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Design and Simulation of an Inductor based Active Cell Balancing Circuit for Lithium-ion Batteries

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***Abstract*—In this modern era where energy demand is increasing at an exponential rate, energy storage devices play a crucial role in meeting the demands when needed. Rechargeable batteries are gaining momentum as the need for storing electrical energy is increasing day by day. Lithium-ion (Li-ion) technology is better than other rechargeable battery technologies due to its performance characteristics. However, under unfavourable charging and discharging conditions and/or differences in internal parameters, Li-ion batteries tend to heat and adversely affect their performance which results in a reduced life cycle. The process of cell Balancing finds an important role in battery packs which takes the issue of cell imbalance into account. An active cell balancing circuit with an inductor as a storage element has been proposed in this study. The balancing of cells is carried out between four lithium-ion cells connected in series. This paper consists of a detailed study of the design and operation of the cell balancing circuit. An algorithm has been developed in stateflow and simulated on MATLAB.**

***Index Terms*—Cell balancing, Kalman filter, State-of-charge.**

I. INTRODUCTION

Modern technology is developing at an exponential rate and an increase in electricity demand is inevitable. In recent years, development in smart grids and electric vehicles (EVs) has opened doors to various energy storing devices and the need for storing electric energy has been intensified. Battery technology is drawing attention in these fields and various battery chemistries have been tested. However, lithium-ion (Li-ion) technology remains paramount due to its high power density, higher power-to-weight ratio, low self-discharge rate and high discharge current capability. Due to its wide range of form factors, Li-ion battery is the top pick for numerous portable and transportation applications. Single Li-ion cells are connected in various series-parallel configurations to form a battery pack for meeting the voltage and current requirements in different applications.

In multicell battery packs, the difference in cell parameters poses a greater risk of limiting the overall pack performance. A weaker cell in a battery pack will discharge early as compared to other cells limiting the overall capacity and may result in over-discharge. On the other hand, the same cell will charge faster than the other cells making it cell susceptible to overcharging. Inconsistent manufacturing processes, ageing effect and thermal effect on the internal resistance of the cell contribute to a reduced cell capacity resulting in differences in state-of-charge (SoC) [1], [2] of individual cells in a battery pack. Operating the battery pack with unbalanced cells may cause a severe risk of safety due to increasing battery temperature caused by the above-mentioned issues. These issues poses a danger to the living but also make the decision of using the battery pack financially inefficient [3].

The Battery Management System (BMS) is a vital electronic component in every battery pack which also acts as a protection for the individual cells [4]–[6]. It monitors temperature of the battery cells and can trigger cooling mechanism of the battery pack when required. BMS comprises of a cell balancing circuit as well as undervoltage and overcurrent protection system and is responsible for efficient operation of the thermal management system of a battery pack. BMS consist of an algorithm that estimates and equalizes the SoCs and estimates state-of-health (SoH) of individual cells which is an essential parameter for determining ageing and efficiency of battery.

The methods of cell equalization or cell balancing is broadly classified into two basic types which are passive cell balancing and active cell balancing. In the passive cell balancing circuit, resistors are used as the primary component of the balancing circuity [7]. Active cell balancing method focuses on transferring energy from one cell to another cell connected in series. The active cell balancing method is achieved by using converters [8], capacitors [9], transformers [10], inductors [11], or a combination of these components [12].

This paper proposes an inductor based active cell balancing model with a control algorithm that aims to maximize the functionality and competence of a battery pack. The major contribution of the paper are as follows:

i) The paper proposes an Inductor based active cell balancing model for 4S Li-ion battery pack which is developed on MATLAB using the component parameters that are determined for giving maximum efficiency.
ii) An algorithm has been developed on stateflow for achieving the cell balancing by using lesser number of components in the circuit.
iii) The proposed model is tested under variable charging and heavy loaded conditions.

The paper is divided into sections as follows: Section II shows an equivalent model of a battery cell. Section III represents the proposed cell balancing system while Section IV demonstrates working of the proposed cell balancing circuit. Design considerations and explanation of the algorithm is shown in the Section V. Subsequently, Section VI shows the resulting graphs of the simulation. Lastly, Section VII concludes the paper.

II. BATTERY CELL MODELLING

Understanding the basic fundamentals of the battery is very important while designing an energy storage system. Equivalent circuit model (ECM) is made by using electrical components such as resistors, capacitors and voltage sources [13]. ECM shown in Fig. 1 has R_0 as the internal resistance of a non-charged battery, R_1 and C_1 as the parallel RC branch showing the temporary state of battery during charge/ discharge process. $V_{\text{oc}}(t)$ is a function of $SoC(t)$ which varies non-linearly. The internal resistance R_0 and the parallel RC branch consisting of R_1 and C_1 are functions of SoC and ambient temperature.

According to Kirchoff's current law, the equation (1) and (2) are given as;

$$\frac{dV_{\text{c}}}{d(t)} = -\frac{1}{R_1}.C_1.V_{\text{c}}(t) + \frac{1}{C_1}.I_{\text{o}}(t) \tag{1}$$

$$V_{\text{o}}(t) = V_{\text{oc}}(t) - V_{\text{c}}(t) - R_0 I_{\text{o}}(t) \tag{2}$$

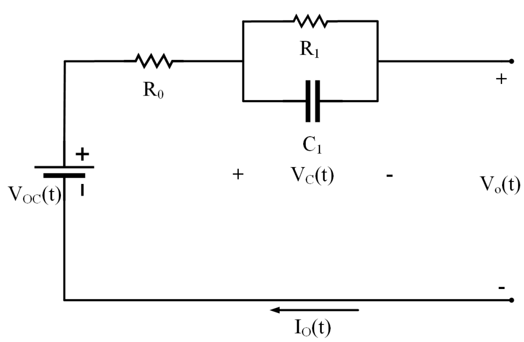


Fig. 1: Equivalent circuit diagram of a cell model.

III. SYSTEM REPRESENTATION OF PROPOSED BALANCING CIRCUIT

The proposed cell balancing circuit shown in Fig. 2 is based on inductive cell balancing topology where the inductor is the main energy storage element. The circuit is designed to efficiently balance four Li-ion cells is series configuration (4S) by changing the duty cycle of the triggering pulse as shown in Fig. 5. The circuit consists of six switches (S1-S6), four capacitors (C1-C4) and three inductors (L1-L3) to balance SoCs of four battery cells (B1-B4). Further, for understanding purpose, the battery cells are paired and grouped as middle cell group and corner cell group. The middle cell group has single pair consisting of B2-B3 while the corner cell group has two pairs B1-B2 and B3-B4. The energy can be transferred bidirectionally among the cells in pairs only. There is no limit on the current values, however it is limited by the physical aspects of the components used in the system.

Small voltage differences in cells are prominent during charging and discharging operations. Carrying out balancing operations continuously will result in high resistive losses and losses due to the current consumed by the control system of the balancing circuit. To avoid this, a SoC threshold value is set beyond which the balancing process will activate and will ensure minimum losses.

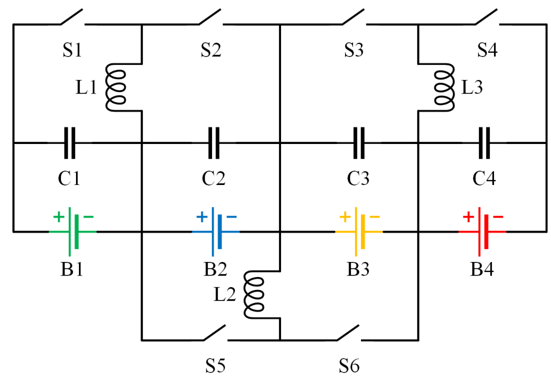


Fig. 2: Proposed Cell Balancing Circuit

IV. OPERATING PRINCIPLE OF CELL BALANCING

The proposed circuit configuration utilises an inductor as the primary energy storage element. The circuit is responsible for transferring energy from the cell with higher SoC level to the cell with lower SoC level by charging and discharging the inductor in a controlled manner. The period of the charging and discharging of the inductor highly influences the balancing time, overall losses and efficiency of the balancing process. Before the balancing process commences, the system calculates the SoC difference between the higher energy cell and lower energy cell and it is compared with the threshold value. This cycle is performed at every instant until the predetermined threshold value is crossed. During the first half of the cycle balancing operation, the switch parallel to the higher energy cell is closed as shown in Fig. 3a, assuming cell B1 is at a higher energy level. This will charge the inductor through the capacitor $C1$ connected across the higher energy cell. The peak current I_{P} at this time is given by (3) as:

$$I_P = \frac{V_H - dV_C}{R}.(1 - e^{-t_{ON}.\frac{R}{L}}) \tag{3}$$

where V_{H}, dV_{C}, R, t_{ON}, L represents voltage of the cell with higher SoC level, capacitor ripple voltage, total resistive losses in the circuit, time interval when the switch is closed and inductor value respectively.

From (3), the switch should be closed for longer interval of time if more energy is to be transferred in one cycle. Moreover, total resistance of the entire circuit should be as low as possible. Ripple voltage on the battery cells may impact the cells' performance and can reduce the life of the battery cell. Therefore, large fluctuations occurring in cell voltages during balancing must be minimized. Ripple voltage on the battery cell, dV_{C} is given by (4).

$$dV_{\text{C}} = I_{\text{AVG}}\frac{t_{\text{ON}}}{C} \tag{4}$$

Here, C is the capacitance value and I_{AVG} is the average current value on the inductor which is given by equation (5):

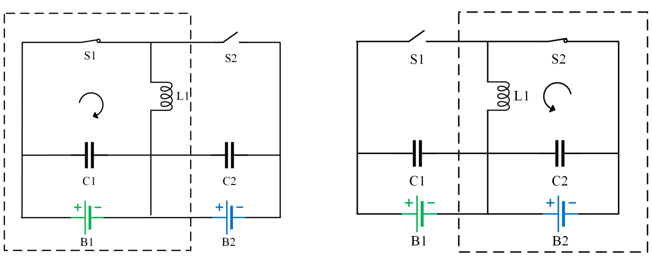
$$I_{\text{AVG}} = \frac{1}{2} \cdot \frac{t_{\text{ON}} . I_{\text{P}}}{T_{\text{tot}}} \tag{5}$$

where T_{tot} is the total time period of a single balancing cycle. From (4) and (5), ripple voltage can be reformed into equation (6) as:

$$dV_{\text{C}} = \frac{1}{2} \frac{{t_{\text{ON}}}^2 . I_{\text{P}}}{C . T_{\text{tot}}} \tag{6}$$

From (6), the ripple voltage is directly proportional to the square of the switch closed time duration and inversely proportional to the capacitor value. Thus by selecting a higher value of capacitor, ripple voltage can be reduced.

In the second half of the balancing cycle, switch S1 is opened and S2 is closed as shown in Fig. 3b. The polarity of the inductor reverses and inductor discharges into lower energy cell through the capacitor C2 connected in parallel to it.



(a) When S1 is closed. (b) When S2 is closed.

Fig. 3: Operating principle of balancing of a cell pair.

The voltage on the inductor V_{L} is given in equation (7) which is further deduced (8);

$$V_{\text{L}}(t) = L \frac{\Delta I_{\text{L}}}{{t_{\text{ON}}}^{\text{O}}} \tag{7}$$

$$V_{\text{L}}(t) = V_{\text{LB}} + V_{\text{LL}} + V_{\text{Sw}} \tag{8}$$

where I_{L}, ${t_{\text{ON}}}^{\text{O}}$, V_{LB}, V_{LL}, V_{Sw} represent the incductor current, the time interval during which the switch (S2) is closed, voltage of the lower battery cell, voltage drop across the inductor and voltage drop across the switch respectively.

Now, ${t_{\text{ON}}}^{\text{O}}$ can be calculated using equation (9) as:

$${t_{\text{ON}}}^{\text{O}} = L \frac{I_{\text{P}}}{V_{\text{LB}} + V_{\text{LL}} + V_{\text{Sw}}} \tag{9}$$

To ensure that the charge is completely transferred or the inductor is fully discharged into the lower energy cell, some additional time t_{ADD} needs to be added to the total time period of the cycle. Failing to add the extra time to the total time, the inductor will add up remaining energy over previous cycles and may result in increase in battery balancing current to undesirable values, damaging the inductor and the ripple voltage exceeding safe margins.

Hence, the total time period of one balancing cycle can be determined with (10) as:

$$T_{\text{tot}} = t_{\text{ON}} + {t_{\text{ON}}}^{\text{O}} + t_{\text{ADD}} \tag{10}$$

V. DESIGN PROCESS

Operation of switches in a cell balancing circuit demands precise triggers. Hence, systematic and precise monitoring and measurement of voltage as well as SoC estimation are crucial. Open circuit voltage (OCV) and Coulomb counting (CC) methods are majorly thought of as viable methods for estimating SoC. OCV of the battery can accurately reflect the SoC of the battery. However, the battery needs to be at no or minimum load condition in order to get accurate results. CC or coulomb integral method is easy to implement and very accurate. Combining the above mentioned methods and implementing Kalman filter [14] will adequately boost the accuracy of estimation significantly.

Triggering the balancing process for a predetermined number of cycles may result in losing track of SoC and thereby losing energy incurring losses in the circuit. In this proposal, cell voltages and SoC values are monitored after every cycle so as to ensure efficient operation of the balancing algorithm. The flowchart of the process is shown in Fig. 4.

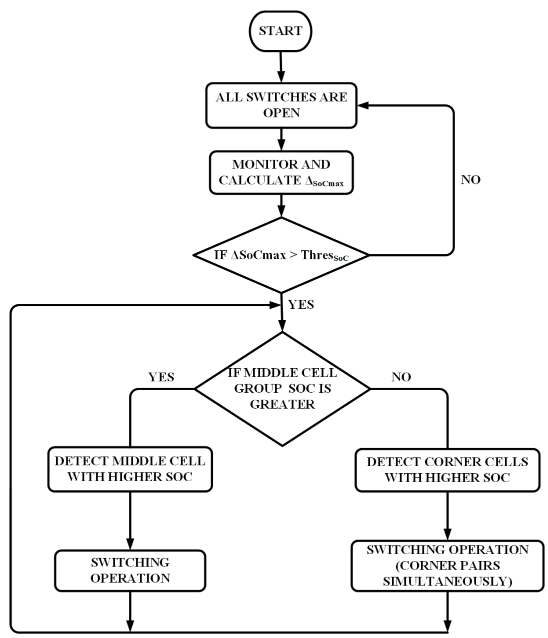


Fig. 4: Flowchart of the algorithm

The system begins with continuous monitoring of the SoC of all the cells and calculates the maximum absolute SoC difference (Δ_{SoCmax}) in the battery pack. Balancing process initiates once the SoC difference has crossed the SoC threshold value ($\text{SoC}_{\text{Thres}}$). Based on Δ_{SoCmax} switching operation is started from either middle cell group or corner cell group. It is observed that if Δ_{SoCmax} belongs to middle cell group, switching operation should be initiated from the middle cell group. Switching operation continues till the SoC level of the middle group cells are matched. In the subsequent step, corner cell group switches are activated for switching operation of the balancing process. The entire process is repeated till the maximum absolute SoC difference in the battery pack is above the SoC threshold limit.

For successful design and for optimal performance of the system, some parameters need to be predefined. Peak current should be defined based on the battery capacity and battery specification. Inductor current calculation should be made under the consideration that the peak current reaches the maximum value where the high energy cell is fully charged. Thus ensuring that the saturation current of the inductor is not exceeded. Lastly, allowable ripple voltage value must be set such that it does not have any adverse effect on the inductor and battery cell. As time t_{ADD} relaxes some components, it is given a value greater than 0. However, it should be selected such that it should not affect balancing time. Other parameter values can be calculated based on these predetermined values.

Switch resistance is referred from IRF540N N-channel MOSFET. Ceramic capacitor is assumed to have low internal resistance. All the parameters mentioned below are determined values of the circuit. It comprises of Inductor (L) of 8.4μH, capacitor (C) of 1μF. Time period of 100ms is considered for each pulse with the duty cycle of 40%.

VI. SIMULATION RESULTS

MATLAB/Simulink is used for simulating the proposed circuit with the help of SimScape tools and stateflow. Four li-ion batteries having a capacity of 3.5Ah and a nominal voltage of 3.7 volts are taken into consideration. For simulation purposes, the maximum SoC difference is set to 25% and the threshold value of SoC is set to 2%. The SoC levels of the cells B1, B2, B3 and B4 are set to 50%, 60%, 70% and 75% respectively. According to the algorithm, the switching operation and effectively the balancing process will commence from the middle battery group.

Fig. 5 shows the waveform of the triggering pulses that are responsible for the control of semiconductor switches S5 and S6. The time period of each pulse is 100ms with a duty cycle of 40% and an amplitude of 7V. The balancing process starts with the operation of switch S6 followed by switch S5 with a time delay of 40ms shown in Fig. 2. The above combination leads to charging and discharging of the inductor $L3$ shown in Fig. 6. When switch S6 is closed and S5 is kept open, the current in the inductor rises from 0A to a peak current of 18.56A resulting in charging of the inductor and subsequent discharging occurs on closing of switch S5 and opening of switch S6 as shown in Fig. 6.

Fig. 7 shows the maximum absolute SoC difference of the battery pack (Δ_{SoCmax}) throughout the cell balancing process upto the set threshold value of 2%.

Fig. 8 represents the SoC values of all the battery cells B1, B2, B3 and B4 with respect to time throughout the entire balancing process. The graph shows a clear view of the process with the balancing of B2 and B3 taking place followed by balancing of pair B1, B2 as well as B3, B4 in accordance with the algorithm mentioned above in Fig. 4. The entire process takes approximately 1046 seconds to reach the threshold value of 2% after which all the switches are opened and the balancing process ends.

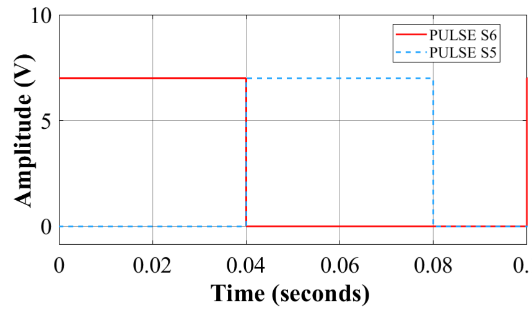


Fig. 5: Triggering pulses.

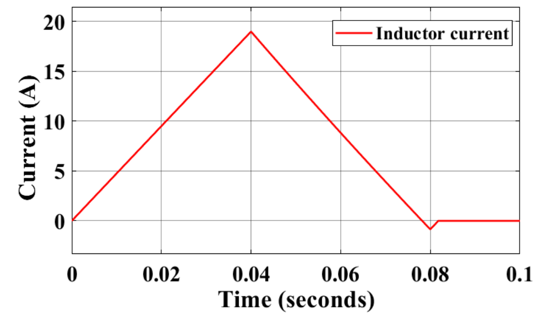


Fig. 6: Inductor current.

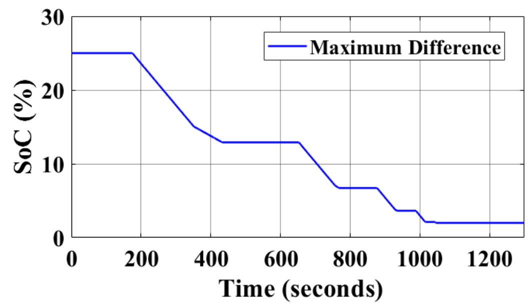


Fig. 7: Maximum absolute SoC difference (Δ_{SoCmax}).

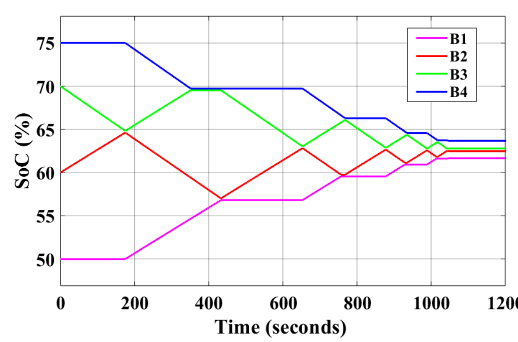


Fig. 8: Balancing process.

Fig. 9 represents the SoC balancing process during charging condition. The cells B1, B2, B3 and B4 inside the battery pack are set at an initial SoC level of 20%, 40%, 50% and 50% respectively which makes (Δ_{SoCmax}) as 30%. The 4S battery pack is charged under an external DC voltage source of 16.8V to simulate charging conditions. The maximum charging current of the battery pack is nearly 5A initially and decreases as the cells inside the battery pack began to charge. The graph provides a clear idea of balancing and charging of the cells simultaneously. The entire process takes approximately 2000 seconds to reach the value of Δ_{SoCmax} equal to 0.2% after which all the switches are opened and the charging process ends with all the cells balanced.

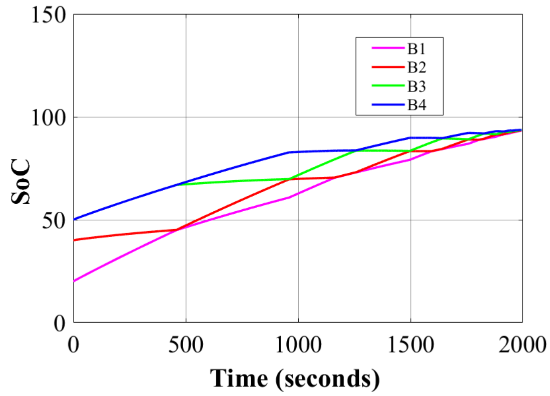


Fig. 9: Balancing process during charging.

Fig.10 represents the balancing process of the battery cells under heavy loaded condition. The cells B1, B2, B3 and B4 inside the battery pack are set at an initial SoC level of 90%, 100%, 95% and 100% respectively which makes Δ_{SoCmax} as 10%. The 4S Li-ion battery pack is discharged using a load drawing 3A current from the battery pack. The graphs depicts the process of balancing and discharging of the cells simultaneously. The entire process takes approximately 468 seconds to reach the value of Δ_{SoCmax} equal to 0.2% after which all the switches are opened and the load continues to draw power from the battery pack with all the cells balanced.

VII. Conclusion

A novel SoC balancing algorithm for 4S Li-ion battery cells is developed using an inductor based active cell balancing method. The same algorithm is tested with battery pack under charging condition and under loaded condition. The cell balancing algorithm successfully balances 4 Li-ion cells connected in series under no-load, charging and heavy loaded conditions. This circuit utilizes lesser number of components as compared to other inductor based cell balancing circuits thus proving to be cost efficient. The whole system operates on simple switching circuits leading to charge transfer between cells. Simulation of the balancing process of all four Li-ion 18650 cells is performed and shown in the paper. These results show the complete balancing of the Li-ion cells having a

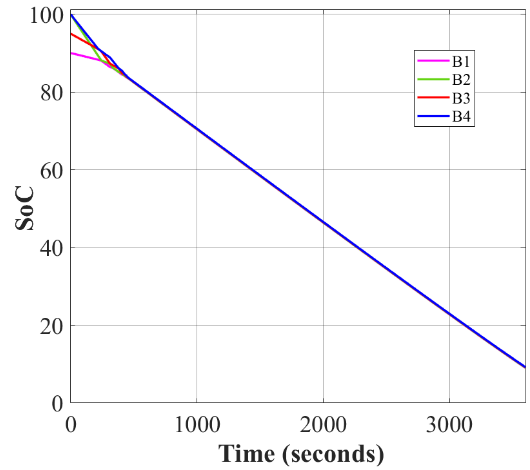


Fig. 10: Balancing process under heavy loading conditions.

maximum SoC difference of 25% in a time span of just 1046 seconds in-spite of following the current and safety limitations of the cell, thus keeping the battery health intact. The result also shows the balancing of these cells under charging and heavy loaded conditions.

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