Ion battery Equivalent Circuit Model can be represented as an electrical circuit composed of several equivalent elements, including a voltage source, resistors, capacitors, and current sources [8]. Each element in the circuit represents a different battery physical property such as its internal ohmic resistance, capacitance, and electrical potential as seen in Fig. 4. Using these models, researchers can better understand how the battery will behave under different conditions. Charging losses and Self-discharge expressed by the parallel resistance R_p and current I_p of the parasitic branch, may also be included in the model, as shown

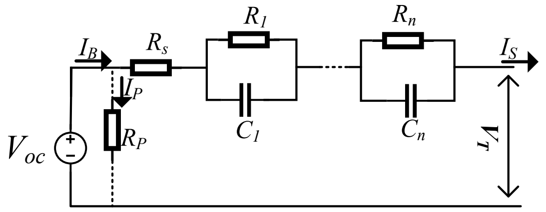


Fig. 4. Typical Equivalent Circuit model with a parasitic branch R_p that represents the self-discharge and charging losses

in Fig. 4. Given that lithium cells have a high coulombic efficiency and a low self-discharge under normal working conditions, the parasitic branch is frequently overlooked when modeling lithium cells.

Model accuracy in real-world applications is highly dependent on model parameters. Various battery modeling methods were investigated in order to simulate the system [9], [10]. The nRC includes some commonly used ECMs. The IR model is also known as the Rint model or the 0RC model, while the one-time constant model or 1RC (1st order) is the Thevenin model. the 2RC model is the (Dual Polarization) DP model [11]. The mathematical complexity of the model grows with the number of RC branches. A complicated Equivalent Circuit Model with more model parameters may result in parameter mismatch, leading to poor accuracy. As a result, the choice of Equivalent Circuit Model is a trade-off between accuracy and complexity. Therefore, the scope of this paper will be limited to the 1st order Equivalent Circuit Model of the Fig. 5.

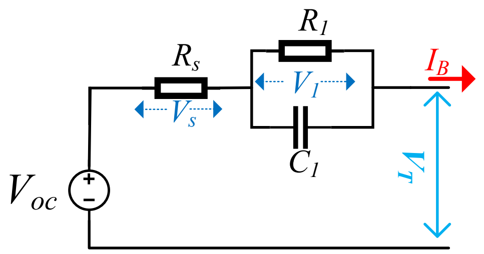


Fig. 5. The 1st order RC Equivalent Circuit Model with a voltage source V_{oc}, an internal ohmic resistance R_s and one RC branch of parallel elements R_1 and C_1 representing the transient response of the battery

The Terminal voltage can be expressed using the Kirchoff voltage law as [12]:

$$V_T\ (t) = V_oc\ (SOC) - R_s\ I_B - V_1 \tag{1}$$

where:

$$dV_1(t) = \frac{-1}{R_1C_1}V_1(t) + \frac{1}{C_1}I_B \tag{2}$$

To simplify the development and simulation of the model in MATLAB, the equations of the model under consideration are presented in discrete form as:

$$V_T(k) = V_{oc}(k) - R_sI_B(k) - V_1(k) \tag{3}$$

$$V_1(k+1) = \mathrm{e}^{\left(\frac{-\Delta t}{R_1C_1}\right)}V_1(k) + R_1\left[1 - \mathrm{e}^{\left(\frac{-\Delta t}{R_1C_1}\right)}\right]I_B(k) \tag{4}$$

The subscript k represent the $\mathrm{k^{th}}$ sampling.

Now, defining a shift operator Z, the above equations can be transformed and lead to the following transfer function:

$$\mathrm{Y_0(k+1) = \frac{B\left(Z^{-1}\right)}{A\left(Z^{-1}\right)}I_B(k) = \frac{a_0 + a_1Z^{-1}}{1 + b_1Z^{-1}}I_B(k)} \tag{5}$$

where ..$Y_0(k)$... is the deviation of the terminal voltage V_T and the open circuit voltage V_{oc}. The coefficients a_0, a_1, and b_1 can be expressed as:

$$\mathrm{a_0 = R_s} \tag{6}$$

$$\mathrm{a_1 = R_s}\left[-\mathrm{e}\left(\frac{-\Delta t}{R_1C_1}\right)\right] + \mathrm{R_1}\left[1 - \mathrm{e}^{\left(\frac{-\Delta t}{R_1C_1}\right)}\right] \tag{7}$$

$$\mathrm{b_1} = -\mathrm{e}^{\left(\frac{-\Delta t}{R_1C_1}\right)} \tag{8}$$

III. VOLTAGE MEASUREMENT TOPOLOGIES AND PACK CONFIGURATIONS

A. *Voltage Sensor Placement*

The complex nature of battery systems can make it difficult to detect and diagnose faults that may occur. One of the critical factors in detecting faults is the voltage measurement topology, which refers to the placement and connection of voltage sensors within the battery pack. Accurate measurements are crucial as the Battery Management System (BMS) functions are highly dependent on information recorded by current, voltage, and temperature sensors. Conventional voltage measurement involves installing a voltage sensor for each cell within the battery pack. This method is the widely used voltage measurement technique in today's applications, where Individual voltage sensors or monitoring integrated circuits (ICs) are used to monitor the voltage values of individual cells [13]. This method has been adopted this paper to achieve accurate balancing of cells connected in series.

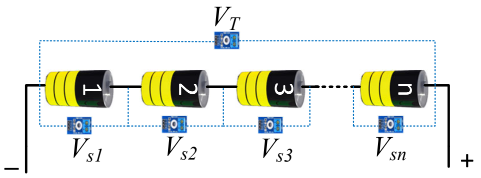


Fig. 6. Conventional voltage measurement tolopogy. The Commonly used scheme in today's applications. Each Cell is monitored by an individual Voltage sensor V_s with one more sensor V_T to monitor the pack voltage

While this approach provides detailed information about the voltage of each cell, it can take time to manage and interpret the large amount of data generated. In addition, this approach may not be suitable for detecting multi-fault scenarios, as it may only provide information about the faulty cell rather than the entire system.

An alternative approach is the interleaved voltage sensor connections, where voltage sensors are placed between multiple cells in the battery pack.This approach provides a more holistic view of the system, as it provides information about the voltage of multiple cells at once. This approach will be adopted in the continuation of this work to show the impact of crossed-style voltage measurement on system complexity and cost. In addition, it can be more effective in detecting multi-fault scenarios, as it can provide information about the interactions between different cells, which may not be evident in conventional voltage measurement.

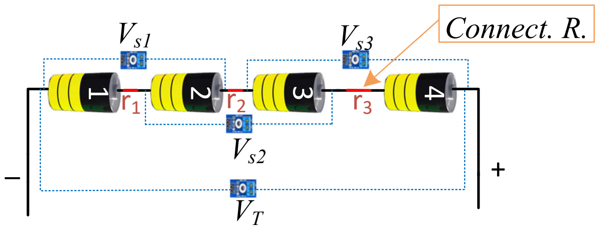


Fig. 7. Interleaved Voltage Measurement topology. Voltage Sensors V_s are deployed in a crossed-style way, and each cell is monitored by 2 Voltage Sensors. Connection resistances r_1, r_2, r_3,etc are also monitored by the V_s

B. Battery Pack Configuration

Another crucial factor to consider in cell voltage measurement and management is the pack configuration. In applications that require high power, particularly Electric Vehicles, where several thousand of battery cells are connected to meet the power requirements, strict monitoring is required to ensure safe operation. A battery pack is commonly assembled using two structures: Series-Parallel (SP) and Parallel-series (PS) connections. Authors in [14] investigated an optimal placement of sensors based on the increased degree of Analytical redundancy to reduce the number of sensors. Sensor sets for both PS and SP are presented in Fig. 8. From the safety point of view, when the parameters vary from one cell to another due to a fault or physical parameter change, the behavior of the two battery connection topologies will vary. Assume, for example, that one cell in sub-module 1 behaves abnormally compared to the other cells, and that a fixed load current is taken into account. All sub-module currents for the Parallel-Series topology are equivalent to the total pack current and stays constant, as illustrated in Fig. 8 (a). In Sub-module 1, any failure in one cell will cause mismatches among the other cells in the same submodule. The submodule to which the faulty cell belongs is the only one that will be impacted; the other modules will not be impacted. On the other hand, in the Series-Parallel connection, the pack current is the total of all the sub-module currents, and the current in each sub-module is equal to the individual cell current as depicted in Fig. 8 (b).The change in one cell will affect both the cell current and the sub-module current, resulting in imbalances among all the sub-module currents. The effect of the faulty cell will then propagate through the whole pack. This is an inherent critical characteristic of the two battery pack configurations that must be considered when designing protection schemes.

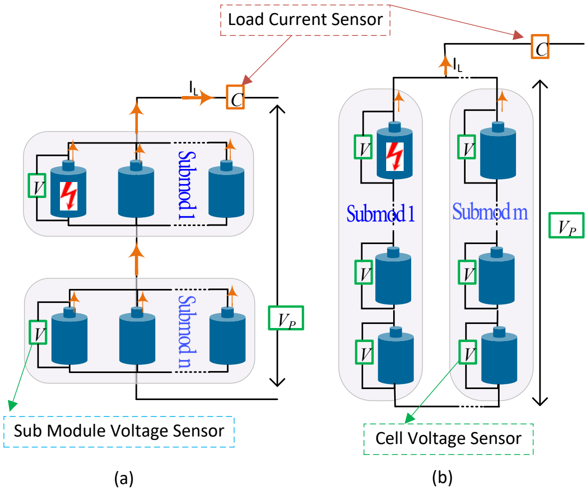


Fig. 8. Battery Pack configuration: (a)Series-Parallel(SP), parallel Cells in the same submodule share one Voltage sensor V; (b) Parallel-Series (PS) configuration, Cells are monitored by individual Voltage sensors V

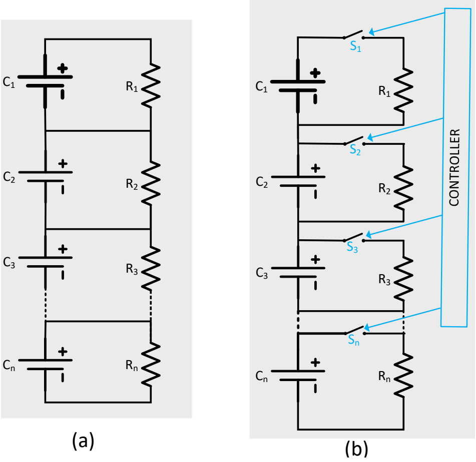
IV. CELL EQUALIZATION

Using multiple cells in a battery pack can lead to imbalances among cells, resulting in reduced performance, decreased battery life, and increased risk of safety incidents [15]. Cell balancing is a key approach to addressing these challenges, as it aims to equalize each cell state of charge, ensuring the battery pack optimal performance and longevity. It is a crucial aspect of battery management systems in battery packs [16], especially for large-scale applications in electric vehicles, and aerospace. Cell balancing is essential for ensuring each cell operates within its optimal State of Charge range. This can improve system efficiency, increase battery life, and reduce the risk of safety incidents. Furthermore, cell balancing can enhance the reliability and safety of the battery pack.The choice of balancing technique depends on the system requirements, including the battery pack size, the charging and discharging rates, and the desired performance and safety features.

The passive balancing method dissipates excess charge from fully charged cell(s) via a resistor until the charge aligns with the lower cells in the pack [15]. The resistor is either in switched mode or fixed mode. In a fixed mode shunt resistor, Fig. 9 (a), the energy is continuously dissipated as heat for all cells. In the switched mode shunt resistor,Fig. 9 (b), the energy from the higher cell is dissipated in a controlled manner.

The switched mode shunt resistor technique may be implemented in two operating modes [17]:

- Continuous mode,in which all relays are controlled by a single on/off signal.



(a) (b)

Fig. 9. Passive balancing Methods: (a)Fixed mode shunt resistor, energy is continuously dissipated as heat for all cells; (b) Controlled mode shunt resistor, energy from the higher cell is dissipated in a controlled manner

- Detection mode, in which the voltages of all cells are monitored. It determines which resistor should be shunted when the imbalance conditions are detected.

The detection mode has been implemented in this paper for It is more effective than the fixed shunt resistor technique, simple and reliable, and works with Li-Ion batteries. In order to ensure that all cells in the pack are charged and discharged evenly, a balancing logic is implemented to control the shunt resistor by sending an appropriate signal to the corresponding MOSFTETS gate as illustrated in Fig. 10. It is working principle is summarized in the following way: i) Voltage across each cell is monitored via an individual voltage sensor; ii) Voltage sensor outputs a voltage signal from individual cell, which is compared to a reference voltage. The reference voltage is set to a threshold value (4,1V in our case) which is typically chosen to be slightly less than the cell maximum safe operating voltage (4.2V); iii) If the voltage across a cell is higher than the threshold voltage, the comparator provides a signal to the control circuit to turn on the MOSFET switch of that cell to dissipate some energy to the resistor in the form of heat. iv) The control circuit keeps track of each cell voltage and selectively activates the MOSFET switches for the cells that need to be balanced; v) The process continues until all of the cell voltages are even.

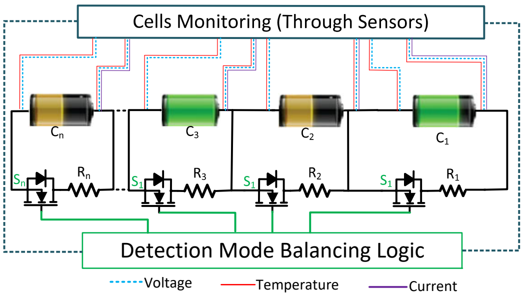


Fig. 10. Implemented detection mode controlled shunt resistor Balancing of series connected cells. individual cells are monitored by the senors. Balancing logic controls the resistors through the MOSFETS gates

V. RESULTS AND DISCUSSION

The behavior of a lithium-ion battery pack with three series-connected battery cells in an nSmP configuration is investigated. A voltage-based passive balancing via switched shunting resistor circuit with appropriate control logic is implemented. To ensure effective cell balancing, voltage, current, and temperature are monitored through sensors connected to each cell. The thermal behavior of each cell is monitored through the temperature sensor placed across it. We employ the commonly used Constant Current Constant Voltage (CC-CV) charging strategy to charge the battery pack. Fig. 11 and Fig 12 present the results of the simulation of a 1RC branch battery equivalent circuit model, focusing on the variations in series resistance R_s, parallel resistance of the RC branch R_1, and capacitance C_1 as the battery discharges from 100% to 0%.

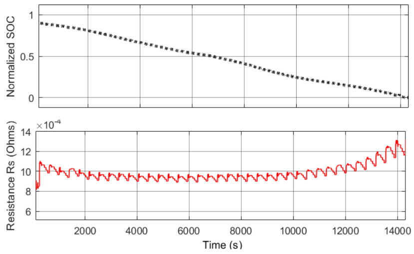


Fig. 11. State of Charge (SOC) and Series resistance (Rs) as function of time. Internal resistance increases by around 36.15% as the battery reaches 0% state of charge

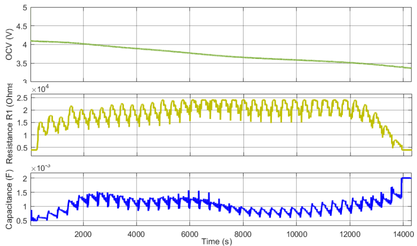


Fig. 12. Estimated parameters: R_0 and RC branch values R_1 and C_1

The relation between the battery State of Charge and the internal resistance R_s as a function of time during battery discharge is depicted in Fig. 11. It can be seen that the internal resistance and open circuit voltage (OCV) exhibit nearly linear changes with respect to the discharge cycle. Specifically, the internal resistance increases by around 36.15% as the battery reaches 0% state of charge.The parallel resistance of the RC branch R_1 and the capacitance C_1 also follow a similar trend, with the values increasing as the battery discharges as shown in Fig. 12. Results in Fig 13 illustrate the charging and discharging process. During charging, the cells are charged at a constant current of 4A until the individual cells approach their upper voltage thresholds

4.2 V which sums the pack voltage to about 12.6V. Then, the charging current is gradually reduced to almost zero to allow the cells to reach full charge as seen in Fig.13.

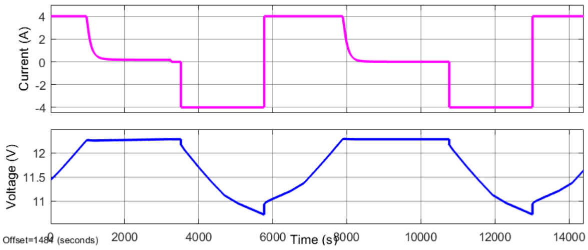


Fig. 13. Constant Current Constant Voltage charge and discharge cycles.Cells are charged at a constant current of 4A until the individual cells approach their upper voltage thresholds 4.2 V. Charging current is gradually reduced to zero to allow the cells to reach full charge

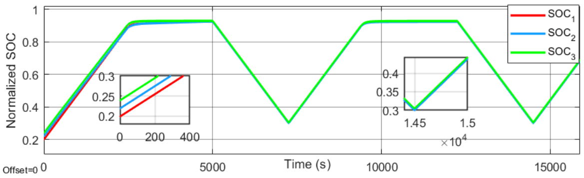
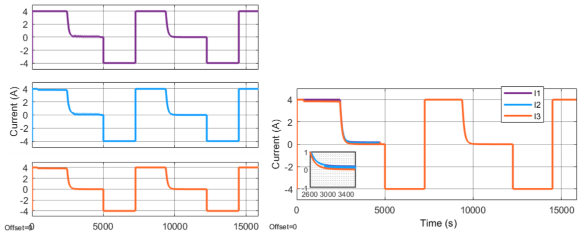


Fig. 14. Individual cell SOCs during charge/discharge. Cells C1, C2 and C3 start off with unbalanced low initial state of charge of 20%, 23%, and 25%, respectively. Cells are balanced before discharging started

The balancing process is depicted in Fig. 14 and in Fig. 15. Cells C_1, C_2 and C_3 start off with unbalanced low initial state of charge of 20%, 23%, and 25%, respectively. The balancing process is performed throughout the charging process, resulting in a balanced pack at the end of the charging cycle. Furthermore, Fig. 14 reveals that the cells remained balanced during the subsequent discharging and charging cycles. We can also see that the cells are allowed to discharge to no less than 30% state of charge to protect them from over discharging. A closer look at fig. 15 shows some discrepancies in current during charging. We can see that the current of the cell with higher voltage (C_3) decreases to zero before other cells during constant voltage charging. This is because its energy is being dissipated through the balancing resistor to allow other cells to reach full charge. The thermal behavior of the cells is depicted from Fig. 16. The figure illustrate the temperature variations for the 3 series connected cells. The 3 cells follow the same trend as their temperature increases during charging and slightly decay during discharging. These results show that even though the temperature stays within operating range, the difference between cell 1 and cell 3 is high and can have a negative impact on the degradation of the pack. The results mean that cell with higher temperature C_3 will age quicker compared to other cells in the pack.



(a)

(b)

Fig. 15. Currents of the 3 series connected cells.Some discrepancies are observed where Current of (C_3) decreases to zero before other cells during constant voltage charging

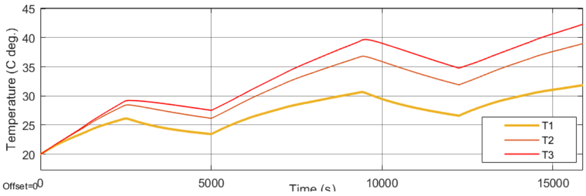


Fig. 16. Thermal behavior of the 3 cells with temperature divergence for the 3 cells.High temperature differences between cell 1 and cell 3 are observed

VI. CONCLUSION

The investigation of a lithium-ion battery pack comprising three series-connected cells in an nSmP configuration has been carried out in this study. A first-order RC equivalent circuit model-based simulation approach has been utilized to predict the behavior of the battery. The changes in the internal resistance and the parallel RC branch elements were investigated as the battery discharged from 100% to 0%. The thermal behavior of the cells was captured and the temperature variations of the three series-connected cells were observed. The results revealed that the temperature difference between cell 1 and cell 3 was relatively high, which could negatively impact the degradation of the pack as degradation is exponentially dependent on temperature. The results of this study demonstrate the importance of effective cell balancing in lithium-ion battery packs. The relationship between the battery State of Charge and the internal resistance suggests that monitoring the internal resistance is crucial to ensure the long-term performance and safety of the battery pack. Additionally, the thermal behavior of the cells must be monitored to ensure optimal performance. In the continuation of this work, interleaved voltage sensor connection strategy will be adopted to analyse the impact of crossed-style voltage measurement on system complexity and cost. Active balancing will also be considered to improve the efficiency of lthium-ion battery system.

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