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Switched-Capacitor Cell Balancing: A Fresh Perspective

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Abstract

No two battery cells can be identical. Charging/discharging a battery pack without monitoring cell voltages or SoC (State-of-Charge) will cause cell voltages to deviate over time and the packs useable capacity to decrease quickly. To redistribute charge uniformly among cells, various cell balancing methods have been proposed in the literature. In this paper, a cell balancing method based on a single switched-capacitor is presented from a brand new perspective. Unlike the traditional balancing methods that rely on the voltage divergence criterion, this paper uses the SoC divergence criterion to shuttle charge from a highly charged cell to a poorly charged cell. Moreover, an equivalent resistance of the single-switched capacitor topology is derived in steady state. For fast cell balancing, design guidelines are provided for selecting a proper switching-time period and the capacitor parameters. Ultracapacitors are recommended to achieve this goal. To demonstrate the effectiveness of the proposed method, numerous simulations are performed on a string of five series connected Lithium-ion cells that have different initial SoCs and electrochemical parameters. Finally, the simulation results are compared with that of a traditional balancing method.

Introduction

Electric and hybrid electric vehicles use Li-ion battery packs that are made up of long strings of cells. These cells are connected in series to achieve higher operating voltages and in parallel to achieve the desired capacity. Not all of the cells in a battery pack are created equally even if they belong to the same manufacturer, model, or the batch of production. There always exist small differences in their internal characteristics such as ([9]):

- voltage
- capacities
- capacity fade rates
- internal impedance
- state-of-charge (SoC)
- charge rates and
- self discharge rates

One of the key external factors effecting the uniformity of the cells is attributed to a non-uniform distribution of temperature. Numerous charging and discharging cycles will also cause cell voltages to drift over time and the pack's useable capacity to decrease quickly. For example, during a charging cycle, cells with lower capacity or higher internal impedance tend to exhibit higher voltage than the rest of the series-connected cells. Once these cells have reached their maximum charge, they undergo overcharging until the remaining cells in the chain reach their maximum charge. This results in temperature and pressure build up leading to possible damage to the cells. While discharging, since the weaker cells exhibit lower voltage than the other cells, they reach the cell under-voltage protection limit faster while the other cells in the pack have sufficient remaining energy. This results in a reduction of the pack's overall usable capacity.

To increase the battery pack capacity and to prevent premature battery failures, the battery management system employs various cell balancing techniques. In general, these techniques can be broadly categorized into two types: Passive and active balancing. The passive balancing technique selectively shunts the current around each cell as it becomes fully charged through bypass resistors during a charging cycle [13, 15]. Although this technique is simple and straightforward, a substantial amount of energy is lost as heat in shunt resistors.

The wasting of energy is effectively leads to overall lower system efficiency, counterproductive to the idea behind electric vehicles.

Active balancing techniques on the other hand, remove charge from a higher voltage cell, store that charge and then deliver it to a lower voltage cell using active energy storage elements such as capacitors and inductors and flyback DC-DC converters [5, 7, 8, 10]. There are two key benefits to the active balancing system. The first benefit is the amount of energy wasted as heat is reduced to only the losses in transferring energy from the battery system to an individual cell. The second benefit is that the balancing can continually operate during the discharge cycle, allowing for continuous balancing that could ultimately lead to longer battery life. A possible downside to this scheme is that the system could continually run during the discharging of the batteries, effectively reducing the amount of power that could be delivered to the load. While the system is potentially having a beneficial effect on the battery system, this extra power consumption has the possibility to have a small detrimental impact. This problem can be remedied through the use of an intelligent control scheme that recognizes when the balancing action is not required. Among various active balancing methods, capacitor cell balancing methods are widely used in various applications for their simplicity and scalability. There are several embodiments of capacitor cell balancing methods in the literature [14, 11, 4, 12].

This paper focuses on a single-switched capacitor cell balancing method. The rest of the paper is organized as follows: Unlike in the traditional balancing methods that rely on the voltage divergence criterion, this paper uses the SoC divergence criterion for balancing. Consider a pack of cells; SoC divergence of the pack at time t, ΔSoC (t), is defined as follows:

$$\Delta\mathrm{SoC}(t) \quad = \quad \mathrm{Max.~SoC}(t) - \mathrm{Min.~SoC}(t).$$

Section II describes the proposed SoC-based capacitor cell balancing method. If the design parameters are chosen in an ad-hoc manner, the switched-capacitor cell balancing method may take long hours to balance cells. Section III provides relevant guidelines to choose the design parameters appropriately for fast balancing. Section IV demonstrates the effectiveness of the proposed method through numerous simulations that are performed on a string of five series connected Lithium-ion cells that have different initial SoCs and electrochemical parameters. The results are compared with a traditional balancing method. The final section of the paper concludes with remarks.

SoC-Based Single Switched Capacitor Balancing

Fig. 1 shows a schematic diagram of four switches being used to balance two cells in series. The two cells are shown with voltages V_1 and V_2. The balancing capacitor (C) enables the transfer of charge from the highly charged cell to the weakly charged cell. This two-cell topology can be scaled as needed to balance more cells in a series string. In order to balance n number of cells, this topology requires a single capacitor and $2n$ number of MOSFET switches.

Balancing can be performed based on two types of divergence metrics: (i) Voltage divergence (ii) SoC divergence. The easiest approach to balance cells is to use the terminal voltage divergence as the balancing criterion [3]. If $V_1 > V_2$, turning on the switches S_1 and S_2 and turning off the switches S_3 and S_4 charges the capacitor. Once the balancing capacitor is charged, turning on switches S_3 and S_4 and turning off switches S_1 and S_2 make the capacitor to pump the stored charge to the low voltage cell V_2. Turning on and off is done at a fixed high frequency.

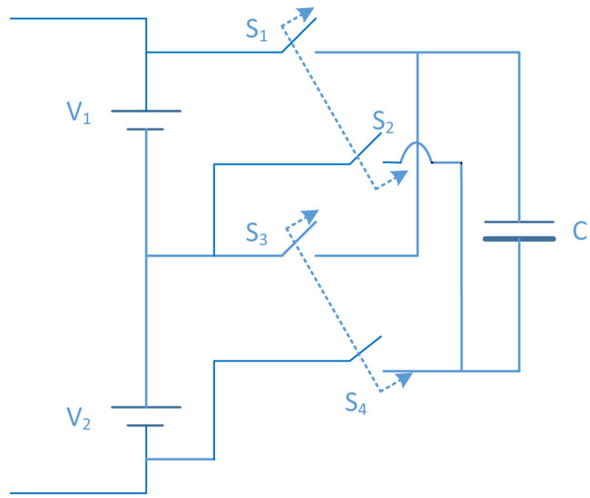


Figure 1. Single switched-capacitor topology for balancing two cells

Cell balancing happens automatically without a need for sensing or control- current always flows from higher to lower voltages.

Since the objective of cell balancing is to ensure that all the cells have the same SoC, and in general, the SoC has a 1-to-1 relationship with the open circuit voltage (OCV) of the battery cell, cell balancing based on the OCV divergence criterion is considered as a more effective method than that using the terminal voltage divergence criterion. The terminal voltages of the cells with the same SOC will vary significantly from the each others' OCV due to different internal impedances. Only if the balancing current is small or the cells are at rest, the terminal voltages can be approximately equal to the OCVs. Under load, the OCV cannot be measured directly and it has to be estimated instead. In practice, OCV estimation is challenging in a mid SoC range because in this region, the OCV is almost flat. For this reason, relying on OCV estimates alone cannot guarantee that all cells will reach 100% capacity at full charge.

Practical SoC estimation methods estimate the SoC by systematically combining the OCV-based SoC estimation with Coulomb counting for increased accuracy and robustness. For example, the author in [2] estimates the SoC based on the regressed OCV and Coulomb counting depending on the current SoC operating range. Motivated by this highly accurate combined SoC estimation methods, in this paper, we propose cell balancing based on the SoC divergence criterion. Unlike the voltage-based balancing, this can also be performed at any time, during charging or discharging or even at idle. The proposed SoC-based cell balancing method is shown in Fig. 2. This method stops balancing if it detects a SoC divergence of 2% or less between any two cells.

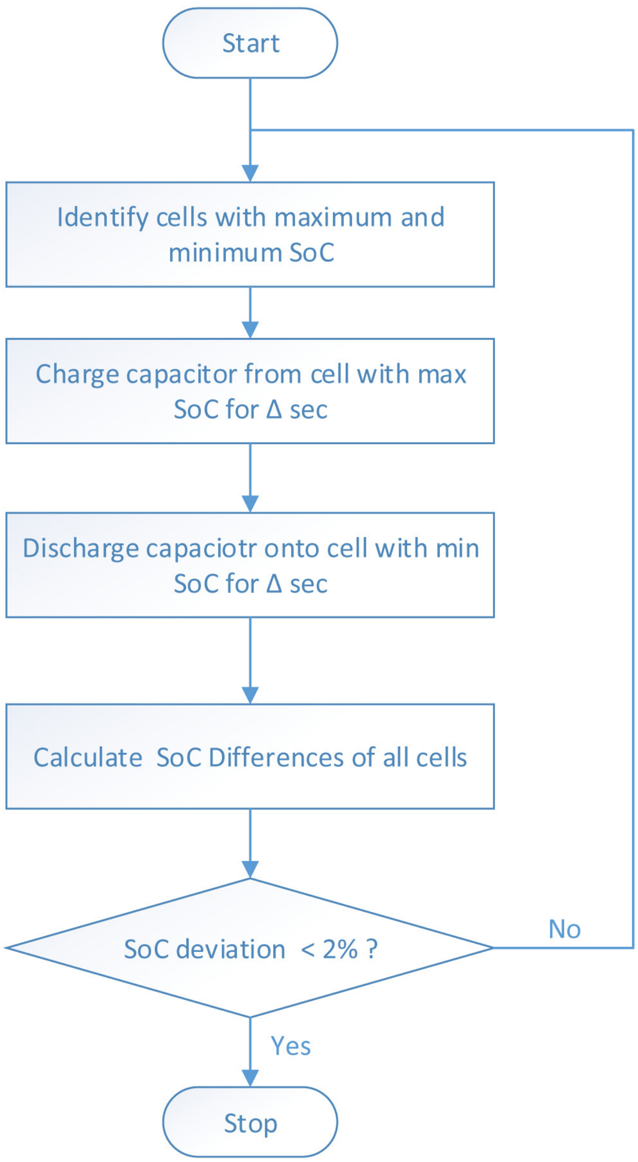


Figure 2. Flowchart for SoC-based cell balancing

Choosing Design Parameters for Fast Balancing

This section presents a method to choose design parameters such as the capacitor (C) and the switching time period (T_s = 2Δ) for fast balancing. Consider a voltage source/battery-capacitor-resistor circuit as depicted in Fig. 3. The resistor R is used to model the capacitor's equivalent series resistance (ESR), switch resistances and various other physical connections. When the switch S is closed, using Kirchoff's voltage law, we write

$$V_b \quad = \quad V_c + RI_c. \tag{1}$$

Because the current flowing through the capacitor $I_c \ = \ C\dot{V}_c$, we write

$$V_b \quad = \quad V_c + RC\dot{V}_c. \tag{2}$$

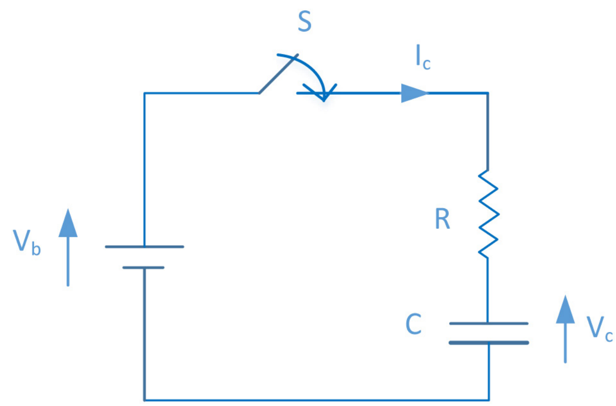


Figure 3. A Simple R-C circuit

Rearranging (2) yields

$$\tau\dot{V}_c \quad = \quad V_b - V_c, \tag{3}$$

where the time constant τ is $\tau = RC$. Hence, the general solution to the ordinary differential equation (3) can be expressed in the following form:

$$V_c(t) \quad = \quad Ae^{-t/\tau} + B, \tag{4}$$

where A and B are unknown constants. Applying the initial and end conditions at times $t = 0$ and $t = \infty$, respectively, in which the capacitor voltages are assumed to be V_0 and V_b, we get

$$V_c(t) \quad = \quad V_b + (V_0 - V_b)e^{-t/\tau}, \tag{5}$$

Referring to the switched capacitor circuit in Fig. 1, if the switches S_1 and S_2 are closed while S_3 and S_4 are open, then $V_0 = V_L$ and $V_b = V_H$, where V_L and V_H are the capacitor voltages at the beginning of a switch cycle and after the capacitor has been charged for Δ seconds (at the middle of a cycle), respectively (see Fig. 4). Hence, we get

$$V_H(t) \quad = \quad V_1 + (V_L - V_1)e^{-\Delta/\tau}. \tag{6}$$

Similarly, when the capacitor is allowed to discharge on to the cell with voltage V_2 for the next Δ seconds, we get $V_b = V_2$ and $V_0 = V_H$. In this case, (5) becomes

$$V_L \quad = \quad V_2 + (V_H - V_2)e^{-\Delta/\tau} \tag{7}$$

In a steady state, the capacitor voltage is periodic, i.e., $V_c(t + 2\Delta) = V_c(t)$, because the battery voltages are assumed to be constant and the amount of charge provided to the capacitor by the high voltage battery is equal to the amount of charge supplied by the capacitor to the low-voltage battery. Solving (6)-(7) for V_L and V_H yields

$$V_L = \frac{e^{-\Delta/\tau}V_1 + V_2}{e^{-\Delta/\tau} + 1} \tag{8}$$

$$V_H = \frac{e^{-\Delta/\tau}V_2 + V_1}{e^{-\Delta/\tau} + 1} \tag{9}$$

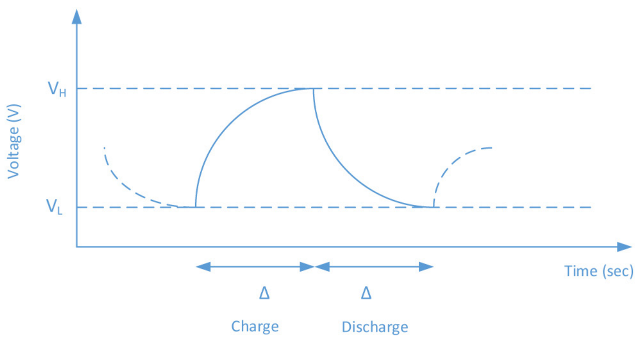


Figure 4. Voltage swing of the balancing capacitor during charging-discharging cycle

The current flowing through the cell and the capacitor is given by

$$I_c(t) = \left(\frac{V_b - V_0}{R}\right)e^{-t/\tau} \tag{10}$$

The average current provided to the capacitor is given by

$$\begin{aligned} \hat{I} &= \frac{1}{\Delta}\int_0^{\Delta} I_c(t)dt \\ &= \frac{1}{\Delta R}\int_0^{\Delta} (V_b - V_0)e^{-t/\tau}dt \\ &= \frac{C}{\Delta}\Big(V_b - V_0 - (V_b - V_0)e^{-\Delta/\tau}\Big) \end{aligned} \tag{11}$$

Because $V_0 = V_L$ and $V_b = V_H$, substituting (9) and (8) into (11) yields

$$\hat{I} = \frac{(V_1 - V_2)}{R_{\text{eq}}}, \tag{12}$$

where the equivalent resistance

$$R_{\text{eq}} = \frac{(1 + e^{-\Delta/\tau})}{(1 - e^{-\Delta/\tau})}R. \tag{13}$$

For fast balancing, R_{eq} should be as small as possible so that a small voltage difference will produce a large balancing current. Also note that from (12) that the balancing current reduces as V_2 approaches to V_1.The equation (13) is a monotonically increasing function of Δ and has a minimum value of $2R$ at $\Delta = 0$. This implies that the switching time period has to be zero for fast balancing. The minimum of R_{eq} is limited by the parasitic resistances in connections, switches and the capacitor, which can not be entirely eliminated. However, the switching time period can be chosen to be low and/or C can be chosen to be large to approach the minimum R_{eq}.This suggests that an ultracapacitor is a good candidate for fast charge shuttling. Indeed, without a theoretical motivation, ultracapacitors have been used previously in cell balancing [6]. If we choose Δ to be $\Delta < \tau$, then $R_{eq} \leq 2.16R$, which implies R_{eq} lies within 8% of its minimum value.

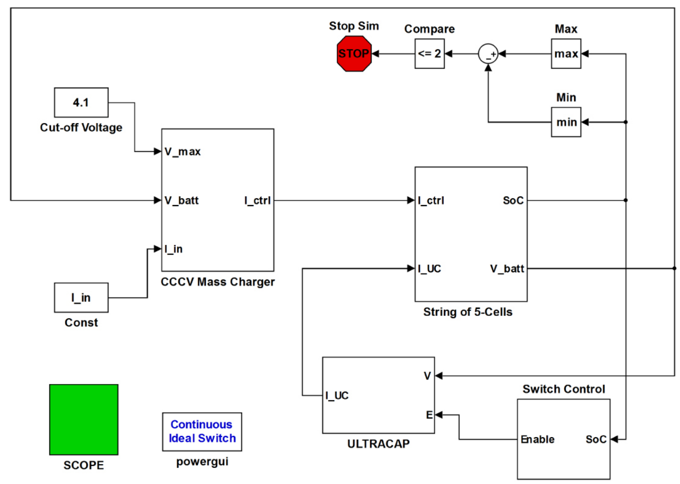
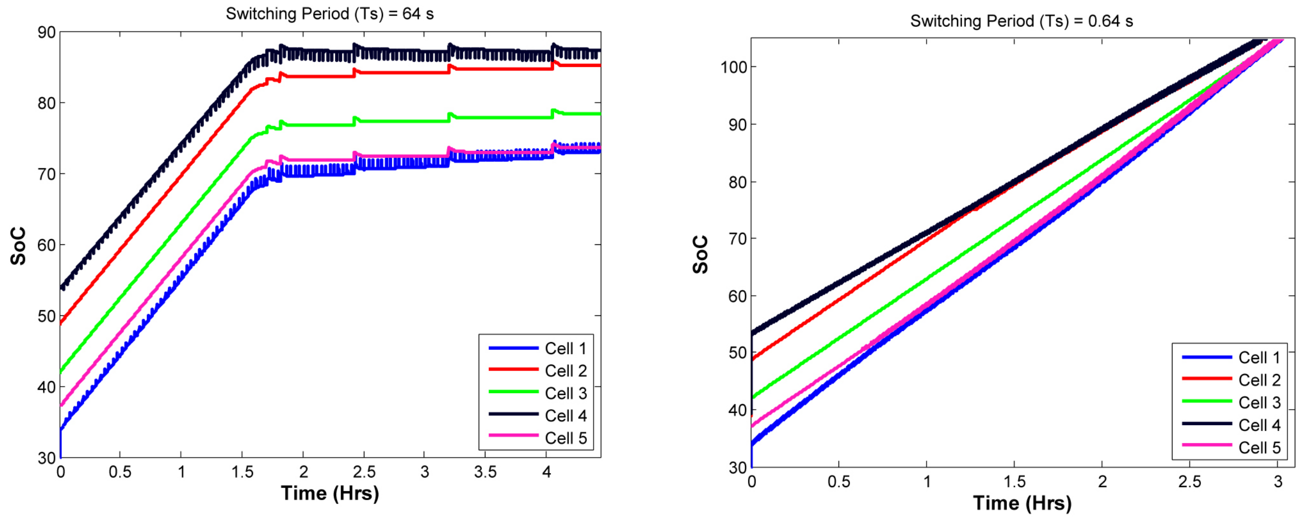


Figure 5. Matlab/Simulink block diagram used to implement the SoC-based switched-capacitor cell balancing method

Computer Experiments

This section presents simulation results for two different scenarios: (i) First, we demonstrate that the speed and the efficiency of the switched capacitor cell balancing can be greatly improved by choosing high frequency switching (see Section III for a theoretical motivation) (ii) We validate the effectiveness of the cell balancing method using SoCs and compare it with that using cell voltages. Fig. 5 shows an overview of the Matlab/Simulink used to simulate the switched-capacitor cell balancing method. Li-ion cells were modeled using electrochemistry as described in [1]. A set of five cells was connected in series and charged by a mass charger. The charger uses the CC-CV (Constant Current Constant Voltage) protocol to maintain a safe operating range for voltage. The switch control block in Fig. 5 generates an enable signal to choose one of the cells for charging/discharging based on the SoC (as explained by the flowchart in Fig. 2). For our simulation, a constant charging current of 1A was used to charge the cells. The capacitance of the balancing capacitor was set to be $C = 16$ F whereas it's ESR was set to be 0.2Ω. In this case, the time constant of the capacitor is 3.2s (= 16 × 0.2).



(a) $T_s = 64\text{s}$ (b) $T_s = 0.64\text{s}$

Figure 6. Effect of Switching Time on Cell Balancing During Constant Current Charging

In the first scenario, the simulation was conducted for two different switching time periods- T = 64s and 0.64s. The cell SoCs were utilized for cell balancing. The initial SoCs of five cell were set to be 34%, 48%, 42% 53% and 37%. The results are shown in Figs. 6(a)-6(b). For the shorter time period case, the cells quickly converge to the cut-off condition approximately in 3 hours (i.e., stop balancing if $\Delta SoC < 2\%$) whereas in the longer switching time period case, the cells struggle to converge even after 4.4 hours. Indeed, as shown in Fig. 7, for the T = 64s case, ΔSoC is almost equal to 14% at the end of the experiment. It is also observed from Fig. 7 that shorter the switching time period is, less the SoC swing becomes.

In the second scenario, to compare the proposed SoC based cell balancing method with the traditional voltage-based cell balancing method, the internal resistance of the cell electrodes were also assumed to be different and set to be 100, 20, 80, 10 and 60 mΩ, respectively. As shown in Figs. 8(a)-8(b), the SoC-based cell balancing method seem to converge faster than the cell voltage method. As can be seen from Fig. 9, ΔSoC is approximately 1-1.5% less than that of the voltage based method throughout charging. Also, as can be seen from Fig. 9, the SoC method has less SoC fluctuation than the voltage method. In brief, the simulation results substantiate that a shorter switching time period and the SoC-based balancing criterion can significantly improve the performance of switched-capacitor cell balancing.

Concluding Remarks

In this paper, a switched-capacitor cell balancing method was presented from a brand new perspective. Unlike the traditional balancing methods that rely on cell voltages, the cell SoC was utilized in this paper to shuttle charge from a highly charged cell to a poorly charged cell. An equivalent resistance of the single-switched capacitor topology was derived in steady state. For fast cell balancing, ultra capacitors are recommended as they have higher capacitance and lower equivalent series resistance. Moreover, the theory and the computer experiments have shown that decreasing the switching time period reduces SoC swing during balancing and shortens the time taken to minimize SoC divergence. Moreover, computer simulations reveal that the SoC-based cell balancing method outperforms the traditional voltage-based method especially when cells have different electrochemical parameters. That is, SoC-based balancing reduces not only the balancing time but also SoC divergence at the end of charging.

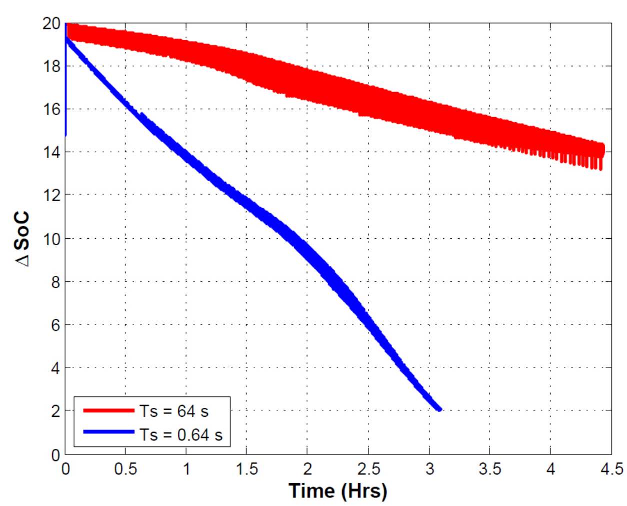
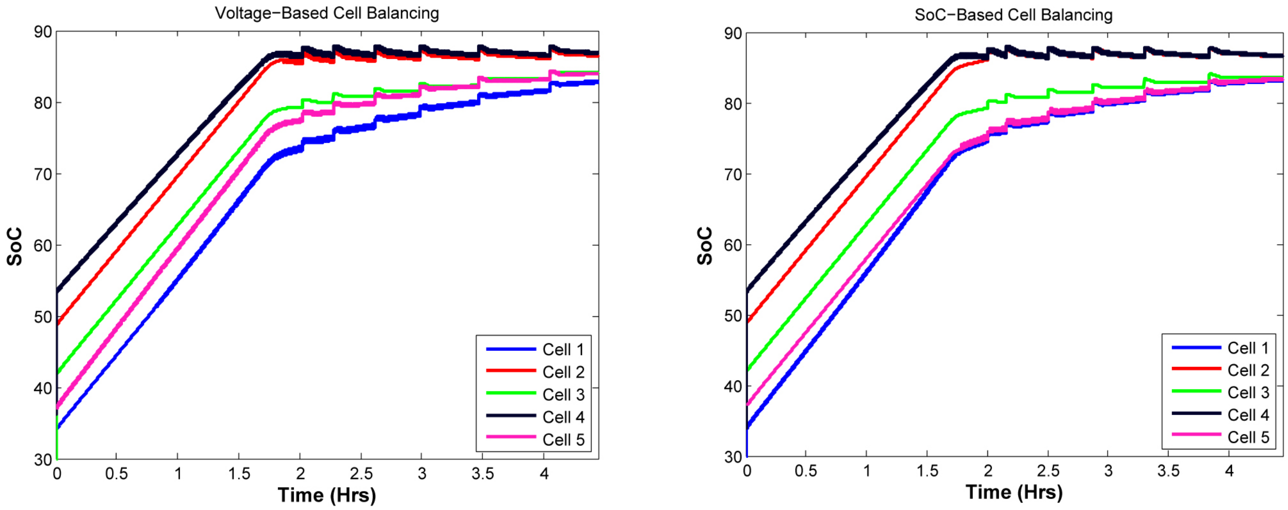


Figure 7. SoC Divergence (ΔSoC) Plot For Two Different Switching Time Periods (T_s)



(a) Voltage Based

(b) SoC Based

Figure 8. Comparison of Two Types of Divergence Criteria Used in Cell Balancing

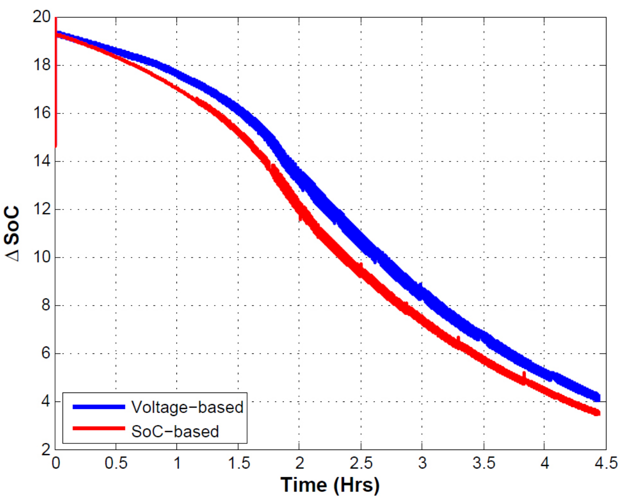


Figure 9. SoC Divergence (ΔSoC) Plot for Two Different Cell Balancing Criteria

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