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Modularized Global Equalization of Battery Cells for Electric Vehicles

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***Abstract*— Battery management system has attracted mounting research attention recently, within which cell equalization plays a key role. Although many research and practices have been devoted to developing system-level structure of cell equalizers, there are still substantial opportunities for performance improvement yet to investigate. This paper proposes a novel architecture for battery cell equalization, referred to as modularized global equalizer. The mathematical model is developed to emulate the equalization dynamics by considering both charging/discharging and energy loss. Analytical formulas are derived to evaluate the performance of the global equalizer. The proposed method is also compared with the state-of-the-art structures in terms of equalization speed and energy loss.**

Keywords: Battery management system, cell, modularized global equalization, electric vehicle.

I. INTRODUCTION

The increasing demand for alternative energy sources to replace gasoline has triggered the development of battery technologies for electric vehicles (EVs). The recent advances in Lithium-ion batteries lead to a promising anticipation in terms of performance, cost and customer acceptance [1].

Due to the voltage and power limitation of individual battery cells, a battery pack in commercial applications often consists of multiple cells to satisfy the energy requirement. However, battery cells are manufactured with certain tolerances both in the voltage and power density. Such inevitable differences within battery cells will drift apart through cycling and could potentially lead to overcharging or over discharging [2]. In addition, the ambient temperature varies within the battery pack, imposing imbalanced effect on cells in different positions. Therefore, to properly maintain all cells balanced is of significant importance for enhancing battery life.

Mounting research efforts have been devoted to investigating efficient cell equalization systems (see reviews [3] and [4]). From the control and system perspective, attentions have been mainly focused on the control scheme and topology of equalization system. For instance, paper [5] presents a switched capacitor equalizer for series strings of batteries, which proves to be capable of achieving equilibrium in a reasonable time period through experiments. Paper [6] proposes a modularized charge equalizer to alleviate the voltage stress in the battery pack with a large number of cells. In paper [7], a layer based equalization architecture is investigated, which could reduce equalization time significantly.

Despite these efforts, the existing equalization architectures often require a large number of equalizers (comparable to the number of battery cells). In addition to cost, this will potentially reduce battery life when considering energy loss associated with equalizers, which has been typically ignored in the existing literature. Therefore, to investigate an equalization system with fewer equalizers that can still deliver robust performance is of great value. The main contribution of this paper is in presenting a modularized global equalization structure and investigating its dynamic behavior of equalization speed and energy loss.

The remainder of the paper is organized as follows: Section II reviews the state-of-the-art equalization structures. Section III is devoted to proposing a modularized global equalizer. In addition, the mathematical model and its performances are evaluated analytically. In Section IV, a comparative study is carried out using simulation to illustrate the advantage of the proposed method. Finally, conclusions are provided in Section V.

II. STATE-OF-THE-ART EQUALIZATION STRUCTURES

Consider a battery pack with an equalization system described below.

- (i) The battery pack consists of B serially connected batteries, $b_1, b_2, \ldots, b_B$. Each cell is linked to a equalizer, which can measure the cell's state of charge (SOC) and then equalize all the linked cells according to a certain strategy.
- (ii) All equalizers have the same equalization cycle τ. Thus the time axis is slotted with cycle time τ.
- (iii) During a cycle τ, each battery b_i could be either discharged or charged at the rate d_i or c_i, respectively.
- (iv) The efficiency of each equalizer e_i is characterized by its equalization rate r_i. The energy loss rate associated with each equalization is denoted as l_i.

Extensive research has been devoted to investigating the equalization structure for such a battery pack. In general, serial-connected, module-based, and layer-based structures have been proved efficient and cost effective to balance the SOC of the battery pack described by assumptions (i)-(iv). Therefore, these three state-of-the-art methods are reviewed in this section individually. Illustrations with a 8-cell battery pack are shown in Figures 1-3, respectively.

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A. Serial Structure

- The system consists of $(B-1)$ equalizers, e_1, e_2, $\ldots$, e_{B-1}. Equalizer e_j connects consecutive pair of battery cells b_j and b_{j+1}.
- In each time slot, if cell b_i has a larger SOC than b_{i+1}, equalizer e_i will transfer r_i units of charge from b_i to b_{i+1}. Otherwise, the same amount of charge will be transferred in the opposite direction. No transfer will take place when the SOC of b_i and b_{i+1} are equal.

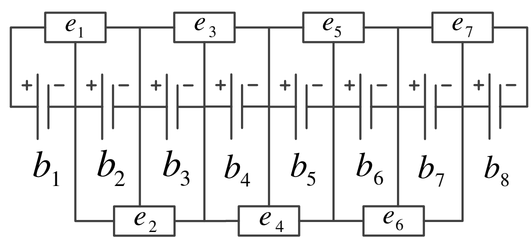

Fig. 1. Serial equalization structure [8]

B. Module Structure

- All battery cells are evenly divided into M modules, each with N battery cells.
- Within the module, $(N-1)$ equalizers balance the SOC of consecutive battery cells in the same manner as the serial structure.
- In the module level, $(M-1)$ equalizers are utilized to connect consecutive pair of modules. In each time slot, if module m_j has a larger average SOC than m_{j+1}, then the equalizer connecting them, e_{jN}, will take r_{jN}/N units of charge from each cell in module m_j and transfer the same amount to each cell in module m_{j+1}, $j=1,\ldots,M-1$. Otherwise the transfer is in the opposite direction. No transfer will take place between two modules when their average SOCs are identical.

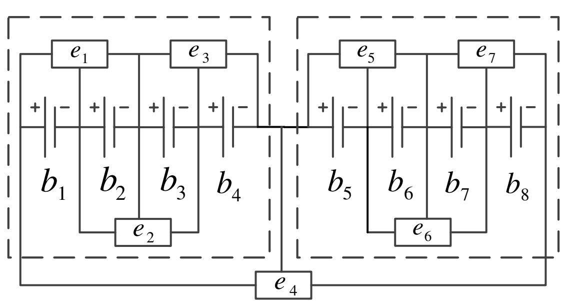

Fig. 2. Module-based equalization structure [8]

C. Layer Structure

- Equalizers are arranged as a binary tree structure with $\log_2 B$ layers. In layer s, there are $B/2^s$ equalizers, $s=1,\ldots,\log_2 B$.
- Specifically for the first layer, every pair of battery cells are connected with an equalizer in between. An upper parallel layer of equalizers combines every two lower layer equalizers together. By analogy, the same structure propagates to the top layer with only one equalizer.
- Each equalizer essentially connects two modules of battery cells combined by equalizers in the lower layer. Therefore, energy transfers in the same manner as the module structure.

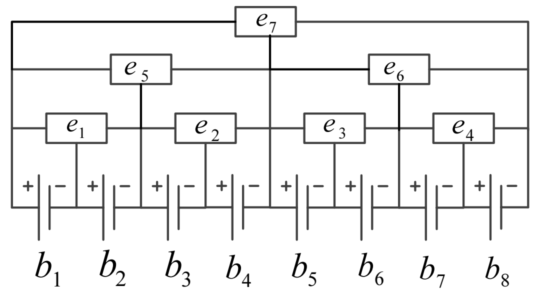

Fig. 3. Layer-based equalization structure [8]

To reduce the number of equalizers and energy loss, below, a new modularized global equalization structure will be presented and compared with the above structures.

III. Modularized Global Equalization

All the equalization structures listed in the previous section are being widely used in practice. However, one common concern is that they typically require a large number of equalizers (e.g., $(B-1)$ equalizers for all three structures). It becomes even more problematic when considering the energy loss during equalization. Therefore, a new structure with less equalizers seems to be a promising solution. In this section, a modularized global equalization structure (shown in Figure 4) is proposed below.

A. Structure

(a) The battery pack defined by assumptions (i)-(iv) is partitioned into M modules, $m_1, m_2, \ldots, m_M$. Each module contains N battery cells equally.

(b) In each module m_i, there is one single global equalizer e_i that can take up the SOC of all the cells within the module and transfer energy from the cell with the largest SOC to the smallest, $i=1,\ldots,M$.

(c) Another global equalizer e_{M+1} equalizes modules in the similar manner as cells. If the average SOC in module m_k is larger than module m_j, the global equalizer e_{M+1} will take r_{M+1}/N units of energy from each cell in m_k and send the same amount to each cell in m_j. The energy loss will also be evenly divided among cells in module m_k.

The global equalizer needs to be "intelligent", since it is required to select two cells to equalize among all the connected cells by sorting their SOCs. In addition, as shown in Figure 4, the number of equalizers is $(M+1)$, which is determined by the number of modules. Since each module typically contains a certain amount of battery cells, we could argue that M is substantially smaller than the total number of cells B. For example, for a 64-cell battery pack with 4

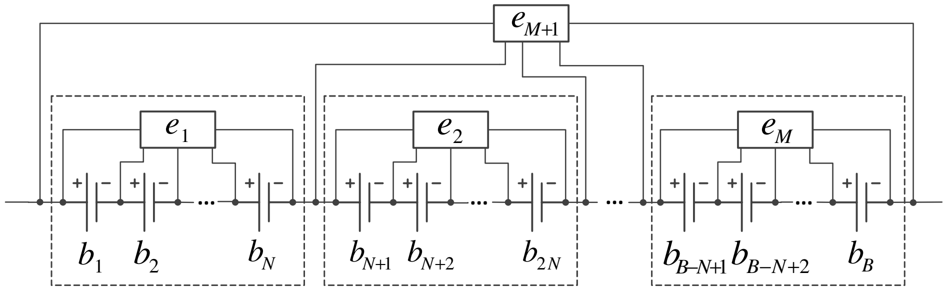

Fig. 4. Modularized global equalization

modules, only 5 rather than 63 equalizers are needed for the modularized global equalization system. In this sense, the proposed modularized global equalization structure could tremendously reduce the number of equalizers involved in the system.

B. Mathematical Model

Denote $x_i(0)$ as the initial SOC and $x_i(n)$ as the SOC at time n for each cell b_i, $i = 1, \ldots, B$, $n = 1, 2, \ldots$. Then the system dynamics could be captured by the following mathematical model, which implies that the current SOC of a specific battery cell depends on its SOC of previous time slot, the charging/discharging operation and equalizing dynamics.

$$\begin{aligned} x_i(n+1) &= x_i(n) - d_i + c_i + I^i_{c^-}(n) r_{\lceil \frac{i}{N} \rceil} \\ &\quad - I^i_{c^+}(n)(r_{\lceil \frac{i}{N} \rceil} + l_{\lceil \frac{i}{N} \rceil}) + I^i_{m^-}(n) \frac{r_{M+1}}{N} \\ &\quad - I^i_{m^+}(n) \frac{r_{M+1} + l_{M+1}}{N}, \\ &\quad i = 1, \ldots, B, \end{aligned} \tag{1}$$

where

$$\begin{aligned} I^i_{c^-}(n) &= \begin{cases} 1, & \text{if } i = \underset{j \in m_{\lceil \frac{i}{N} \rceil}}{\operatorname{argmin}} \{x_j(n)\}, \\ 0, & \text{otherwise}, \end{cases} \\ I^i_{c^+}(n) &= \begin{cases} 1, & \text{if } i = \underset{j \in m_{\lceil \frac{i}{N} \rceil}}{\operatorname{argmax}} \{x_j(n)\}, \\ 0, & \text{otherwise}, \end{cases} \\ I^i_{m^-}(n) &= \begin{cases} 1, & \text{if } i \in \underset{p \in \{m_1, \ldots, m_M\}}{\operatorname{argmin}} \{\frac{\sum_{k \in p} x_k(n)}{N}\}, \\ 0, & \text{otherwise}, \end{cases} \\ I^i_{m^+}(n) &= \begin{cases} 1, & \text{if } i \in \underset{p \in \{m_1, \ldots, m_M\}}{\operatorname{argmax}} \{\frac{\sum_{k \in p} x_k(n)}{N}\}, \\ 0, & \text{otherwise}, \end{cases} \\ m_i &= \{(i-1)N + 1, (i-1)N + 2, \ldots, iN\}. \end{aligned}$$

Here $\lceil \frac{i}{N} \rceil$ implies the index of module which cell b_i belongs to, i.e., $m_{\lceil \frac{i}{N} \rceil}$. Since equalizers have the same order index as modules, $r_{\lceil \frac{i}{N} \rceil}$ and $l_{\lceil \frac{i}{N} \rceil}$ present equalization rate and energy loss rate of the equalizer associated with cell b_i. Functions $I^i_{c^-}(n)$ and $I^i_{c^+}(n)$ indicate whether battery cell b_i holds the smallest and largest SOC at time n, respectively. While indicator functions $I^i_{m^-}(n)$ and $I^i_{m^+}(n)$ illustrate if battery cell b_i belongs to the smallest and largest SOC module at time n correspondingly.

An illustration of the mathematical model for an 8-cell battery pack with 2 modules working in a discharging circumstance is given in Figure 5, where T_{eq} and S_{eq} denote the number of cycles and the SOC when all cells reach equilibrium, respectively. Specifically, the initial SOC and discharging rate of each battery cell are shown in Table I, while all equalizers are assume to be identical with $r_i = 0.001$ and $l_i = 0.00001$, $i = 1, \ldots, 3$. As one can see, initial SOCs scatter within the allowable range. Within 674 units of time, all the SOCs reach to a convergent point $S_{eq} = 0.440$.

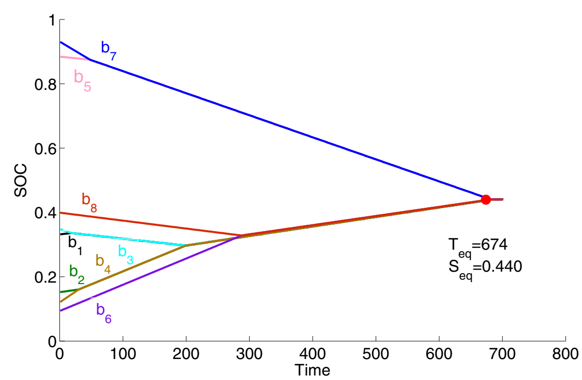

Fig. 5. Illustration of the mathematical model of global equalization ($B = 8, M = 2$)

TABLE I
THE INITIAL SOCS AND DISCHARGING RATE OF BATTERY CELLS

	b_1	b_2	b_3	b_4
Initial SOC	0.3317	0.1522	0.3480	0.1217
Discharging rate ($\times 10^{-4}$)	0.0474	0.3424	0.7360	0.7947
	b_5	b_6	b_7	b_8
Initial SOC	0.8842	0.0943	0.9300	0.3990
Discharging rate ($\times 10^{-4}$)	0.5449	0.6862	0.8936	0.0548

C. Performance Evaluation

To evaluate the equalization time and the average SOC when the system reaches equilibrium, we assume that no energy loss is involved in equalization, and charging/discharging rate and equalization rate are identical for all the cells and equalizers, respectively, i.e.,

$$l_i = 0, \quad i = 1, \ldots, M+1, \tag{2}$$
$$r_i = r, \quad i = 1, \ldots, M+1, \tag{3}$$
$$d_i = d, \quad i = 1, \ldots, B, \tag{4}$$
$$c_i = c, \quad i = 1, \ldots, B. \tag{5}$$

In this sense, Equation (1) could be simplified as follows:

$$\begin{aligned} x_i(n+1) &= x_i(n) - d + c + I_{c^-}^i(n)r - I_{c^+}^i(n)r \\ &\quad + I_{m^-}^i(n)\frac{r}{N} - I_{m^+}^i(n)\frac{r}{N}. \end{aligned}$$

Consider the structure shown in Figure 4, the equalization procedure essentially consists of two steps: intra-module and inter-module. Specifically, in the inter-module level, charges are extracted and distributed evenly among the cells within the module. Hence, the inter-module equalization will not affect the equilibrium of the intra-module level. In addition, the charging and discharging for each cell are also identical. Therefore, the equilibrium SOC for each module $\overline{x}_i$ could be estimated using the initial SOC within the module, i.e.,

$$\overline{x}_i = \frac{1}{N}\sum_{j\in m_i} x_j(0), \quad i = 1, \ldots, M. \tag{6}$$

Then the equalization time for each module T_i could be obtained as follows:

$$T_i = \frac{\sum_{j\in m_i} |x_j(0) - \overline{x}_i|}{2r}, \quad i = 1, \ldots, M. \tag{7}$$

In the inter-module equalization, the equilibrium SOC for all modules $\overline{X}$ can be characterized as

$$\overline{X} = \frac{1}{M}\sum_{i=1}^{M} \overline{x}_i. \tag{8}$$

Then the equalization time for equalizer e_{M+1} could be calculated similarly:

$$T_{M+1} = \frac{\sum_{i=1}^{M} |\overline{x}_i - \overline{X}|}{2r}. \tag{9}$$

Since all equalizers function independently, the largest value of T_i, $i = 1, \ldots, M+1$, determines equalization time T_{eq}. Similarly, the equalized SOC S_{eq} could be obtained by combining the overall equilibrium SOC and the charging/discharging effect.

Theorem 1: Under conditions (2)-(5), the performance of modularized global equalizer described in (a)-(c) could be expressed as follows

$$\begin{aligned} T_{eq} &= \max_{i\in\{1,\ldots,M+1\}} \{T_i\}, \\ S_{eq} &= \overline{X} + cT_{eq} - dT_{eq}, \end{aligned}$$

where T_i and $\overline{X}$ are calculated from (6)-(9).

The above theorem illustrates the fact that the modularized global equalizer guarantees that the system reaches equilibrium within a finite period of time. In addition, T_{eq} highly depends on the initial SOC pattern and exhibits negative correlation with equalization rate.

When conditions (2)-(5) are relaxed, the system dynamics become sophisticated and analytical expressions on T_{eq} and S_{eq} seem impossible to obtain. Nevertheless, the diversity of charging/discharging rate and equalizers and the involvement of energy loss could merely affect the system quantitatively, rather than qualitatively. Therefore, the argument that the system reaches equilibrium within finite period of time still holds.

IV. Comparison with State-of-the-art Equalization Structures

In order to demonstrate the performance of the modularized global equalization, simulation studies are carried out in comparison with serial, module and layer equalization structures. To conduct numerical experiments, the initial SOC of cell b_i, $i = 1, \ldots, B$, is generated randomly and independently from the uniform distribution $U(0,1)$. In practice, all equalizers are typically designed to be identical. Thus we assume all equalization rate r_i to be 0.001 and energy loss rate l_i is equal to 0.00001. Moreover, to emulate the charging/discharging dynamics, charging rate c_i and discharging rate d_i for cell b_i are selected randomly and independently according to uniform distribution $U(0.0001, 0.001)$.

With the same system parameter settings, comparative studies with respect to the key performance, equalization time T_{eq} and equalized SOC S_{eq}, are investigated for four types of equalization structures. Note that strict equilibrium may not be reached due to the sensitivity of equalizers. Therefore, a tolerance factor ϵ is introduced and set to be 0.02, i.e., $\epsilon = 0.02$. When the absolute difference of the maximum and minimum of SOCs for all the cells falls below ϵ, equilibrium is deemed to be attained. The simulation starts from the simplest case where the battery pack consists of 8 cells, and then scales up to 16 cells and 64 cells.

A. 8 Cells with 2 Modules

First consider a 8-cell battery pack with 2 modules. To illustrate the system performance in different application scenarios, the simulation function is divided into four cases: equalization without charge/discharge or energy loss, during charging, with energy loss only, and with charging and energy loss.

1) Equalization without charge/discharge or energy loss: Simulation in this scenario simply tests the equalization speed for serial, module, layer and global structures, since there is no additive or dissipative energy involved once initial SOCs are determined. With the initial SOC randomly generated, the equalization processes for four types of structures are illustrated in Figure 6. Clearly, serial, layer and module structures exhibit similar equalization speed, while equalization time for the proposed global structure is slightly longer.

2) Equalization during charging: To compare the equalization performance during charging, random charging rate will be assigned to each cell after their initial SOCs are

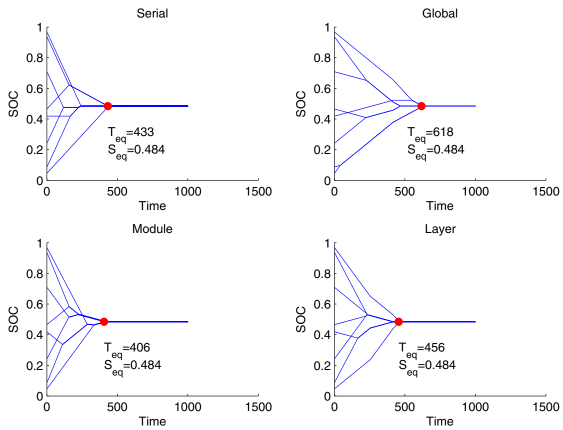

Fig. 6. No charge/discharge or energy loss ($B = 8, M = 2$)

generated. As shown in Figure 7, with an ascending trend, equilibrium could still be achieved in such scenario for all four structures. Moreover, the differences for their T_{eq} and S_{eq} are negligible. Since discharging is the reverse process of charging, similar performance could be obtained for discharging analogously.

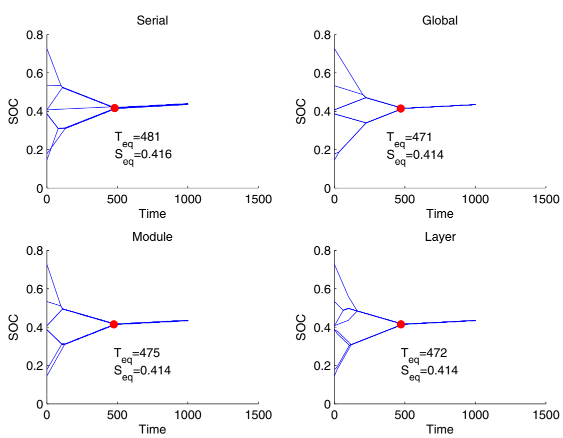

Fig. 7. Equalization during charging ($B = 8, M = 2$)

3) Equalization with energy loss: Energy loss associated with equalization is inevitable in physical systems. Therefore, in this scenario, equalizers are regarded as dissipative sources, with its energy loss rate fixed for each equalization cycle. The simulation results are described in Figure 8. In terms of equalization speed, the global equalizer is almost identical with module and layer structures, but dramatically faster than the serial one. Meanwhile, S_{eq} of the global equalization turns out to be the largest among the four structures, since it involves the smallest number of equalizers (only 3 for global equalization and 7 for the other three structures in this case) and its energy loss is significantly reduced accordingly.

4) Equalization with charging and energy loss: Combining scenarios 2) and 3) results in a common situation that

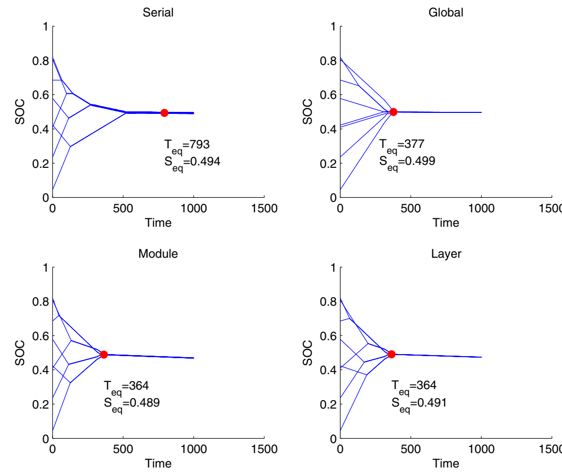

Fig. 8. Equalization with energy loss ($B = 8, M = 2$)

occurs quite often while the battery pack is in operation. As shown in Figure 9, the overall SOC is rising over time because charging rate is slightly higher than energy loss rate. Moreover, global equalizers take a relatively longer time to achieve equalization, but its S_{eq} is the maximum.

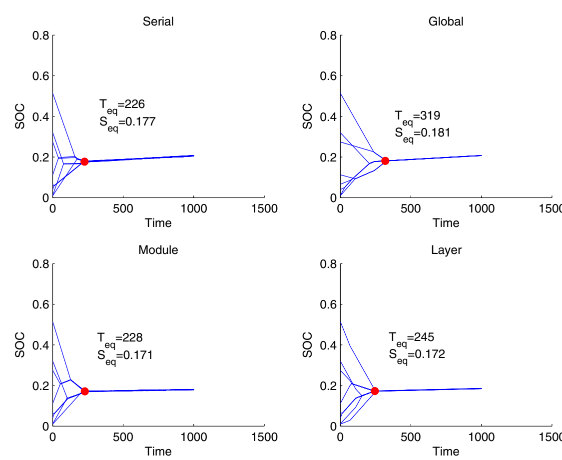

Fig. 9. Equalization with charging and energy loss ($B = 8, M = 2$)

B. 16 Cells with 4 Modules

From the previous case, equilibrium has been demonstrated to be achieved for all four structures regardless of charging/discharging and energy loss. Therefore, for the rest of the simulation, only scenario 3), equalization with energy loss, is utilized to illustrate the comparative performance as the pack size increases.

In a 16-cell battery pack with 4 modules, similar simulation is carried out and results are shown in Figure 10. The serial equalization takes relative longer time to achieve equilibrium, while minimal difference in the equalization time T_{eq} could be observed for the other three equalization structures. As for the equalized SOC, S_{eq} is equal to 0.581

for the global equalizer, and 0.576, 0.551, and 0.556 for serial, module, and layer equalizers, respectively. As one can see, the global equalizer outperforms the others by 1%-5% on energy saving in this case.

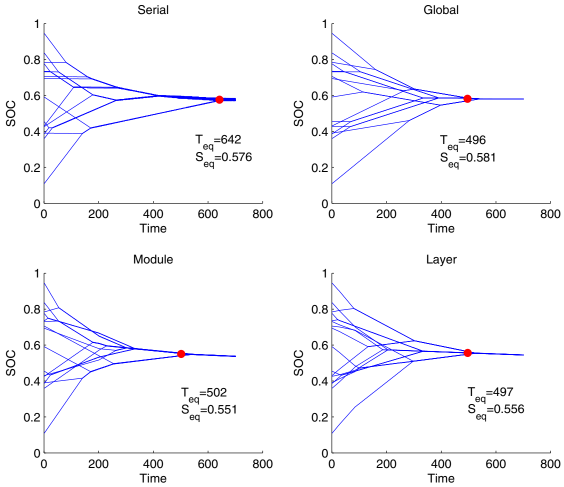

Fig. 10. Equalization with energy loss ($B = 16, M = 4$)

C. 64 Cells with 8 Modules

When the battery pack size increases to 64 cells with 8 modules, the serial equalization fails to converge. Comparing the global equalizer with module and layer ones, similar as the previous case, T_{eq} remains comparable among them as the battery pack scales up (shown in Figure 11). However, according to a simple calculation with respect to S_{eq}, the energy loss for the global equalizer is saved by approximately 10% and 16% compared to layer and module equalizer, respectively. Furthermore, it is worth to mention that equilibrium means that the difference of SOC is minimal (falls within the tolerance ϵ), rather than zero. In this sense, the equalization process will still continue when equilibrium is reached, which results in more energy waste. As one can see, the aforementioned energy loss is significant in module and layer equalization, while only a relatively small amount for serial and global equalization. Also note that global equalization only uses 9 equalizers while the other three all use 63 equalizers, which is 7 times more.

D. Discussions

The above simulation study provides a holistic view of equalization dynamics in different scenarios for four types of equalization structures. In general, our proposed modularized global equalization structure, compared with the other three state-of-the-art structures, takes similar time to reach equilibrium. As the size of the battery pack increases, T_{eq} is also getting larger. Nevertheless, a much smaller number of equalizers used in global equalization induces considerable reduction on both the cost of the system and energy loss during the equalization process. The energy saving of global equalization becomes more significant as the battery pack

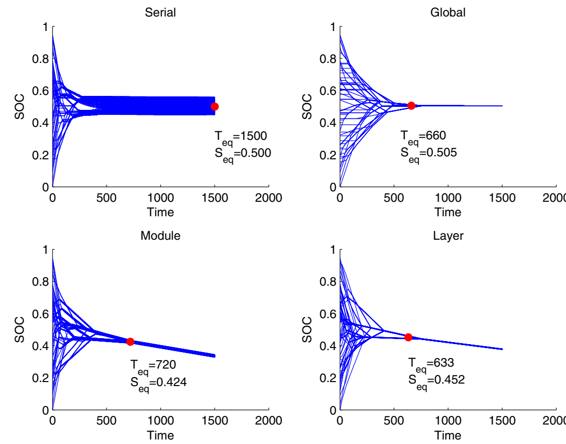

Fig. 11. Equalization with energy loss ($B = 64, M = 8$)

scales up. Therefore, we could argue that our proposed global equalization outperforms others by its substantial reduction on energy loss and cost.

V. Conclusions

In this paper, a modularized global equalization method is introduced to balance the SOC of battery cells. In addition to developing mathematical model to emulate system dynamics, analytical formulas are derived to evaluate equalization performance. Finally a comparative simulation study with the state-of-the-art equalization methods is carried out in terms of equalization speed and energy loss. Simulation results show that the proposed global equalization takes comparable time to reach equilibrium as the serial, layer and module equalizations, while its energy loss during equalization is the minimum. Moreover, the number of equalizers is reduced substantially. Therefore, the global equalization could find itself promising in applications where rigorous restrictions are imposed on cost and energy loss.

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