Energy Conversion Circuit Laboratory

A Single-Capacitor Equalizer Using Optimal Pairing Algorithm for Series-Connected Battery Cells

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Abstract - In a series string, the behaviors of batteries are different due to mismatch of impedance, initial state-of-charge, and self-discharging rate. Among various equalization methods, the switched-capacitor equalizer seems to be the most promising method due to automatic equalization, low-cost, and small size. However, the equalization speed becomes slower and the power loss gets higher when the number of series cell increases. This paper proposes an equalizer that uses only one capacitor and a fishbone-shaped switch-matrix to transfer energy between any cells by an optimal pairing algorithm that makes the switching decision. By adopting one extra current sensor, the equalization speed increases while the power loss is reduced. For verification, simulations for six series-connected 18650 Li-ion battery cells have been implemented, which shows that the state-of-charge of all cells are equalized within 4% difference with high speed and the total power loss in the equalizer is reduced to 52% of conventional methods.

Keyword: Optimal pairing algorithm, state of charge (SOC), switched-capacitor (SC) equalizer, series-connected battery, SOC equalization.

1. INTRODUCTION

In order to increase the system voltage range, low voltage battery cells are connected in series. However, the characteristics of battery cells are different from each other due to the imbalance between cells impedance even under the same operating condition. Fig. 1 shows the inconsistency issue in series cells during a charging and a discharging process. To overcome the inconsistency issue in series-connected battery configuration, various battery equalization techniques are reported in [1]. Among them, the converter-based and the inductor-based equalization techniques show high performance with fast speed and high equalization performance. However, the practical applicability of them is rather low due to the bulky and weight of the magnetic component, and the system cost.

On the other hand, switched-capacitor equalizer seems to be the most promising technique due to its simplicity. However, the equalization speed of the classical-structure switched capacitor equalizer [2] is rather slow and the power loss is considerable because of the pulsed equalization current. In [3], a double-tiered structure is proposed to reduce the equalization time. Similarly, a chain-structure is presented, which uses four extra switches and one capacitor to transfer energy between the first and the last cell in the series string [4]. A star-structure in [5] proposes a multi-port gateway to transfer energy from any-cell to any-cell, which connects all capacitors into the same pole. Anyway, even though the equalization time is significantly reduced by these switched capacitor topologies, the component count and power loss increase dramatically as the number of series connection increases. Besides, the equalization process is non-stoppable due to lack of monitoring device, which causes unnecessary switching loss.

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To mitigate these limitations, this paper proposes a single-capacitor equalizer for a series-connected battery string. The equalization structure and the optimal pairing algorithm are described in Section 2, the verifications are performed in Section 3, and the conclusion is made in Section 4.

2. PROPOSED ARCHITECTURE

2.1. *Conventional switched-capacitor equalizer*

In conventional SC structures, each battery cell is connected with two series-connected switches and one capacitor serves as a carrier to transfer the charge between two adjacent battery cells. The classical structure in Fig. 2(a) has a single-tiered structure of the series-connected capacitors. All S_iH and S_iL switches are alternately turned ON at the same time by two complementary PWM signals. Between two states, there should be a short dead-time period to protect the capacitor and prevent short-circuit between the battery terminals. Although the energy is transferred between adjacent cells automatically, it takes a long time to transfer energy from one cell to far away cell. In a similar fashion, additional tiers of capacitors can be added to the classical structure to reduce the equalization time, which constructs a double-tiered

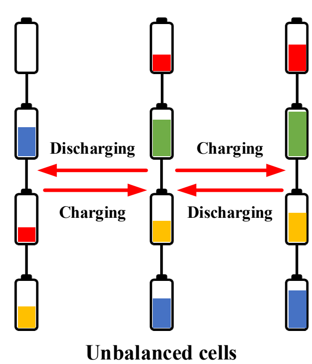


Figure 1: *Possible inconsistency in series-connected battery.*

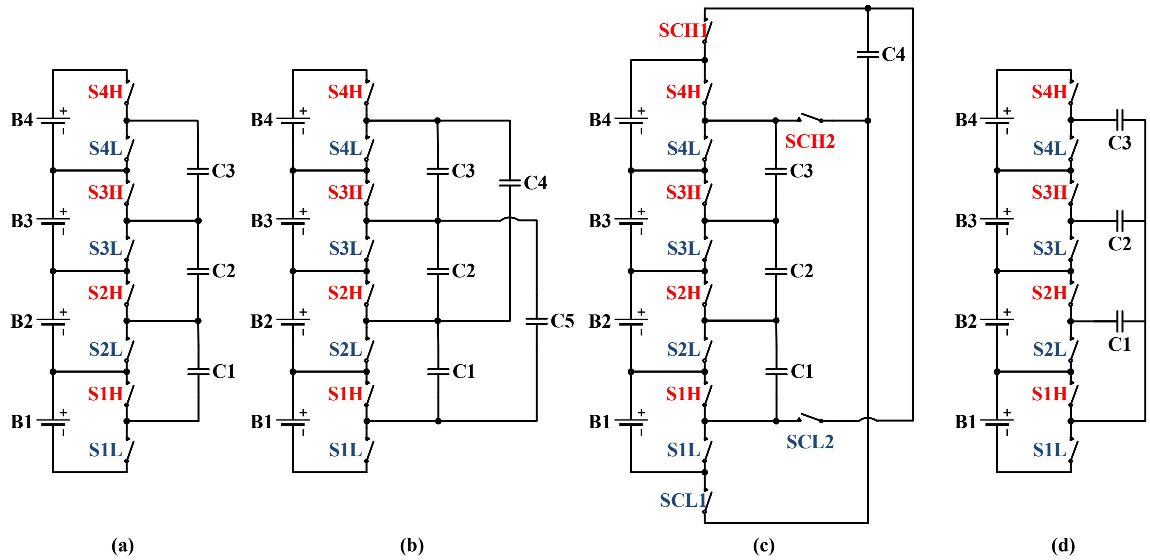


Figure 2: *Conventional SC equalizers - (a) classical structure, (b) double-tiered structure, (c) chain structure, and (d) star structure.*

structure as in Fig. 2(b). This structure significantly reduces equalization time but the component count increases instead. Meanwhile, the structure in Fig. 2(c) appends four additional switches and one capacitor to transfer energy from the first to the last cell in the series string. Although, the average distance between cells reduces to a half, the equalization performance is still low because there is only one circulating flow of energy transfer. On the contrary, the capacitor network of the star structure in Fig. 2(d) creates a multi-port gateway to transfer energy between any-cells by keeping one pole of the capacitors as a common node.

Generally, the performances of SC equalizers are dependent on initial SOC rates and the relative position of cells in the series string. The worst-case scenario happens when the highest SOC and the lowest SOC cells are located at two opposite ends of the series string, where the charge from the highest SOC cell has to be transferred to the lowest SOC cell through a maximum number of adjacent cells. As a result, the efficiency and the performance of the equalizer decrease as the series connection increases. Furthermore, although the battery voltages are equalized after the long period of equalization process, the SOCs of all cells tend to be mismatched due to the hysteresis effect caused by repeated battery charging and discharging cycles during the equalization process.

2.2. *Proposed single-capacitor equalizer*

The proposed method is inspired by the switch-matrix equalizer in Fig. 3, which is patented by Motiv Power System, Inc [6]. The voltages of battery cells are monitored by a multi-channel battery monitoring integrated circuit (BMIC). Besides, multiple current sensors are coupled to battery cells to measure the process currents. By utilizing the measured information, the SOC rates of battery cells are estimated, and then, based on the SOC rate of cells, a combination of donor and receiver cell is decided to equalize the energy through a switch-matrix and one capacitor. Thus, the charge is transferred directly between any-cells. However, multiple voltage and current sensors are required to operate it.

The proposed SC equalizer has a similar structure as shown in Fig. 4. But, instead of multiple voltage and current sensor, only one bi-directional current sensor is adopted to measure the equalization current, which is fed into the optimal pairing algorithm to be proposed. The equalization process is divided into two separated steps as shown in Fig. 5. The equalization capacitor, C, alternately connects with each battery cells through the corresponding switches, S_iH and S_iL, in the matrix to observe the process current flowing between the host and the guest cells during the scanning time, Tm. The optimal combination is decided by the algorithm that will be explained in section 2.3, and the chosen host-guest pair is equalized during the equalization time, T. In the proposed structure, the equalization speed is fast because the energy is directly transferred from any cell to the other cell. Furthermore, it reduces the power loss by involving only four switches in one cycle of the equalization process.

The topology comparison in Table I shows that the proposed equalizer requires fewer component counts than the conventional SC equalizers in Fig. 2 and the complexity of the proposed circuit is simpler than the conventional switch- matrix method in Fig. 3. What's more, the other cells are not involved in the energy transferring, which eliminates the hysteresis effect. As a result, the battery cells have enough time to recover its steady-state cell voltage, which helps the enhancement in

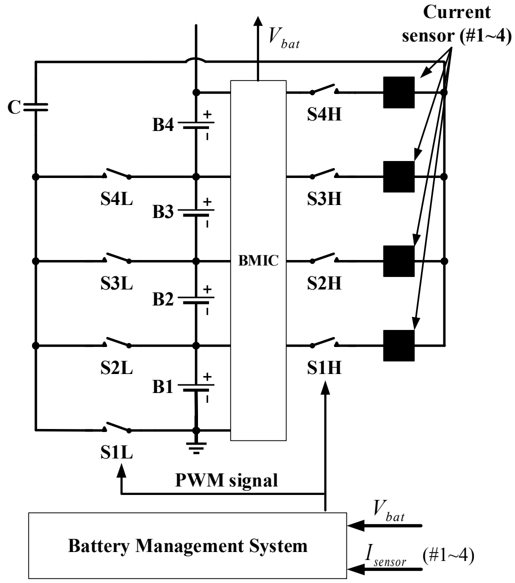


Figure 3: *Conventional switch-matrix equalizer.*

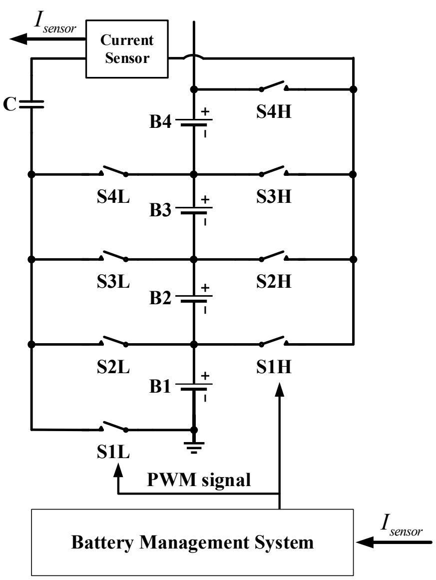


Figure 4: *Proposed equalizer structure.*

Table I: *Topology comparison.*

	Total switches	*Capacitor*	*Activated switches*	*Current sensor*
Classical	*2N*	*N – 1*	*2N*	-
Double-tiered	*2N*	*2N – 3*	*2N*	-
Chain	*2N+4*	*N*	*2N + 4*	-
Star	*2N*	*N – 1*	*2N*	-
Switch-Matrix	*2N*	*1*	*4*	*N*
Proposed	*2N*	*1*	*4*	*1*

**N: number of the series-connected battery cells.*

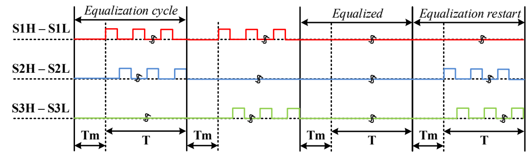


Figure 5: *Switching patents in the equalization process.*

the equalization speed as well as the accuracy of SOC estimation.

2.3. *Optimal pairing algorithm*

To achieve optimal performance, a dynamic pairing algorithm is also proposed in Table II. The equalization cycle starts with a current scanning step. Every battery cell is sequentially associated each other for a short interval, T_m, to measure the initial equalization current for each battery pair. For example, the host cell #1 and the guest cell #2 are selected to observe I_{12}; and then cell #1 with cell #3 for I_{13}, and cell #1 with cell #n for I_{1n}. After cell #1 is paired with all other cells, cell #2 becomes the host and I_{21}, I_{23}, … I_{2N} are recorded in the memory. When all the pairing combinations are scanned, the upper diagonal matrix of the absolute value of the equalization currents, what is called equalization current matrix, is constructed as Table III.

Next, the comparison and selection process are executed to choose a pair of cells which shows the largest equalization current in the current matrix. Finally, the complementary PWM signals are sent to the corresponding switch-pair in order to equalize the two cells. This energy transferring process continues during a predefined time interval, T, before another new equalization cycle repeats. Eventually, the whole equalization process stops when every element in the equalization current matrix are less than a cut-off current threshold, I_{min}, which mean the equalization of all cells are achieved. Among the three steps – current scanning, comparison and selection, and equalization - the current scanning and comparison steps are periodically repeated, but the equalization step resumes only when the any element in the equalization current matrix becomes larger than I_{min}.

3. VERIFICATION

3.1. *Performance indices for comparison*

When the conventional and the proposed equalizers are tested during the same operation time and under the same condition, the equalization performance can be evaluated by the degree of SOC equalization (DoSE) in (1) and the degree of voltage equalization (DoVE) in (2), where $\Delta SOC_{initial}$ and $\Delta V_{initial}$ are the SOC and voltage difference between the highest and the lowest cell in the initial time; ΔSOC_{final} and ΔV_{final} are the SOC and voltage difference between the highest and the lowest cell when the equalization process is stopped. Unity DoSE or DoVE means perfect equalization, while null DoSE or DoVE stands for no equalization. Because of the hysteresis effect, the SOC may still mismatch (low DoSE) even though the cell voltages are almost equalized (high DoVE), which is the reason why two indices are required:

$$DoSE = \frac{\Delta SOC_{initial} - \Delta SOC_{final}}{\Delta SOC_{initial}} \quad (1)$$

$$DoVE = \frac{\Delta V_{initial} - \Delta V_{final}}{\Delta V_{initial}} \quad (2)$$

Meanwhile, the equalization speed of equalizer is evaluated by the required time to achieve a 10% difference of SOC rate. The lower time has higher equalization speed.

3.2. *Simulation implementation*

To verify the proposed SC equalizer, simulations are implemented in Matlab/Simulink for six series-connected 18650 Li-ion battery cells. The original target cell has the capacity of 3.7V/2600mAh, but the capacity of the batteries in the simulation is scaled down by 100 times to 26mAh in order to reduce the simulation time and computation burden. The proposed and the conventional methods are applied to randomized initial SOCs in the worst-case order ($SOC_{1, 2, 3, 4, 5, 6}$ = *71, 83, 78, 77, 86, 93%)*. The switching frequency is set to 20kHz and the equalization capacitance is fixed to 470uF. The scanning time, T_m, and the equalization time, T, for the proposed method are set to 10ms and 5s. After 100 seconds, the equalization process is stopped and the performances of equalizers are calculated and presented in Table IV.

3.3. *Performance comparison*

The performance comparison table shows that the proposed method has good performance, which is almost equivalent to the conventional switch-matrix method by fewer sensors. Whereas, the conventional SC equalizers show relatively poor performance due to the worst-case condition and a large number of series connection.

The simulation waveforms of the classical, the double-tiered, the chain and the star structure are illustrated as Fig. 6, respectively. Evidently, in the conventional SC equalizers, the energy flows sequentially between cells so that each cell repeats charging and discharging cycles (current plot) to make an autonomous equalization (SOC and voltage plot). However, because battery cells have little time to recover the voltage, the difference of voltages (ΔV) instantly decreases then reducing the equalization current. That's why the equalization speed becomes further slow in the classical and the chain structure. For the same reason, the final differences of

***Table II:** Pseudocode of optimal pairing algorithm*

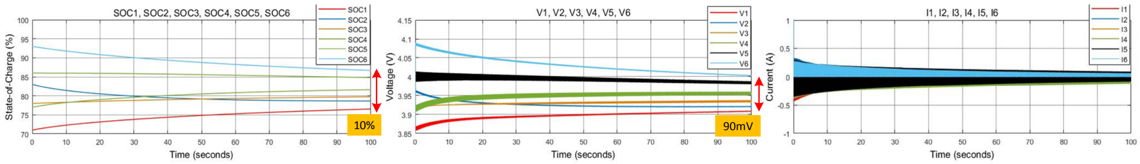
1	**Start the process.**
	Initialization
2	N ← "number of cells".
3	*T* ← "equalization time for each pair".
4	*Imin* ← "cut-off current".
5	Tscan ← "scanning time for each pair".
6	*Cur_scan* = *max_Cur* = 0.
7	*i* = *j* = *t* = *0*
8	*I[i][j]* = *0*
	Current scanning:
9	**Repeat** the following:
10	**If** *i* > N, terminate the repetition, **otherwise.**
11	*i* ← *i* + *1*
12	**Repeat** the following:
13	**If** *j* > N, terminate the repetition, **otherwise.**
14	*j* ← *j* + *1*
15	**If** *i* = *j* **then** *j* ← *j* + *1*; *P_host* ← *i*; *P_guest* ← *j*
16	**Repeat** the following:
17	**If** *t* > T_{scan}, terminate the repetition, **otherwise.**
18	command(*P_host*) ← *PWM1*
19	command(*P_guest*) ← *PWM2*
20	*I[i][j]* = absolute value of *Cur_scan*.
	Comparison & selection:
21	**Repeat** the following:
22	**If** *i* > N, terminate the repetition, **otherwise.**
23	*i* ← *i* + *1*
24	**Repeat** the following:
25	**If** *j* > N, terminate the repetition, **otherwise.**
26	*j* ← *j* + *1*
27	**If** *I[i][j]* > *max_Cur*
28	**then** *max_Cur* = *I[i][j]*,
29	*P_host_optimal* ← *i*; *P_guest_optimal* ← *j*.
	Equalization process:
30	*Δt* ← *"time counting"*
31	**Repeat** the following:
32	**If** *Δt* = *T*, terminate the repetition, go to line 8, *Δt* ← *0*, **otherwise.**
33	**If** *max_cur* less < *Imin*
34	**then** *command(P_host_optimal)* ← *0*
35	*command(P_guest_optimal)* ← *0*
36	**Elseif** *max_cur* > *Imin*
37	**then** *command(P_host_optimal)* ← *PWM1*
38	*command(P_guest_optimal)* ← *PWM2*
39	*Δt* ← elapsed time.

***Table III:** Equalization current matrix*

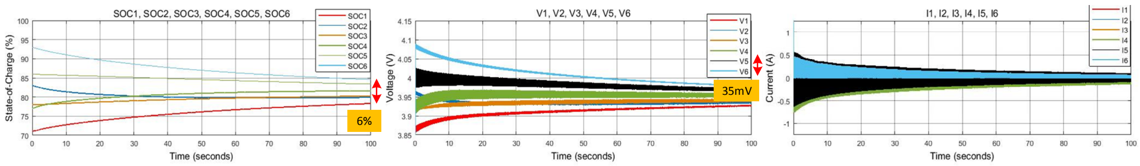
	B_1	B_2	B_3	…	B_N
B_1		$\lvert I_{12}\rvert$	$\lvert I_{13}\rvert$	…	$\lvert I_{1N}\rvert$
B_2	$\lvert I_{12}\rvert$		$\lvert I_{23}\rvert$	…	$\lvert I_{2N}\rvert$
B_3	$\lvert I_{13}\rvert$	$\lvert I_{23}\rvert$		…	$\lvert I_{3N}\rvert$
⋮	⋮	⋮	⋮		⋮
B_4	$\lvert I_{1N}\rvert$	$\lvert I_{2N}\rvert$	$\lvert I_{3N}\rvert$	…	

SOC (ΔSOC) are still high even after the battery voltages are almost equalized in the double-tiered and the star structure, which so-called hysteresis effect.

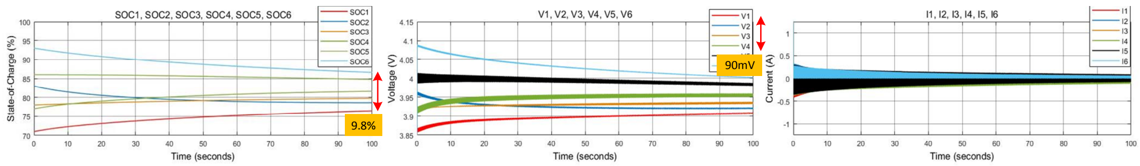
The simulation results of the conventional switch matrix and the proposed method are shown in Fig. 7 and Fig. 8, respectively. Because the equalization is executed between only two cells, the other cells have a sufficient



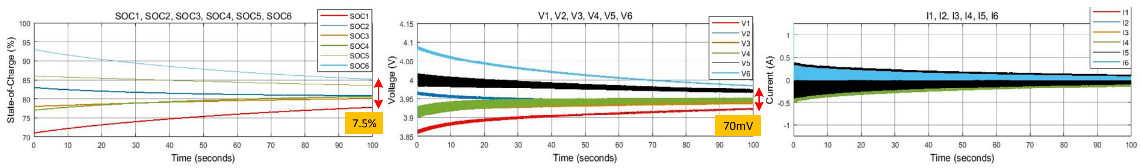
(a) Classical structure



(b) Double-tiered structure

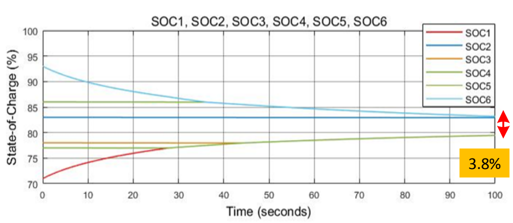


(c) Chain structure

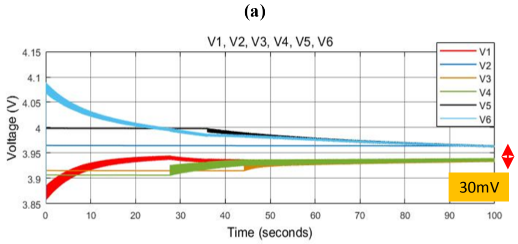


(d) Star structure

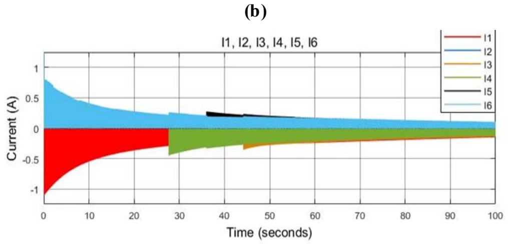
Figure. 6: *The simulation results of the conventional SC methods: state-of-charges (%), cell voltage (V), and branch-current (A)*



(a)

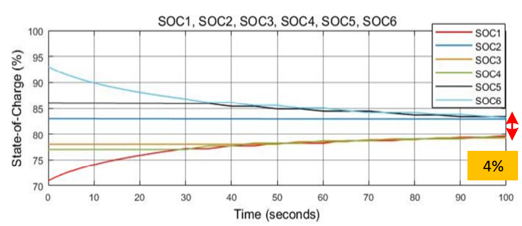


(b)

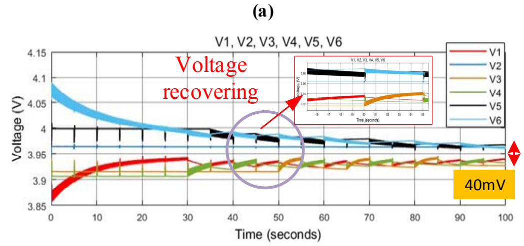


(c)

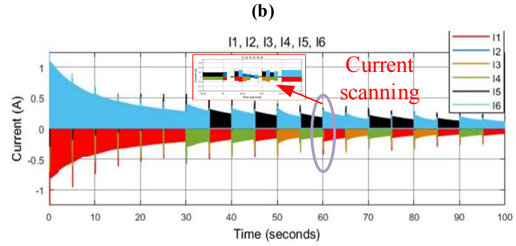
Figure 7: *Simulation result of the conventional switch matrix method: (a) state-of-charge (%), (b) voltage (V), (c) current (A)*



(a)



(b)



(c)

Figure 8: *Simulation result of the proposed method: (a) state-of-charge (%), (b) voltage (V), (c) current (A)*

Table IV: Equalization performance comparison

	Classic	Double-tiered	Chain	Star	Switch-Matrix	Proposed
$\Delta SOC_{initial}$ (%)	22	22	22	22	22	22
ΔSOC_{final} (%)	10	6.0	9.8	7.5	3.8	4.0
DoSE (%)	55	73	55	66	83	81
$\Delta V_{initial}$ (mV)	230	230	230	230	230	230
ΔV_{final} (mV)	90	35	90	70	30	40
DoVE (%)	61	85	61	70	87	83
P_{loss} (mW)	6.3	15.4	5.7	11.6	8.0	7.98
Time to achieve 10% ΔSOC (s)	100	52	94	65	28	30

time of rest to recover the steady state voltage during the idle time, which helps to alleviate the hysteresis effect and increase the DoSE index. The current profile of the proposed method in Fig. 8(c) shows the optimal pairing algorithm. Every other 5 seconds, the equalization currents are scanned and the host-guest pair is chosen. In this simulation, cell #1 and #6 are chosen during the first six equalization cycles. In the next cycle, cell #1 and #4 are chosen for optimal equalization current.

From the simulation results, the total power loss, P_{loss}, in the switches is calculated and compared also in Table IV. For the calculation, equivalent series resistance (ESR) of the equalization capacitor and the switching losses as well as the gate drive losses are ignored, and only conduction losses in the switches are considered where $R_{DS(ON)}$ of each switch is assumed to 50mΩ.

It is remarkable that the power loss in the proposed method is reduced dramatically because only four switches and two battery cells are working at the same time. From Table IV, the total power loss of the proposed method is reduced to 52 percent of the double-tiered SC and 69 percent of the star structure SC equalizer. The classical and the chain structure SC equalizer have lower P_{loss} because they have lower equalization current resulting poor DoSE. The equalization speed of the switch-matrix and the proposed method in Table IV are almost similar and higher than the conventional SC equalizers.

4. CONCLUSION

This paper proposes a single-capacitor SC equalizer with the optimal pairing algorithm. The proposed method uses only one capacitor and one fishbone switch-matrix to directly transfer energy from any cell to the other. The simulation results show that the SOCs are equalized within 4% and both the DoSE and the DoVE performance indices are over 80%. Besides, the total power loss of the proposed method is less than the star-structure or the double-tiered SC equalizers, and the equalization speed is faster than any other conventional SC equalizer. Moreover, the performance of the proposed method is almost equivalent to the conventional switch-matrix method although the component count and the complexity of the circuit are considerably reduced.

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