Active cell balancing for a 2s Lithium ion battery pack using flyback converter and push-pull converter

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Abstract. The usage of Lithium ion (Li-ion) batteries has been increasing day by day due to environmental concerns. One of the major applications in which Li-ion batteries are used is electric vehicles (EVs). Li-ion batteries are highly sensitive to over-voltage, under-voltage and temperature conditions unlike other batteries. Li-ion batteries need real-time monitoring and a battery management system (BMS) is used for this purpose. This paper talks about active cell balancing schemes using transformer switching. Active cell balancing is done to balance the imbalances created in the battery pack to maintain a constant state of charge (SOC). A comparative study on pack-to- cell configurations of active cell balancing using switched transformer method is done to draw conclusions.

Keywords: Electric vehicles (EVs), Battery Management System (BMS), State of Charge (SOC), State of Health (SOH), State of function (SOF), active cell balancing, passive cell balancing

1. Introduction
Battery packs in EVs do not consist of a few huge cells, instead a pack of several cells are connected either in series or in parallel or both as per the power requirement of the drive motor. Each one of the cells in the battery pack need to be monitored to be operated in optimum range of temperature and voltage. This is where BMS plays an important role. It performs various functions such as voltage sensing, current sensing, temperature sensing, SOC estimation, SOH estimation, SOF estimation, cell balancing, impedance detection, safety controls, on-board diagnosis, networking and information storage [1]. This is a hard-real time system and most of these functions happen simultaneously to ensure that the battery pack operates efficiently and safely. BMS acts like the brain of the battery pack. These functions are prioritized as the processor takes decisions based on the scenarios. All the cells in the battery pack must have the same make, terminal voltage, capacity and must be of the same chemistry. The operating temperatures and voltages vary for different battery chemistries. Once the battery pack starts to discharge, cells in the pack go out of balance and this imbalance increases [2]. This imbalance, if not rectified, is carried on to consecutive load cycles, reducing the battery life and efficiency. Batteries being one of the most expensive parts in an EV needs to be taken care of to ensure reliability and safety. The various estimations done in BMS accurately speaks about the battery parameters which cannot be measured directly. Communication buses such as Controlled Area Network (CAN) or Joint Test Action Group (JTAG) are used to communicate between various modules in a BMS[3]. BMS used in EVs are complicated as it has to monitor a system which performs many functions simultaneously.
Cell balancing is one of the important functions of BMS. Imbalances in the cell are caused due to various side reactions happening in the cell. The impedance of the cells increases and differs from one another, creating this imbalance. Cell balancing is a hardware circuit which is controlled by switches to transfer or dissipate the extra charge. Cell balancing can be done through two ways namely active cell balancing and passive cell balancing. In passive cell balancing, the extra charge of the cell with the maximum voltage in the battery pack is dissipated whereas in active cell balancing, the extra charge of the cell with maximum voltage is transferred to cells with lesser charge. The algorithm used for passive cell balancing is simple and doesn’t need high computational power. One major disadvantage of passive cell balancing is the dissipation of extra energy in the form of charge. Active cell balancing, on the other hand, transfers the charge between cells, thus eliminating the need for dissipation. But the algorithm associated with active cell balancing is complex and needs high computational power [4]. Yet active cell balancing can be used for accurate cell balancing for high-end vehicles. Active cell balancing has four main divisions in it namely cell bypass, cell-to-pack, pack-to-cell and cell-to-pack-to-cell. Active cell balancing can also be classified based on the circuit configuration used [5]. The differences between active and passive cell balancing are given in Table 1. Shunting methods and switches are mainly used to transfer charge from one cell to the other, creating this imbalance. Cell balancing is a hardware circuit which is controlled by switches to transfer charge from cell to cell. The switching in the balancing circuit is decided by the algorithm. Voltage imbalance tolerance needs to be specified in the program based on the application and the battery pack specification.

Capacitor and inductor in the circuit might cause long equalization times and hence are not preferred for larger battery packs. Switched transformer is one such method which has minimal losses and no equalization times. This method can be used for higher battery packs which needs quick reactions to the imbalances caused [6]. A common practice is to use a DC-DC converter to step the voltage values during the transfer. The DC-DC converter used for electric vehicle applications should be economical, highly efficient, reliable, with lesser ripples and interrupts [7].

| S.No | Active cell balancing          | Passive cell balancing       |
|------|--------------------------------|------------------------------|
| 1    | Extra energy is not wasted     | Extra energy is dissipated   |
| 2    | High complexity                | Easy implementation          |
| 3    | Lesser power losses            | Higher power losses          |
| 4    | Expensive                      | Economic                     |

This paper deals with comparing the outputs obtained from active cell balancing for a 4s Li-ion module for through switched transformers using a flyback converter and a push pull converter. Section 2 deals with the specifications of the system and environment considered, section 3 deals with the algorithm used and section 4 talks about the results obtained for the simulation of the same through MATLAB-Simulink software and thus compares the results obtained through these two methods of active cell balancing to draw a conclusion.

2. System Specifications

Figure 1 depicts the block diagram of the cell balancing system along with the battery module. The method of switched transformer to balance the cells follows active cell balancing scheme and pack to cell type transfer. The primary of the transformer is loaded with the pack voltage and the secondary transfers voltage to different cells and hence the name [8]. This method of using switched transformer eliminates the use of capacitors and inductors which leads to power losses and complications. It also is more efficient in terms of power transfer and consumes less time to balance. The battery considered here is a 2s battery pack.
Table 2. BMS and Cell specifications.

| S.No | BMS Specification                  | Value       |
|------|-----------------------------------|-------------|
| 1    | Nominal Voltage                   | 3.3V        |
| 2    | Nominal capacity                  | 2.5Ah       |
| 3    | Discharge cut-off voltage         | 2.5V        |
| 4    | Charging cut-off voltage          | 3.55V       |
| 5    | Charging/ Discharging current     | 0.3C(54A)   |
| 6    | Maximum short time discharge current | 10C(1800A) |
| 7    | Life cycles at 80% DOD            | 2000 cycles |
| 8    | Balancing resolution              | 90mV        |

The converters used are a flyback converter and a push-pull converter. The high switching frequencies gives a pulsating DC output which is later rectified and filtered to a constant DC. A suitable PWM is required to trigger the switching in the converters [9]. The cell with the lowest voltage is selected and the extra charge is transferred to this cell through the secondary of the transformer. The overall functionality of both the methods considered is same with the same system specifications for accurate comparison. The specification of the BMS and the cells considered are given in Table 2 and Figure 1 shows the structure of the proposed system.

The cell specification is considered with reference to standard LiFePO₄ cells available. This chemistry is chosen as it has a good specific energy and life cycle. Life cycles of a pack tells the number of load-cycles a battery pack can be used for. This is estimated using the SOH of the pack. The converter has been designed based on the input and output required. As cell balancing is done only for one cell at a time, the primary voltage of the transformer considered for a 2s Li-ion pack is 6.6V, the secondary voltage is considered to be around 3V compensating the losses due to switches and diodes. As the voltage level of the secondary is small, the small losses due to diodes and switches is significant.

![Figure 1. Proposed System.](image)

2.1. Flyback Converter Design

A flyback converter can be used as a AC-DC converter or a DC-DC converter. The converter is derived from a buck-boost converter and has high switching speed. The converter is a transformer with switching scheme where primary and secondary do not hold charge at the same time due to its design. Using transformer switching method of cell balancing provides isolation between primary and secondary. The output-input voltage relation with the duty ratio is as given by (1),

\[ V_o = V_i \left( \frac{D}{1-D} \right) \left( \frac{N_2}{N_1} \right) \]  

(1)
With a fixed voltage ripple ratio, the capacitance \((C)\) can be obtained from (2). Similarly, with a fixed current ripple ratio, the magnetizing inductance \((L_m)\) of the converter can be found from (3),

\[
\frac{\Delta V_0}{V_0} = \frac{D}{R \times C \times f}
\]

\[
L_m = \frac{V_c \times D}{\Delta i_s \times f}
\]

The duty cycle\((D)\) of the converter is found using the first equation with the known primary and secondary voltage. The voltage ripple considered is 5\% in equation (2) and the current ripple considered is 1\% in (3) for magnetizing inductance calculation. The efficiency of the converter can also be calculated with these parameters. The frequency of converter considered is 50kHz.

2.2. Push-Pull Converter

A push pull converter also has a DC-DC isolation transformer which provides input-output isolation. This works at very high switching frequency. The polarity of primary and secondary is opposite. This is the case with flyback converter as well. The output from the secondary is a pulsating dc output. This is rectified by the two diodes and the filter present at the output end. Thus, a constant desired DC is obtained with the help of push-pull converter [10]. Same voltage ripple and current ripple is used to find the inductance, capacitance of the filter and the duty ratio. The switching frequency of the converter is same as for the flyback converter which is 50kHz. The input-output relationship with the duty ratio is given by (4).

### Table 3. Converter specifications.

| Converter       | Flyback        | Push-Pull      |
|-----------------|----------------|----------------|
| Primary Voltage | 7.5V           | 7.5V           |
| Secondary Voltage | 2.5V       | 3V             |
| Capacitance     | 2.13uF         | 83nF           |
| Inductance      | 6mH            | 0.6mH          |
| Switching Frequency | 50kHz   | 50kHz          |

\[
V_0 = 2 \times V_s \times \left( \frac{N_s}{N_p} \right) \times D
\]

As with the flyback converter, fixed value of current ripple can be used to find the inductance of the LC filter as shown in equation (5). Voltage ripple ratio can be used to find the capacitance value in the LC filter of the converter as shown in equation (6). The converter parameters so calculated are listed in Table 3.

\[
\Delta i_s = \frac{V_s \times \left( \frac{1}{2} - D \right) \times T}{L_s}
\]

\[
\frac{\Delta V_0}{V_0} = \frac{1 - 2 \times D}{32 \times f^2 \times 2 \times L_s \times C}
\]
3. Algorithm and Implementation
The different modes of operation are the charging mode, discharging mode and the idling mode. Cell balancing is preferred to be performed during charging and idling modes of operation. Discharging of the battery pack may cause the cells to go below cut-off voltage. Here the cut-off voltage is 2.5V. Once this threshold is reached, the load is cut off and the BMS has to give a low charge indication. The time required to discharge the battery completely depends on the battery overall capacity. With many cells in a pack, the imbalance is inevitable and this needs to be balanced to make efficient use of the battery pack [11]. In the same manner, once the pack is put to charge and one of the cells reach the cut-off voltage for charging mode, the charger is cut off from the pack and a full charge indication is given. A BMS can also monitor temperature conditions. Accurate ranges for the selected battery chemistry, must be chosen for both charging and discharging cycles, as the reaction inside a cell differs during charging and discharging. If cell balancing is done during charging condition, it is done after the cell with the highest voltage reaches a threshold [12]. Based on the processor used, the mode in which the cell balancing done can also be changed to discharging or more than one mode can be chosen for better accuracy.

Different algorithms can be used to balance cells. The algorithms can be tested in a practical environment to understand the compatibility with different case scenarios and circuits. One of the most common algorithms used in cell balancing finds the cell with the least voltage, the cell with the maximum voltage and generate the difference between them as shown by the flowchart in Figure 2. Based on the vehicle configuration, type and specification, a threshold is set for this difference value, which is then corrected using the balancing circuits. Balancing of cells needs efficient functioning of hardware and firmware to give accurate results. Fault in either the hardware or firmware might cause extensive charge depletion of the battery, thus reducing the useful life and capacity of the battery pack [13].

![Figure 2. Overall flowchart of cell balancing.](image)

The threshold for balancing used in this paper is 35mV. Any value sensed that is greater than this triggers the balancing circuit until the condition is satisfied. The threshold chosen should be a small value as individual cells deal with small voltage values; a slight difference can have the potential to cause huge imbalances when operated over a period of time. But if the threshold value chosen is very small, it might increase the power requirement and computational cost of the system. Therefore, a trade-off exists between increased efficiency and computation cost. It is always desirable to choose a threshold value which keeps the cells in the battery pack balanced most of the time.
3.1. Working of Flyback converter

The dc source in the setup is the battery pack. As the configuration used in this balancing is a pack-to-cell type, the complete battery pack voltage is observed at the primary side of the transformer. The load in this setup is an individual cell. All the cells in the pack are connected with the help of switches. One or more switches can be closed based on the processor’s output. The switch which is supposed to be closed is also decided by the algorithm used in cell balancing. This work uses the least voltage method to find the cell which needs balancing.

![Figure 3. Circuit diagram of a flyback converter.](image)

The switching frequency used is 50kHz. The DC at the input side is converter into a pulsating DC with the help of the pulse generator. In a flyback converter, the secondary and primary are not ON, at the same time. This is because of the diode(D1) configuration used. The pulsating DC which is present at the secondary side is converted into a constant DC output with the help of D1 and the capacitor(C) is charged. This is then given to the load. During the first half of the cycle, SW1 is ON and the primary is conducting, but D1 is reverse biased and the output is supplied with the charge present in C from the previous cycle. During the second half of the cycle, SW1 is OFF, primary resists conduction, but as the polarity reverses, the secondary conducts as D1 is now forward biased, supplying the output and charging C. The working of the converter can be depicted by using Figure 3.

Magnetization effects are significant at this high frequency and hence the values of the magnetizing inductance (L_m) need to be designed based on the voltage and the current ripple. Similarly, the capacitor is also designed to meet the requirement. The output across C is connected to individual cells with the help of relays or switched. The switch selection must also be done to meet the requirements of voltage and currents passing through the pack.

The voltage and current ripple values should be kept as small as possible to avoids spikes in the output. A constant output for the system is always desirable. This should also be compatible to be used with the circuit elements available with predefined values [14].

3.2. Working of a Push-Pull converter

A conventional push-pull converter has two switches on the input side, two diodes and a LC filter on the output side. The transformer used in this type of converter is centre tapped on both the input and the output side. The two switches aren’t ON together at any given time. During the first half cycle, Switch1 is ON, Switch2 is OFF, and the upper tapping of the input side starts conducting. This allows conduction on the secondary side. Yet D1 is ON and D2 is OFF due to the current direction. The LC filter rectifies the pulsating DC output due to the high frequency switching. The input in this setup is always the battery pack, and the output is one of the cells in the battery pack [15]. The circuit diagram is shown in Figure 4.

During the second half cycle, Switch2 is ON an Switch1 is OFF as the current direction is reversed. This enables conduction of the lower tapping on the primary side. The secondary starts conducting as
well, and this time, D2 is ON and D1 is OFF due to the reversed direction of the current. The LC filter, gives a constant output to the load [16]. The switches when turned ON together causes damage to the converter and hence should be avoided. This converter gives a constant DC output with lesser noises and high efficiency due the presence of two switches and diodes. The values of the LC filter are designed by setting a value of the current and voltage ripple, and the input-output voltage of the transformer. The switching frequency remains 50kHz for this system to make a comparison based on the time taken to balance the imbalance of the cells in the battery pack [17].

4. Results
The proposed method of active cell balancing using transformer switching has been done using MATLAB/Simulink. A comparison has been made between the setup using push- pull converter and flyback converter. For any pack, the cells showing imbalance can be used to fix the imbalance and test the schematic used. Here a 2s lithium ion battery pack, having a nominal voltage of 3.3V and a rated capacity of 2.5Ah has been used. An imbalance of 2% has been injected initially, to check the system performance. The mode of operation is discharging as a load of 2.5Ω has been given to the battery pack. The schematic is simulated for 70sec and the results are recorded.

4.1. Flyback Converter
The Figure 5, shows the primary and secondary voltages of the flyback converter. The pack used is a 2s pack, with a nominal voltage of 3.3V, due to switch losses, a primary voltage of 7.5V is obtained. The secondary works as per the diode mode of operation and the switching cycles. It gives a voltage of 2.4V. The constant 6.6V input is converter into a pulsating one due to switching. The switch voltage goes upto 11.5V during every first half cycle as shown in Figure 6. The switching frequency is 50kHz which is very high. This enables fast switching thus giving a constant supply to the load. The current consumed by the switch is small and around 0.035A while it is ON. As shown in Figure 7, the output from the flyback converter gives an output voltage of 3.5V. The output voltage is a constant DC voltage and this voltage steps down to charge single cell after compensating the losses for the switches. The output current should be constant and small. A higher value of current might lead to accelerated side reactions causing extra charge depletion.
Figure 5. Primary and Secondary voltages of the transformer.

Figure 6. Voltage and current of SW1.

Figure 7. Converter output voltage and current.

Figure 8. Cell SOCs of the cell.

Figure 9. Cell voltages of the 2s pack.
The respective plots from Figure 8 and Figure 9 correspond to the SOCs and the cell voltages of the 2s battery pack that was considered. The cell voltages have a difference of almost 2V initially, but as time passes by, this imbalance is reduced and by the end of 70sec, it converges towards one another making the difference equal to 33mV. The imbalance in the SOCs which exists in the initial state tend to continue without increasing for all the 70sec, as voltage is not the sole indicator of the SOC of a cell. Voltage imbalance adds to SOC imbalance. As shown in Figure 9, the imbalance is maintained to be constant as there is no further increase in voltage imbalance. The currents of the cell are constant as depicted by Figure 10. The currents are equal in both the cells, as the battery chemistry, rated voltage and capacity of both the cells is the same. The MATLAB schematic for implementing active cell balancing using flyback converter is shown in Figure 11.

4.2. Push-Pull converter

Figure 12. Secondary and Primary voltages of the transformer.
Figure 12, shows that the primary voltage is 7.5V and the secondary voltage comes up to 3V. This is very similar to the ratings of the flyback converter as well. The pulses are later rectified by the LC filter which gives a constant dc at the output of the converter.

![Figure 13. Voltage and Current outputs in Switch1.](image1)

![Figure 14. Voltage and Current outputs in Switch1.](image2)

As shown in Figure 13 and Figure 14, the voltages and currents of both of the switches are equal in magnitude and they correspond to 14.9V and 2.9A respectively. The magnitudes of both current and voltage are higher in push-pull converter switches when compared to the flyback converter. Switch2 here has a phase delay of 1m sec and is not turned ON when Switch1 is turned ON. The duty ratio of both the switches is considered to be the same. The voltage across the switches when they are ON is two times of the source voltage as the secondary is conducting as a whole, and a voltage that is equal to the source voltage is observed across each tapping.

The converter output voltage is similar to that of the flyback converter’s output voltage. As shown in Figure 15, the output voltage goes up to 3.6V, very similar to that of flyback converter output. The output current of both the cells is the same, as depicted by Figure 16, due to similar cell chemistries, nominal voltages and rated capacities. Using differently rated cells in a pack is not recommended, as it might cause huge imbalances and the pack is not maintained in a stable condition no matter how powerful the processor used is.

![Figure 15. Converter current and voltage output.](image3)
An imbalance similar to that of SOC has been injected in the pack. Cell voltages had a difference of almost 1.5V initially, as shown in Figure 18, but this converges eventually and by the end of 70sec and the difference becomes as small as 29mV. The SOCs decrease as time passes by, as shown in Figure 18, but the imbalance remains constant as there is no further voltage imbalance which is clear from Figure 17. This is the same for balancing using any methods, until the side reactions are not accelerated due to temperature rise or excessive charging or discharging. The overall schematic in MATLAB-Simulink using the push-pull converter is shown in Figure 19. Table 4 depicts the comparison of flyback and push-pull converter in terms of switch voltage, current, converter current, SOC imbalance and cell voltage imbalance. Its observed that switch voltage and current is high in push-pull converter while cell voltage imbalance is very less compared to flyback converter.
Table 4. Comparison of output parameters.

| Parameter                  | Flyback converter | Push-Pull converter |
|----------------------------|-------------------|---------------------|
| Switch voltage             | 11.5V             | 14.9V               |
| Switch current             | 0.035A            | 2.9A                |
| Converter output           | 3.5V              | 3.6V                |
| SOC imbalance              | 1%                | 1%                  |
| Cell voltage imbalance     | 33mV              | 29mV                |

5. Conclusion

The active cell balancing scheme using switched transformer has been simulated for a 2s lithium ion battery pack, taking nominal voltage as 3.3V and rated capacity as 2.5Ah for 70sec in MATLAB/Simulink. This setup has used flyback converter and push-pull converter to draw a comparison between the both of them. The threshold for triggering the balancing circuit has been given as 35mV in the algorithm. Both flyback converter and push pull converter make it close by the end of 70sec standing at a voltage imbalance of 33mV and 29mV respectively. It takes less than 70sec go below the set threshold limits for both the setups. The push-pull converter has given a better result with respect to the converter output and correcting the voltage imbalances over a given period of time. DC-DC converters such as push-pull converters and flyback converters are widely used in electric vehicles. Using transformers to transfer energy is an efficient way at higher frequencies due to reduced volume and noises. It also provides input output isolation which is important in pack-to-cell configurations. But due to these features, the cost of the device might go higher, though it increases the efficiency.

6. References

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