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Research Article

INVESTIGATION AND DESIGN OF AN ACTIVE CELL BALANCING SYSTEM FOR LI-ION BATTERIES

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Keywords
Lithium-ion Battery,
Cell Balancing,
Battery Management System,
Active Cell Balancing,
Buck Boost Converter.

Abstract

A type of active battery cell balancing system based on buck-boost converters is proposed in this study. By using equivalent circuit model of the battery cells, proposed active balancing circuit is examined in detail. An algorithm is developed to actively control the balancing operation. The algorithm is also utilized to prevent any failures in the balancing operation. The proposed system is simulated under low and heavy load. The simulation results indicates that 25 mV imbalance between potentials of two battery cells can be balanced out in approximately 147 seconds under low load and in 127 seconds under high load.

Lİ-İYON BATARYALAR İÇİN AKTİF HÜCRE DENGELEME SİSTEMİ İNCELEMESİ VE TASARIMI

Anahtar Kelimeler
Li-İyon Batarya,
Hücre Dengeleme,
Batarya Yönetim Sistemi,
Aktif Dengeleme,
Azaltan Arttıran Dönüştürücü.

Öz

Bu çalışmada lityum iyon bataryalar için gerilim azaltan-arttıran dönüştürücü tabanlı bir aktif hücre dengeleme sistemi önerilmektedir. Aktif hücre dengeleme devresi batarya hücreleri için eş değer devre modeli kullanılarak detaylı olarak incelenmiştir. Dengeleme işlemini aktif olarak kontrol eden bir algoritma geliştirilmiştir. Algoritma dengeleme sürecinde oluşacak hataları önleyecek şekilde tasarlanmıştır. Önerilen sistemin düşük ve yüksek yük altında çalışma durumları için benzetimi yapılmıştır. Benzetim sonuçlarına göre farklı şarj durumlarındaki iki hücre arasındaki 25 mV'luk fark düşük yük altında yaklaşık olarak 147 saniyede, yüksek yük altında 127 saniyede dengelenmektedir.

Alıntı / Cite

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1. Introduction

Battery technology is attracting attention increasingly due to the development of energy applications such as electric vehicles (EVs) and smart grids. For many years, various type of batteries have been used such as nickel-cadmium and lead acid. Today, lithium-ion technology is the fastest growing and most promising battery chemistry. Lithium-ion batteries stand out among others with the features of low self-discharge rate, higher energy density, higher power density and slow loss of charge when not in use (McDowall vd., 2002; D. S. Repila and J. E. W. Poxon, 2006; Y. Lee and and M. Cheng,2005; M. Ki m vd., 2014; H. Park vd., 2007). On the other hand, lithium-ion batteries pose some safety risks and their performance is sensitive to overcharging and overheating (McDowall vd., 2002; D.

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S. Repila and J. E. W. Poxon, 2006; Y. Lee and and M. Cheng, 2005; M. Kim vd., 2014; H. Park vd., 2007).

Single lithium-ion cell requires monitoring in order to prevent cell voltage from exceeding predefined limits of the chemistry. In practical applications, multiple battery cells are connected in series to obtain sufficient supply voltage values. Manufacturing inconsistencies, differences in self-discharge rate, cell capacity reductions with aging, thermal runaways and different cell impedance values can be listed as the main reasons for the differences between cell voltages (Jian Cao vd., 2008; M. Daowd vd., 2011; W. F. Bentley, 1997). Although all of the batteries in a battery pack initially have almost the same capacity, voltage and internal resistance, the performance of the package varies depending on the performance of the cells. Some cells are rapidly discharged and some cells are slowly discharged, causing voltage and capacity imbalance. The imbalances among cells cause serious failures. Over time, accelerated capacity degradation can be observed in a battery pack. Also, there might be incomplete charging and discharging of the pack. Assuming one cell is fully charged before the others then the battery protector stops charging the entire pack. In this case, the other cells which are not fully charged yet cause the battery pack having less energy than its rated capacity. On the other hand, if one particular cell is fully discharged before the others, the battery protector cedes operating while the capacity in the other cells are not fully utilized. Therefore, a cell balancing circuit considerably increases the battery performance and the life time.

The system containing the cell balancing circuit is called the battery management system (BMS). The battery management system consists of an electronic system that manages battery cells. A battery management system has a circuit and an algorithm that can start or finish balancing by monitoring the voltage of the cells in the battery pack in order to balancing between the cells. It also can activate the required cooling system by monitoring the temperature of the cells.

Balancing circuit topologies can be categorized as passive balancing and active balancing.

In passive balancing, cells are balanced by disposing the energy in the higher cells via a resistance. This method is relatively simple and easy to implement but the release of energy as heat makes it harder to control thermal runaways. This technique is also favorable in low-cost system applications (M. Kim vd., 2014; H. Park vd., 2007; Jian Cao vd., 2008; W. Lee vd., 2011; A. Baughman and M. Ferdowsi, 2005; Carmelo Speltino vd., 2010; M. Daowd vd., 2011; K. Zhi-Guo vd., 2006).

The more sophisticated active cell balancing method can transport the energy from one cell to another, from one cell to battery pack or from the battery pack to a particular cell by using energy converters, transformers, inductors and/or capacitors as charge storage components (M. Daowd vd., 2011; K. Zhi-Guo vd., 2006).

As an active balancing method, capacitive cell balancing utilizes external energy storage devices, capacitors for shuttling the energy between the cells (A. Baughman and M. Ferdowsi, 2005; Carmelo Speltino vd., 2010; M. Daowd vd., 2011; K. Zhi-Guo vd., 2006). This method can be categorized into four topologies; (1) the switched capacitor, (2) single switched capacitor, (3) double-tiered capacitor and (4) modularized switched capacitor topologies. This balancing method provides easy control and small energy loss. However, it requires longer balancing durations. Additionally, to reduce resistive losses and make balancing faster, large capacitors must be used which eventually increases the overall size of the system.

In inductive cell balancing method, inductors or transformers are used to transfer the energy between different cells in the pack (M. Daowd vd., 2011; K. Zhi-Guo vd., 2006; P. Sang-Hyun vd., 2007; S. Li vd., 2013; Markus Einhorn vd., 2011). Equalization time with this method is much faster than that with the capacitive cell balancing method. The main drawbacks of this method are not being able to work in high frequencies and low efficiency due to magnetics losses.

Energy converters used for cell balancing split in several categories such as; buck-boost (C. Moo vd., 2003; Juan Zhao vd., 2003), fly back (C. Bonfiglio and W. Roessler, 2009; XueZhe Wei vd., 2009), ramp (T. Stuart and Z. Ye, 1996) and full-bridge (L. Maharjan vd., 2009). It is an important parameter with the control of the balancing process. They have good balancing times and little energy loss.

This paper aims first to show how proposed balancing circuit works with a control algorithm that prevents any failure for lithium-ion batteries. As a second goal, design process of the circuit and cell behaviors under different loads during balancing are intended to be conveyed to the reader. In this study;
-Reliable modelling development has been constructed based on cell experiment.
-Parameter selection was performed for the optimized performance.
-A novel control algorithm was developed.
-Small balancing time, compactness, modularity and low cost design is suggested.
-Experimental study based on selected parameters is continuing.

The study is organized as follows: Section 2 provides a meaningful model for the battery cells. In Section 3, operation principle of the proposed balancing circuit is analyzed. Design parameters and control algorithm of the circuit is thoroughly explained in Section 4. Subsequently, simulation results are determined in Section 5. Finally, following sections 6 includes conclusion.

2. Battery Cell Model

Developing a good understanding of cell behavior is critical when designing energy storage systems for electric applications. There are several ways to model a battery, however, equivalent circuit model (ECM) is an effective way to simulate the real performance of a battery by building circuit with using electrical components such as voltage sources, resistors and capacitors. In this paper, the model consists of an ideal voltage source VOC that represents the open-circuit voltage of the battery cell, a series resistance as an internal resistance of the cells and a parallel RC network in order to describe the battery transient response during charging and discharging as illustrated in Fig.1 (Dazhong Mu vd., 2013).

In the equivalent circuit model given in Figure 1: R_0 shows the internal resistance of the non-charged battery, the RC parallel equivalent $R_1//C_1$ (R_1 equivalent polarization resistance and C_1equivalent polarization capacitor) indicates the temporary state of the battery during charge / discharge. Voc (t) is a non-linear function of SoC (t). Using Kirchhoff's law, the dynamics of the circuit can be expressed as follows:

$$\frac{\mathrm{dV_c}}{\mathrm{d(t)}} = -\frac{1}{\mathrm{R_1.C_1}}.\mathrm{V_c(t)} + \frac{1}{\mathrm{C_1}}\mathrm{i_b(t)} \tag{1}$$

$$\mathrm{V_b(t)} = \mathrm{V_{oc}(t)} - \mathrm{V_c(t)} - \mathrm{R_0 i_b(t)} \tag{2}$$

In the model given in Fig.1, the equivalent circuit parameters R_0, R_1 and C_1 are the functions of SoC and temperature.

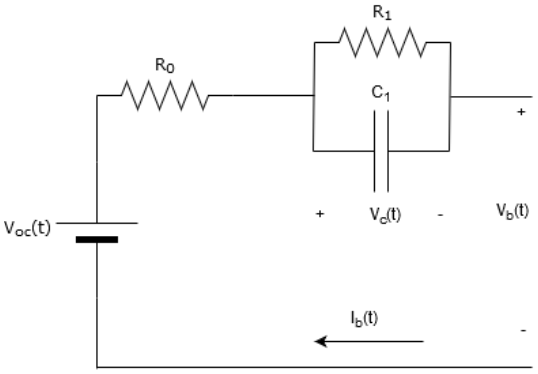

Figure 1. Equivalent circuit model of the battery.

The experimental data was obtained by testing Panasonic 18650GA 3.45 Ah lithium-ion battery cells. ARBIN BT2000 Battery Tester and temperature chamber offer to run tests at desired pulsed current discharge rate and controlled temperature environment. As shown in Fig.2, 3.45A pulsed current was applied 19 times. 69500 point data was taken to get accurate battery voltage.

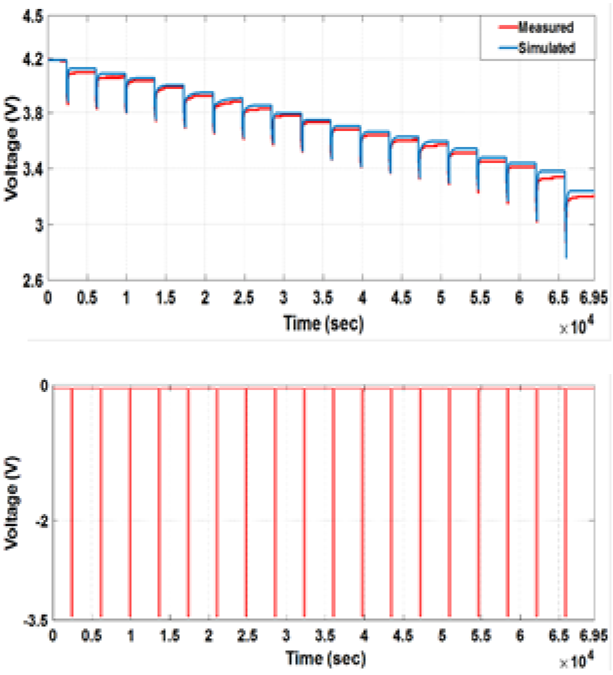

Figure 2. Experimental and simulated data of the battery cell voltage in 1C discharging at 20ºC.

To extract the value of the model components, MATLAB/Simulink estimation tool is used. All components are functions of SoC and aging effect is neglected. The estimated parameters at 20ºC are shown in Fig.3.

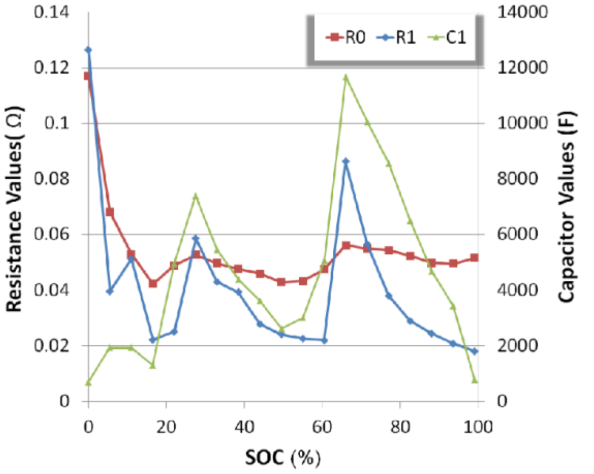

Figure 3. Extracted estimation parameters.

To validate model results, the error between measured and estimated cell voltage under the pulsed and continuous loading conditions is observed as depicted in Fig.4. The error percentage is below 2% between 20% and 100% SoCs.

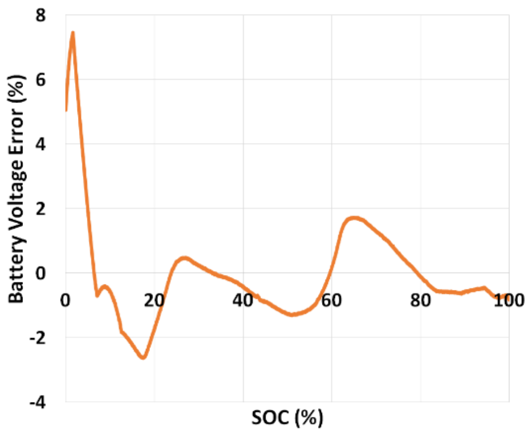

Figure 4. Comparison between model and experimental of cell's voltage.

3. System Description and Operation Principle

The proposed cell balancing circuit is shown in Fig.5. The circuit contains two capacitors, an inductor, two diodes and two switches for two battery cells. The proposed system can be used for any chemical cell characteristics and different number of cells. Moreover, there are no limits on high or low current values. The energy can only shuttle between adjacent cells bidirectional (Moran, J, 2009).

In charging and discharging operations, there are always slight differences among the cells in use. Balancing the battery cells continuously can be expensive and ineffective due to resistive losses and current drawn by the control algorithm. Therefore, the balancing circuit begins charge distribution once the voltage difference between any two cells exceeds the predetermined threshold voltage.

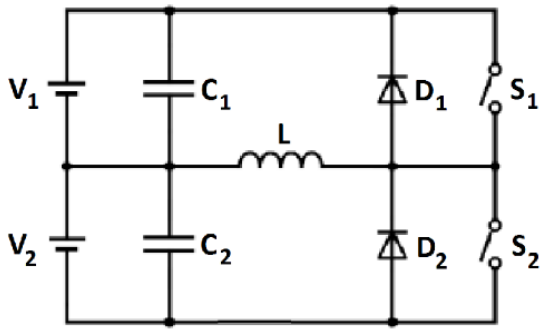

Figure 5. Proposed cell balancing circuitry.

Inductors are the main storage components of the circuit which transfer energy from higher energy to lower energy cells. After detecting higher and lower energy cells, the switch which is parallel to the higher energy cell is closed. The inductor located between the balancing cells, is charged through capacitor of higher energy cell as illustrated in Fig.6. The peak current on the inductor at t_{on} is;

$$I_{PEAK} = \frac{V_{higher} - dV_C}{R} . (1 - e^{-t_{on}\frac{R}{L}}) \quad (3)$$

where V_{higher}, dV_C, L, R and t_{on} denote the voltage of higher energy battery cell, ripple voltage, inductance value, sum of the resistive losses and the interval of time during the switch is closed, respectively.

From (3), in order to transfer more energy in one cycle, switch should be in close-state for a larger amount of time and should have lower total resistance values. However, ripple voltage on cells must be considered. During balancing, large increment and decrement occurring on cell voltages may ruin the battery performance and battery life time.

$$dV_c = I_{av}\frac{t_{on}}{C} \quad (4)$$

where C is capacitor value and I_{av} is the average current on the inductor which can be expressed as;

$$I_{av} = \frac{1}{2}\frac{I_{PEAK}.t_{on}}{t_{period}} \quad (5)$$

Thus, the ripple voltage can be rewritten as;

$$dV_c = \frac{1}{2}\frac{I_{PEAK}.t_{on}^2}{C.t_{period}} \quad (6)$$

From (6), ripple voltage is directly related to square of the switch closed time and peak current. By selecting a large capacitor value, we can pull ripple voltage back in safe margins. Ripple voltage and the saturation current of the inductor are limiting factors defining how much charge can be transferred in a cycle.

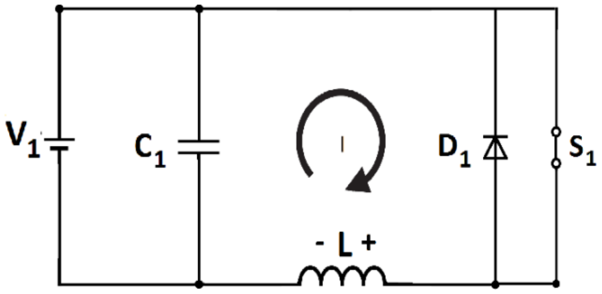

Figure 6. Cell balancing circuit while charging inductor.

In the subsequent cycle, the closed switch is opened as shown in Fig.7. The diode which parallels to the lower energy cell is forward biased thus polarization of the inductor is changed with the applied negative voltage.

The inductor discharges into lower energy battery cell through the capacitor. The voltage on the inductor;

$$V_L(t) = L\frac{dI_L}{dt} = L\frac{\Delta I_L}{t_{on}} = V_{lower} + V_f - V_{indloss} \quad (7)$$

where V_{lower}, V_f, $V_{indloss}$ and t_{off} refers to voltage of lower cell, forward bias voltage of the diode, voltage loss on the inductor and the interval of time through which switch is closed, respectively.

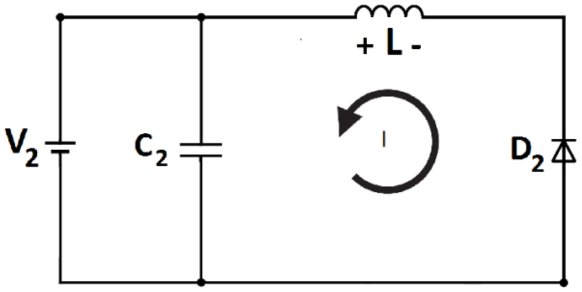

Figure 7. Cell balancing circuit while charging low energy cell.

Then, t_{off} can be calculated as:

$$t_{off} = L\frac{I_{PEAK}}{V_{lower} + V_f - V_{indloss}} \qquad (8)$$

Finally, in order to make sure that inductor is fully discharged into low energy battery cell, some redundant time $t_{redundancy}$ should be added when calculating the total period of the switching time. Otherwise, the remaining energy on the inductor from the previous cycle may cumulatively cause exceeding the predetermined balance current. Thus, the inductor may be damaged or after number of cycles, the ripple voltages on cells may reach dangerous levels. Furthermore, $t_{redundancy}$ relaxes capacitor value.

$$t_{period} = t_{on} + t_{off} + t_{redundancy} \qquad (9)$$

4. Design Process

Cell balancing circuits need precise trigger points to accurately operate. With the help of gauge cells, the battery cells can be protected and the circuit is controlled. However, measuring operation has some critical points. In voltage based balancing algorithms, voltage difference between battery cells increases and decreases during one balancing cycle. Monitoring battery cell voltages during the balancing process may stop or reverse the balancing direction as shown in Fig.8(a) and 8(b). In Fig.8(a), initially the battery cell voltages are measured as V_{oh} and V_{ol}. If V_{oh} and V_{ol} difference is higher than $V_{threshold}$, balancing starts. From start to t_{on}, V_{oh} ripples through lower voltage level whereas V_{ol} stays at same voltage level therefore the voltage difference may become smaller than $V_{threshold}$ and the operation automatically stops. In another case that is depicted in Fig.8(b), the ripple voltage is considerably high, V_{ol}' might be much higher than V_{oh}' between t_{on} and t_{period}. Thus, balancing direction becomes reversed and the operation fails.

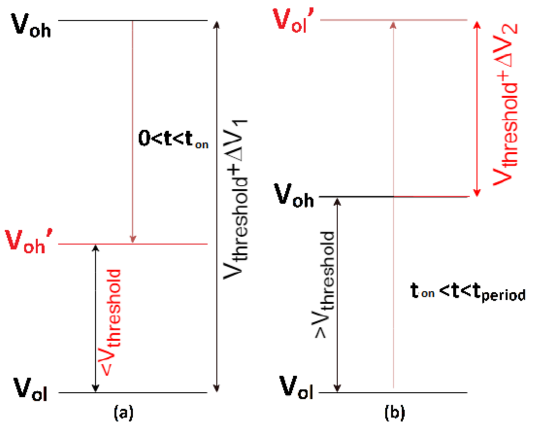

Figure 8. Cell voltages representation in some possible cases.

As an example, a simulation result in Fig.9, proves that voltage difference may become lower than reverse threshold level during balancing process. On the other hand, because of settling time of cell voltages during this process, cells sometimes could not reach their actual values in just one period. Fig. 9 shows that the voltage difference is not the same with actual voltage level during balancing process if $t_{redundancy}$ is kept insufficiently small. That's why, measuring cells' voltages at which level has an important effect on cell balancing circuit.

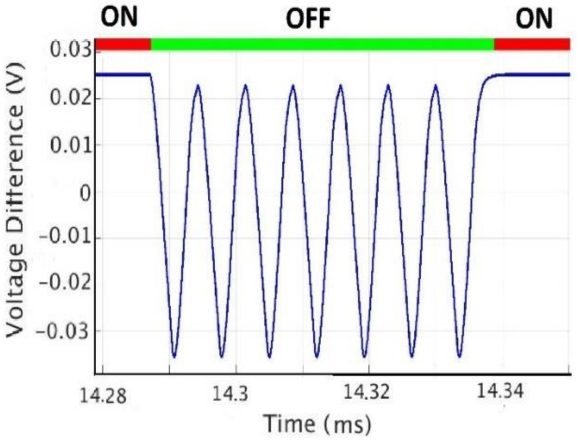

Figure 9. An example of voltage difference between cells.

In this study, the battery cell voltages are measured just once at the end of the each predetermined cycle. If cells are unbalanced, the balancing operation lasts until the cycle counter is equal to a specific cycle number and subsequently the balancing operation is forced to stop for a specific interval of time. Meantime, battery cell voltages are measured at the end of the delay where they reach to the actual voltage level. Sampling voltage differences in such periods provide easy control. The flowchart of the operation is given in Fig.10. At the start, system measures the voltage levels of all the related cells. Following to that, system checks whether the predefined threshold is exceeded or not. If battery cells need balancing the system does not monitor cell voltages during the sixty seconds cycle, it only balances the cells. Following to that, during sixty seconds the system goes to rest and the cells are not in balance. When the determined cycle number is reached, the whole operation returns to beginning.

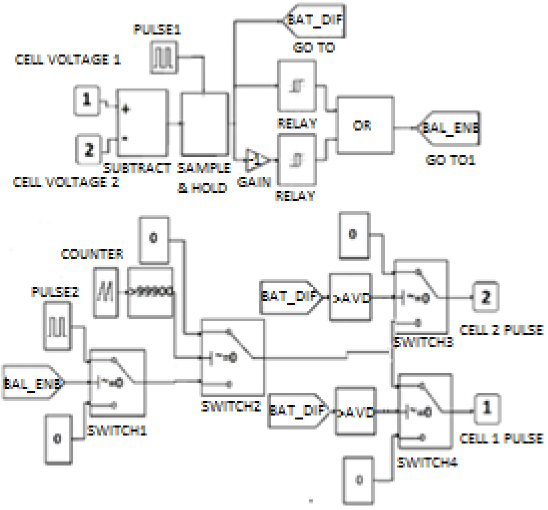

Figure 11. Simulink model of the control algorithm.

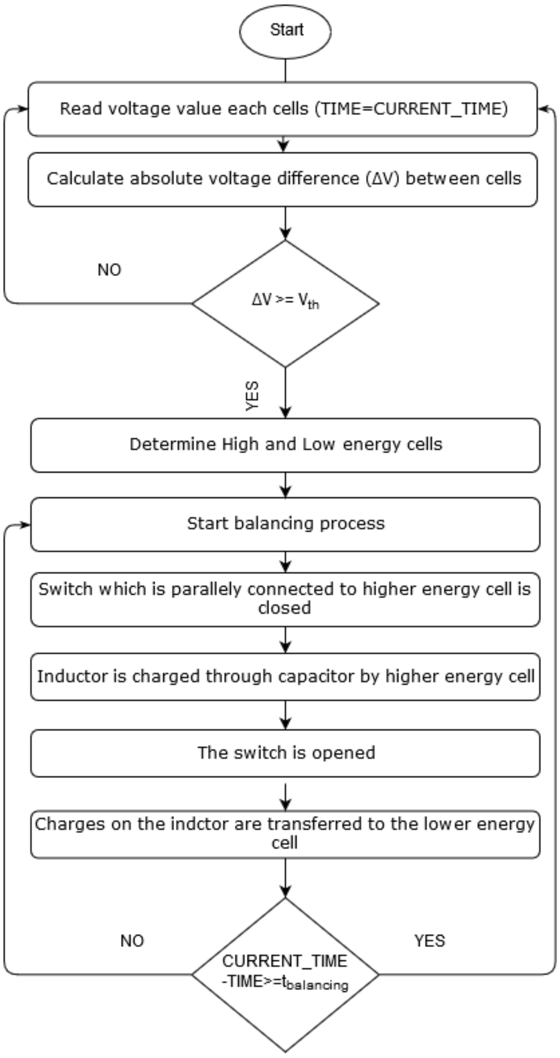

Figure 10. Flowchart showing the algorithm of the cell balancing procedure.

A Simulink model is developed to control switches. The model simply samples the voltage difference at the end of the 100000th multiples of t_{period}. Using relay block, not only the threshold level but also the acceptable voltage difference (AVD) is defined. AVD parameter is used to precisely determine the moment when the cell balancing process is not necessary any longer. In the case of results of any relay blocks are 1, balancing enables. Counter and compare blocks stop the balancing process for the last 100 cycle of the process in order to be able to precisely collect measurement data. If the difference exceeds over threshold, depending to the sign of the difference, model gives proper pulse signals to the switches.

In order to successfully design the proposed system, some of the parameters are needed to be preassigned to get targeted performance from the system. Firstly, the peak current and the value of the inductor should be specified depending on the capacity of the battery cells. Since peak current reaches maximum value where high cell voltage is fully charged, the calculation of the inductor current should be made under this circumstances. Thus, designer guarantees to not exceed the saturation current of the inductor. As a last input, allowable ripple voltage should be set. At this point, t_{off} from (8) can be found. As mentioned earlier, $t_{redundancy}$ relaxes some design parameters. However, it can be taken as 0 to keep balancing time small as possible. By observing (3), t_{on} is reversely proportional to low cell voltage. So, it also should be put in the formula where low cell voltage is fully discharged. Later on, t_{period} can be found from (9). Since dV_c is known, required capacitor value also can be calculated from (4).

Parameters are determined as in Table 1. Switch resistance is referenced from IRF3206PbF N-channel Power MOSFET. The usage of Schottky diodes and ceramic capacitors are assumed due to low forward bias voltage and low value of the internal resistances.

Table 1. Design Parameters.

PARAMETERS	VALUE	UNIT
L	4.7	µH
C	10	µF
DUTY CYCLE	%45	-
T_{PERIOD}	11.23	µs
V_F	0.5	V

5. Simulation Results

As a simulation environment, MATLAB/Simulink is used with SimScape tools. Simulation is made for 3.45 Ah 3.6V nominal Panasonic 18650GA Li-Ion cells. The simulations are made under the condition of heavy load and very low load to observe behavior of the cells easier. For this simulation, maximum voltage difference is 50 mV and acceptable voltage difference is 25mV. The voltage of the top cell is accepted as high energy cell for this simulation.

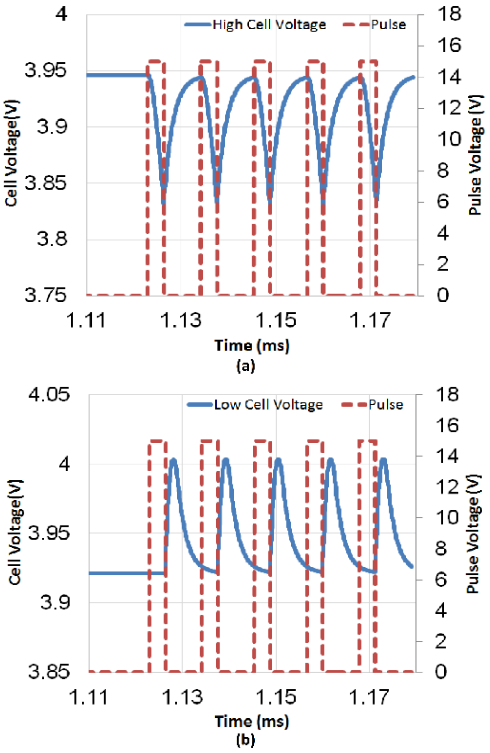

Figure 12. (a) High cell and switch control voltages. (b) Low cell and switch control voltages.

In Fig.12 (b), low cell voltage and switch control voltage are plotted. When the switch is closed, low cell keeps its voltage. When the switch is opened, low cell gains some energy from the inductor instantaneously.

As illustrated in Fig.13, the inductor is charged during t_{on} and discharging during t_{off}. The total area under the current on the inductor shows how much charge is transferred in a cycle. As seen from (3), the current on the inductor or also called as the balancing current is dependent on the cell voltage which charges the inductor. Since balancing system is only activated in the range of 2.8V and 4.2V of cell voltages due to keep them in safe levels, maximum balancing current is reached where high cell is at 4.1V. In this case, the maximum balancing current is chosen 4.1A. The simulation results shows the peak current is approximately 4A for given cell voltages.

While inductor discharging, the current of the diode that locates parallel to lower cell, tells us the diode turns current direction to the lower cell as shown in Fig.14.

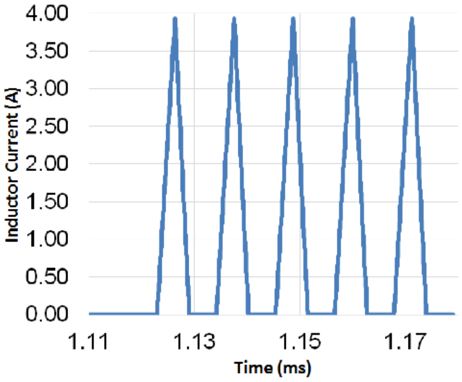

Figure 13. Current of the inductor during balancing.

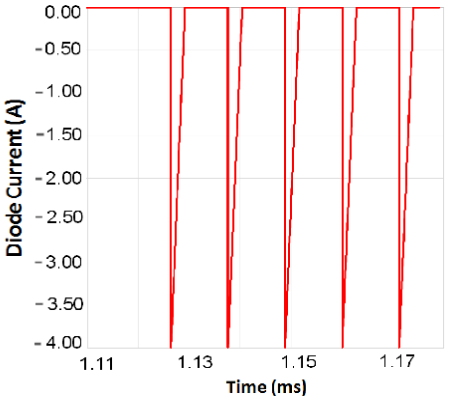

Figure 14. Current of the diode while balancing.

Under low load, two cells initially at 72% and 89% SoCs are balanced in about 147 sec as shown in Fig.15. Two distinct regimes can be seen in the voltage profiles for both of the cells. During balancing, higher cell voltage drops while energy is transferred to the lower cell, which is accompanied by the low cell voltage being increased. Then there can be seen a flatter region where the balancing stops. For the low load condition as depicted in Fig.15, this corresponds to a recovery in the voltage of the higher cell whereas the voltage drops slightly for the lower cell. This is due to the capacitance of the cells and can be interpreted as the relaxation of the batteries after charge/discharge conditions.

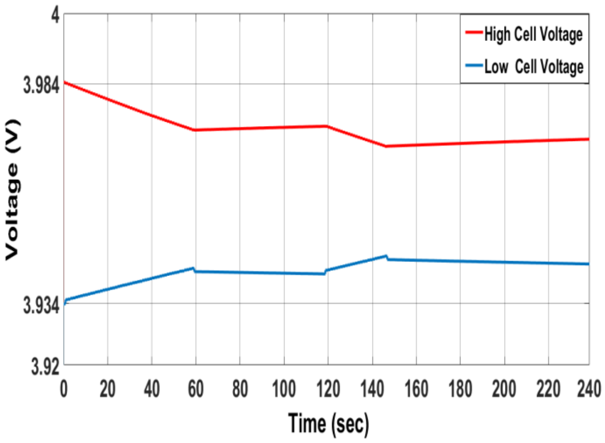

Figure 15. Cell voltages under low load.

Furthermore, the circuit is processed under heavy load conditions. Since load is higher than balancing current shuffled between the cells, both cell voltages decreases as shown in Fig.16. The balancing lasts approximately 127 sec. After the balancing stops both cell voltages are observed to drop linearly as imposed by the load.

6. Conclusion

In conclusion, an equivalent circuit model of 3.45 Ah Panasonic 18650GA is obtained. Even though we neglect aging effect, the error between model and experimental data is small at some SoC ranges. By using model of the battery cells, proposed battery cell balancing circuit is examined.

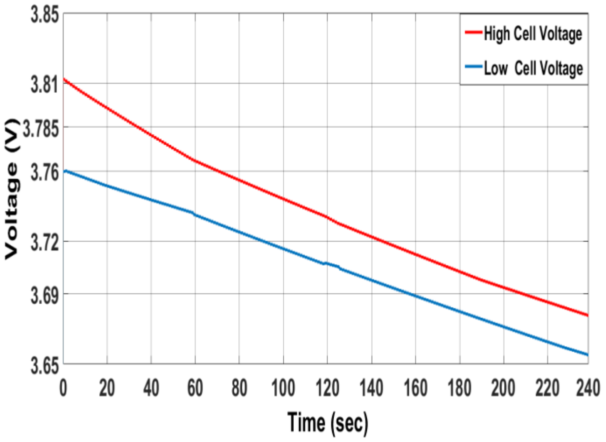

Figure 16. Cell voltages under heavy load.

A control algorithm is developed to activate balancing operation and to prevent any failures in balancing operation for 2 cells. The circuit is simulated under low load and high load in MATLAB/Simulink. The voltage behaviors of the cells and the current on the inductor are observed. The simulation results indicates that 25 mV difference is closed approximately in 147 seconds under low load and 127 seconds under high load where the maximum balancing current 4A for given SoCs of the cells. Also under heavy load, proposed circuit succeeds to balance cells. As all other energy converters, the proposed circuit faces with high number of components and complex control especially for more cells.

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Conflict of Interest

No conflict of interest was declared by the authors.

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