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# A Cell-to-Cell Battery Equalizer With Zero-Current Switching and Zero-Voltage Gap Based on Quasi-Resonant LC Converter and Boost Converter

Yunlong Shang, *Student Member*, *IEEE*, Chenghui Zhang, *Member*, *IEEE*, Naxin Cui, *Member*, *IEEE*, and Josep M. Guerrero, *Senior Member*, *IEEE*

***Abstract*—In conventional equalizers, the facts of bulky size and high cost are widespread. Particularly, the zero switching loss and zero-voltage gap (ZVG) between cells are difficult to implement due to the high-frequency hard switching and the voltage drop across power devices. To overcome these difficulties, a direct cell-to-cell battery equalizer based on quasi-resonant LC converter (QRLCC) and boost DC-DC converter (BDDC) is proposed. The QRLCC is employed to gain zero-current switching (ZCS), leading to a reduction of power losses. The BDDC is employed to enhance the equalization voltage gap for large balancing current and ZVG between cells. Moreover, through controlling the duty cycle of the BDDC, the topology can online adaptively regulate the equalization current according to the voltage difference, which not only effectively prevents over-equalization but also abridges the overall balancing time. Instead of a dedicated equalizer for each cell, only one balancing converter is employed and shared by all cells, reducing the size and implementation cost. Simulation and experimental results show the proposed scheme exhibits outstanding balancing performance, and the energy conversion efficiency is higher than 98%. The validity of the proposed equalizer is further verified by a quantitative and systematic comparison with the existing active balancing methods.**

***Index Terms*—Equalizers, zero-current switching, DC-DC power converters, battery management systems, lithium-ion batteries, electric vehicles.**

## I. Introduction

DUE to high energy density, low self-discharge rate, and no memory effect, lithium-ion batteries play important roles in high power battery applications such as electric vehicles (EVs) and hybrid electric vehicles (HEVs). However, since one single cell has limited voltage and capacity, it is required to construct battery packs with hundreds or thousands of single cells connected in parallel and/or in series to meet the power and energy requirements of EVs or HEVs [1]-[6]. For example, the power battery pack in BMW's MINI E is composed of 5,088 single cells (48 cells in parallel and 106 cells in series) [7]. Unfortunately, series-connected lithium-ion cells bring a key technical issue: serious imbalance between cell voltages or SOCs is generated due to manufacturing inconsistencies and unique performance characteristics of individual cells in a typical pack. Furthermore, after a number of charge/discharge cycles, the imbalance tends to grow over time. This reduces enormously the available capacity of the battery pack, and even leads to premature cells degradation and safety hazards (e.g., explosion or fire, etc.) due to the overcharge or overdischarge of cells. Consequently, equalization for series-connected batteries is essential to prevent these phenomena and to extend the life time of the battery pack. Obviously, as one key technology of battery management system (BMS), the battery equalization for series-connected lithium-ion batteries has become a research focus.

Numerous balancing methods have been proposed and well summarized in [8]-[10]. As described in Fig. 1, these equalization methods can be classified into three main groups: the dissipative methods [8], [11]-[14], the nondissipative methods [15]-[41], and battery selection method [42], [43]. Furthermore, each group can be further divided into several categories. The tree trunk, the tree large branches, the tree branches, and the tree leaves in Fig. 1 represent the classification process of the equalization methods from coarse to fine. The ground represents the balancing strategies, which include the voltage-based, SOC-based, and pack capacity-based strategies [44], [45].

A review of literature shows that the conventional equalizers are not suitable for lithium-ion batteries due to the following facts:

1) The size of the conventional equalizers is prone to be bulky because large amounts of transformers, MOSFETs, and floating drive circuits are necessary.

2) Lithium-ion battery offers a relatively flat open circuit voltage (OCV) across a broad range of SOC from 20% to 80% [11], [36]. In other words, even though the SOC difference between cells is large, the corresponding voltage difference still remains small. Consequently, the equalization current of the conventional equalizers is very small. Particularly, the power devices would not conduct normally when the voltage difference between cells is less than the voltage drop across power devices.

3) ZVG between cells can not be achieved due to the voltage drop across the power devices.

4) The switching loss is very high because the switches are conducted in high-frequency hard switching mode.

5) The equalization current, which depends on the voltage

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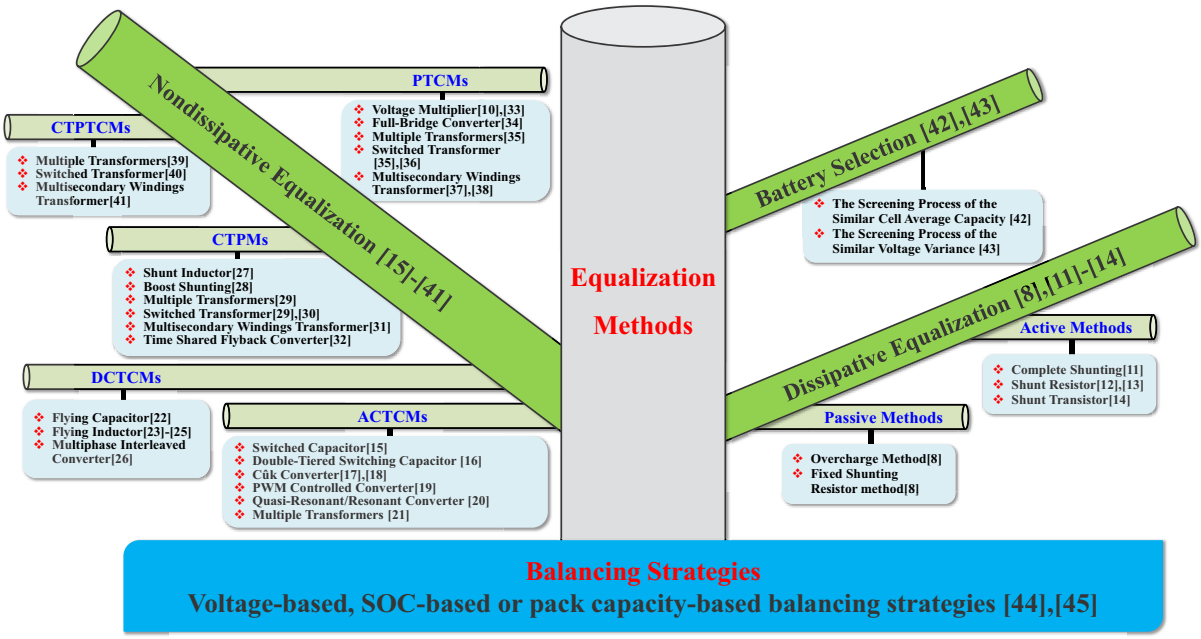


Fig. 1. Conceptual tree of equalization methods.

difference between cells, is difficult to regulate as needed, leading to a long equalization time or over-equalization.

To solve these problems, a direct cell-to-cell equalizer based on QRLCC and BDDC is proposed. The QRLCC is employed to achieve ZCS, which results in a reduction of power losses and electromagnetic interference (EMI). The BDDC is employed to enhance the maximum cell voltage gap so that large equalization current and ZVG between cells can be achieved. Through controlling the duty cycle of the BDDC, the equalizer can online adaptively regulate the equalization current according to the cell voltage difference, which effectively prevents over-equalization and abbreviates the overall balancing time. Moreover, this topology is able to transfer energy directly from the source cell at any position to the target one at any position in the pack, resulting in a great improvement of equalization speed and efficiency. In addition, since there are few MOSFETs, a small number of floating drive circuits and no transformers, and all the cells in the battery pack share one LC filter plug converter and one BDDC, the presented solution promises to solve the dilemma of bulky size and high cost.

This paper is organized as follows. State of the art in battery balancing methods is reviewed in Section II. In Section III, the design concept and the operation principle of the proposed system are analyzed, and a numerical approach for enhancing the equalization speed is proposed. Simulation and experimental results are presented in Sections IV and V, respectively. The comparative studies with the conventional equalizers are presented in Section VI.

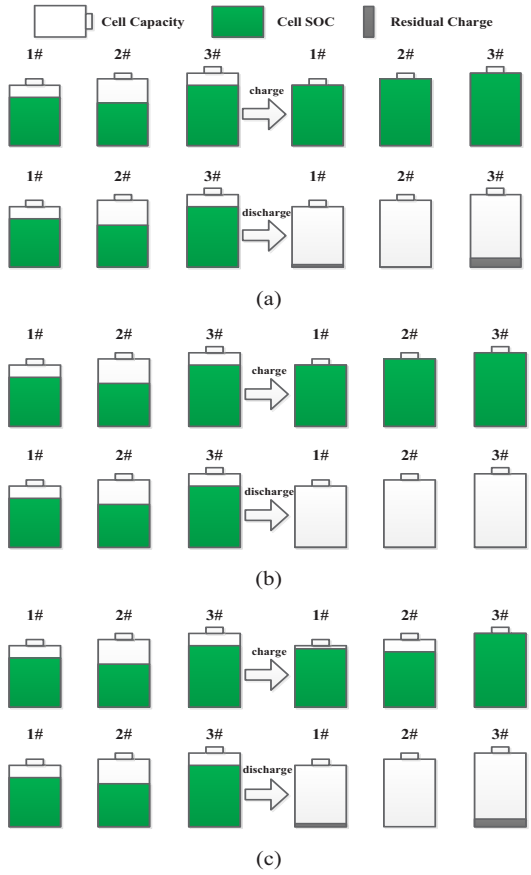


Fig. 2. Charge and discharge processes of three cells connected in series with different balancing methods. (a) Dissipative balancing methods. (b) Nondissipative balancing methods. (c) Battery selection method.

## II. Review of Battery Balancing Methods

### A. Dissipative Equalization

The dissipative equalization, also known as cell bypass method (CBM), employs a dissipative element connected as

a shunt to bypass or drain extra energy from one cell. The dissipative equalization methods can be further divided into two categories, i.e., passive methods (no active control is used to balance) and active methods (external circuitry with active control is used to balance). The passive equalization methods include the overcharge method and the fixed shunting resistor method [8]. The active equalization methods include the complete shunting method [11], the shunt resistor method [12], [13], and the shunt transistor method [14]. Fig. 2 (a) shows the charge and discharge processes of three cells connected in series with the dissipative balancing methods, where the three cells' initial SOCs and capacities are randomly given obeying the normal distribution. The cell voltage equalization with these methods is achieved by consuming the excess energy from the cells with higher voltage. Therefore, the available capacity of the battery pack in series with the dissipative methods is expressed as

$$C_{Bp} = \min_{j=0,1,\ldots,n-1}\{C_{B_j}\} \tag{1}$$

where $C_{Bp}$ is the battery pack capacity in Ah. $C_{B_j}$ is the cell capacity of the $jth$ cell $B_j$ in Ah, and *n* is the number of cells. The dissipative equalization is the cheapest one, and it is easily to be modularized and controlled. Owing to the individual shunt for each cell, it only takes one switching cycle to equalize the cell voltages to a same voltage level, showing excellent equalization speed. However, the excess energy is converted into heat rather than be stored, which leads to the energy waste and thermal management issues, and reduces greatly the available capacity of battery packs.

### *B. Nondissipative Equalization*

Nondissipative balancing methods employ nondissipative charge-shuttling elements or voltage/current converters to move energy from one cell to another or from one cell to the pack or from the pack to one cell. According to the energy flow, nondissipative balancing methods can be further classified into four groups as follows.

1) Adjacent cell-to-cell methods (ACTCMs)

As the name suggests, the charge is transferred between two adjacent cells with this method. The ACTCMs consist of five methods: the switched capacitor [15], the double-tiered switching capacitor [16], the cûk converter [17], [18], the PWM controlled converter [19], the quasi-resonant/resonant converter [20], and the multiple transformers [21]. Fig. 3 shows a typical ACTCM, i.e., the switched capacitor method, where one switched capacitor is implemented in every two adjacent cells and the equalizing path is controlled by the complementary switches $S_{i1}$ and $S_{i2}$ ($i$=1,2,...,$n$). For example, when $S_{11}$ and $S_{21}$ are turned ON, while $S_{12}$ and $S_{22}$ are turned OFF, the capacitor $C_0$ is connected in parallel with $B_0$. On the contrary, when $S_{11}$ and $S_{21}$ are turned OFF, while $S_{12}$ and $S_{22}$ are turned ON, the capacitor $C_0$ is connected in parallel with $B_1$. Through these two states constantly switching, the energy exchange between any two adjacent cells is achieved. Fig. 4 (a) farther shows the directed graph topology of the ACTCMs, where $A_0$-$A_{n-2}$ represent the individual cell equalizers, e.g., the switched capacitors $C_i$ ($i$=0, 1, ... , $n-2$) in Fig. 3. The charge is only transferred from one cell to an adjacent one through an individual cell equalizer with this method. It would take a large amount of time to transport charge from the source cell to the target one, particularly when they are on opposite ends of the pack. In addition, the charge would have to travel through all the cells and individual cell equalizers, and this results in a high efficiency penalty. Moreover, the ZVG between cells is difficult to obtain due to the voltage drop across the power devices. The outstanding advantages of this system are the modular design, the extremely low voltage stress, and the easy control.

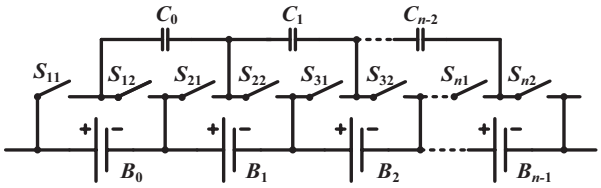


Fig. 3. Switched capacitor method.

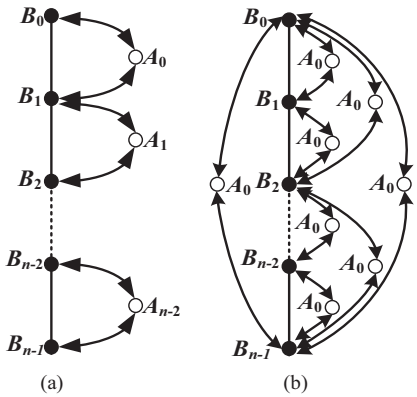


Fig. 4. The directed graph topologies of cell-to-cell balancing methods. (a) ACTCMs. (b) DCTCMs.

2) Direct cell-to-cell methods (DCTCMs)

To overcome the disadvantages of the ACTCM, a DCTCM using a common equalizer is introduced. By using a common equalizer such as a capacitor, this method achieves the direct cell-to-cell charge transportation between any two cells in the battery stack. The DCTCMs consist of three methods: the flying capacitor [22], the flying inductor [23]-[25], and the multiphase interleaved converter [26]. Fig. 5 shows the flying capacitor method, where only one switched capacitor is shared by all cells and the equalizing path is controlled by $n$ pairs of switches $S_i$ and $Q_i$ ($i$=1,2,...,$n$). For example, when $S_1$ and $Q_1$ are turned ON, and others are turned OFF, the capacitor $C$ is connected in parallel with $B_0$. When $S_3$ and $Q_3$ are turned ON, and others are turned OFF, the capacitor $C$ is connected in parallel with $B_2$. Thus, the energy exchange between any cells at any position in the pack can be achieved. Fig. 4 (b) farther shows the directed graph topology of the DCTCMs, where $A_0$ represents the common cell equalizer, e.g., the switched capacitor *C* in Fig. 5. The charge can be transferred directly from the source cell at any position to the target one at any position in the pack with this method.

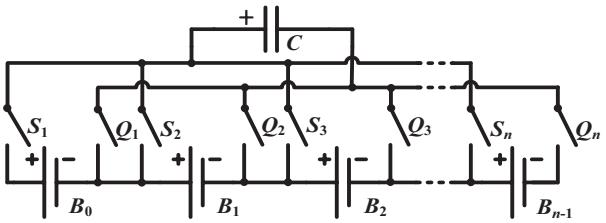


Fig. 5. Flying capacitor method.

Consequently, high efficiency can be obtained for high power applications. Over-equalization is prevented as the equalizing current is proportional to the voltage difference between the source cell and the target one, but this also leads to a slow balance. In addition, this method cannot obtain ZVG between cells due to the voltage drop across the power devices.

3) Cell-to-pack methods (CTPMs)

The charge is transferred from the most charged cell to the pack. The CTPMs consist of six methods: the shunt inductor [27], the boost shunting [28], the multiple transformers [29], the switched transformer [29], [30], the multisecondary windings transformer [31], and the time shared flyback converter[32]. When one cell is more charged than the other cells, and the other cells are balanced in a same voltage level, the CTPM has the best equalization performance. It only takes one switching cycle to complete the charge transportation. When one cell is less charged than the others while the others are balanced, this is the worst case for this method, which need $n-1$ switching cycles to complete the charge transportation. Therefore, the average switching cycle is $n$/2, showing poor equalization speed. When the target cell is balanced by the mean of discharge with this method, the cell also will be simultaneously charged through the battery pack. Therefore, the average conversion efficiency with this method is slightly lower than the one conversion efficiency when $n$ is large. In addition, this method can obtain ZVG between cells but suffers from over-equalization and high switching losses.

4) Pack-to-cell methods (PTCMs)

The charge is transferred from the pack to the least charged cell in the battery pack. The PTCMs consist of five methods: the voltage multiplier [10], [33], the full-bridge converter [34], the multiple transformers [35], the switched transformer [35], [36], and the multisecondary windings transformer [37], [38]. When one cell is less charged than the other cells, and the other cells are balanced in a same voltage level, the PTCM has the best equalization performance. It only takes one switching cycle to complete the charge transportation. When one cell is more charged than the others while the others are balanced, this is the worst case for this method, which need $n-1$ switching cycles to complete the charge transportation. Therefore, the average switching cycle is $n$/2. The PTCMs have the same advantages and disadvantages as the CTPMs.

5) Cell-to-pack-to-cell methods (CTPTCMs)

These methods allow the cell-to-pack equalization in case a cell has a higher voltage than the others in the battery pack, and the pack-to-cell equalization in case a cell has a lower voltage than the others. The CTPTCMs consist of three methods: the bidirectional multiple transformers [39], the bidirectional switched transformer [40], and the bidirectional multisecondary windings transformer [41]. Compared with the CTPMs and the PTCMs, the CTPTCMs have higher equalization speed and average conversion efficiency at the cost of control complexity.

Obviously, nondissipative balancing methods are all active equalization ones. Fig. 2 (b) shows the charge and discharge processes of three cells connected in series with the nondissipative methods. These methods seek to transfer efficiently energy from the strongest cell to the weakest one via different approaches until the cell voltages are equalized to the same level. Therefore, the available capacity of the battery pack in series with nondissipative balancing methods can be expressed as

$$C_{Bp} = \underset{j=0,1,\ldots,n-1}{\text{mean}}\{C_{B_j}\}. \tag{2}$$

### C. Battery Selection

The battery selection, which builds up the battery pack by selecting the cells with similar properties, can be divided into two different screening processes to select the similar cells. In the first screening process [42], the cells with similar average capacity are selected by discharging at different current regimes. The second one [43] is applied to select the cells from the first process with the similar voltage variance under the pulse discharging/charging currents at different SOC points. By using the battery selection method, the series-connected battery string is not enough to remain balanced because the self-discharges of cells vary differently along their lifetime. It can only be useful in the case of complementing a balancing system. Fig. 2 (c) shows the charge and discharge processes of three cells connected in series with this method. It can be observed that the battery pack capacity with this method is limited by the barrel theory also known as Liebig's law of the minimum [46]. Therefore, the available capacity of the battery pack in series with battery selection can be expressed as

$$\begin{aligned} C_{Bp} = &\min_{j=0,1,\ldots,n-1}\{Cr_{B_j}\}+ \\ &\min_{j=0,1,\ldots,n-1}\{(1-SOC_j)*Cr_{B_j}\} \end{aligned} \tag{3}$$

where $Cr_{B_j}$ and $SOC_j$ are respectively the remaining cell capacity in Ah and the SOC of the $jth$ cell $B_j$.

It can be summarized from the above discussion that the nondissipative equalization has higher available battery pack capacity and higher efficiency than the dissipative equalization and the battery selection. Nevertheless, the existing nondissipative equalization methods feature bulky size and high implementation cost ubiquitously, because large amounts of transformers, capacitors, inductances, MOSFETs, and floating drive circuits are necessary. What is more, they suffer from the problems e.g., long equalization time, high switching loss, and over-equalization. Therefore, a high-efficiency battery equalizer with ZCS and ZVG is highly desired for enhancing the available capacity and life cycle of the battery packs.

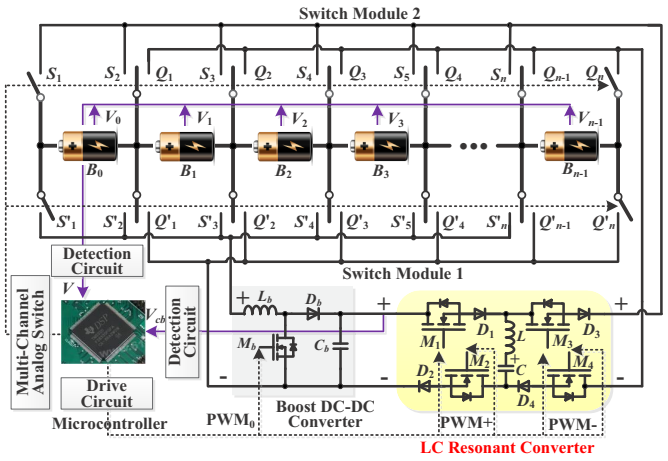


Fig. 6. System configuration of the proposed equalizer for $n$ cells based on QRLCC and BDDC.

## III. Proposed Equalizer Scheme

### A. Concept of the Proposed Equalizer

Fig. 6 shows the system configuration of the proposed equalizer for $n$ battery cells, which consists of three parts, i.e., the QRLCC, the BDDC, and the selection switch modules. The QRLCC, as the core of the proposed equalizer, is made up of a LC filter plug converter, four MOSFET switches, and four diodes. The MOSFET switches are divided into two pairs (i.e., $M_1$, $M_2$ and $M_3$, $M_4$). They are controlled by a pair of complementary pulse width modulation (PWM) pulses, enabling the QRLCC to operate alternatively between the state of charging and the state of discharging. The diodes are employed to isolate the cells to be equalized from the battery pack. The major role of the QRLCC is to achieve the energy transportation with ZCS. The BDDC, which is simply implemented by using a boost converter, can regulate the voltage of the source cell to a higher value in order to obtain large equalization current and ZVG between cells. Moreover, through controlling the duty cycle of the BDDC, the equalizer can online adaptively regulate the equalization current according to the cell voltage difference, which effectively prevents over-equalization. The selection switch modules consist of 2$n$ pairs of relays, through which the energy can be transferred from the cell with the highest voltage at any position to the one with the lowest voltage at any position in the stack, resulting in an improvement of the equalization speed and efficiency.

### B. Operational Principle

In this paper, the equalization is achieved by directly interchanging energy between the source cell with the highest voltage and the target one with the lowest voltage in a battery pack. To realize this, a microcontroller with voltage monitoring integrated circuit is employed. The microcontroller collects the voltage data to find out the source and target cells in real time. Then, the microcontroller drives the selection switch modules to connect the BDDC with the source cell and to link the QRLCC with the target cell. A PI controller is employed to control the output voltage of the BDDC so that

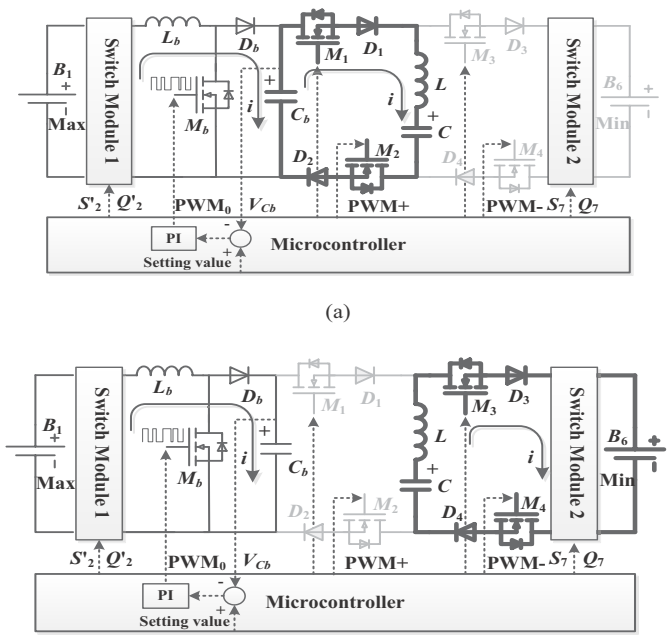


Fig. 7. Two consecutive working states of the proposed equalizer. (a) Working state I. (b) Working state II.

the equalization current can be regulated according to the cell voltage difference for fast equalization and preventing over-equalization. The equalization with two consecutive working states is shown in Figs. 7 (a) and (b), respectively. Before describing the two states, the second battery $B_1$ is assumed to be overcharged, and the seventh battery $B_6$ is undercharged. Thus, the cell selection switches $S_2'$, $Q_2'$ and $S_7$, $Q_7$ are first turned ON before the operation of the BDDC. In the balancing process, the cell selection switches $S_2'$, $Q_2'$ and $S_7$, $Q_7$ are kept ON until the new generation of the source and target cells. The four MOSFET switches in the QRLCC are controlled by a pair of complementary PWM pulses, i.e., PWM+ and PWM−. To be specific, $M_1$ and $M_2$ are turned ON simultaneously in the first half of a switching cycle, while $M_3$ and $M_4$ are turned ON in the second half-cycle. Particularly, ZCS is achieved when the resonant frequency of the QRLCC is an integer multiple of the switching frequency. The multiple cycles of the oscillation in one switching cycle will lead to a small average equalization current. Thus, it is optimum to set the switching frequency equal to the resonant frequency.

Working state I: $M_1$, $M_2$ are turned ON, and $M_3$, $M_4$ are turned OFF. The QRLCC is connected in parallel with the BDDC through $M_1$, $D_1$ and $M_2$, $D_2$, as shown in Fig. 7 (a). $C_b$, $L$, and $C$ form a resonant loop, and the current path from $B_1$ is constructed. The capacitor $C$ is charged by $C_b$. Then, the voltage across $C$ $V_c$ begins to increase. Since the output voltage of the BDDC is always regulated to a constant value and $C_b$ is considerably larger than $C$, the output voltage of the BDDC can be seen as an ideal voltage source in a very short time. Thus, the current flowing into the QRLCC is equal to that flowing out of the cell $B_1$. Meanwhile, because of $M_3$ and $M_4$ maintaining OFF, $B_6$ acts as an open path, thus the

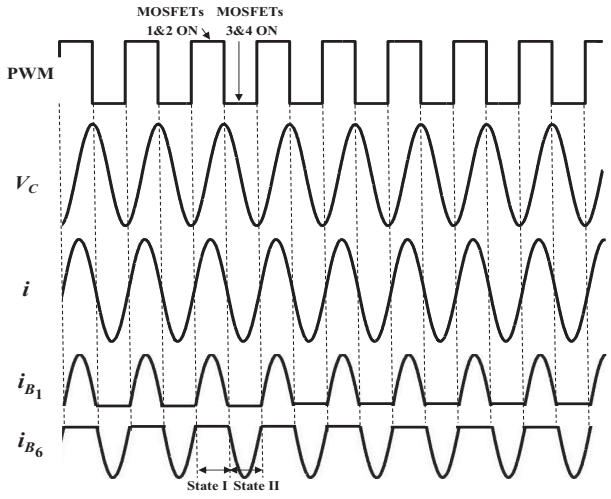


Fig. 8. Timing diagram representing energy transfer from $B_1$ to $B_6$. It is specified that the current flowing out of a cell is positive, and vice is negative.

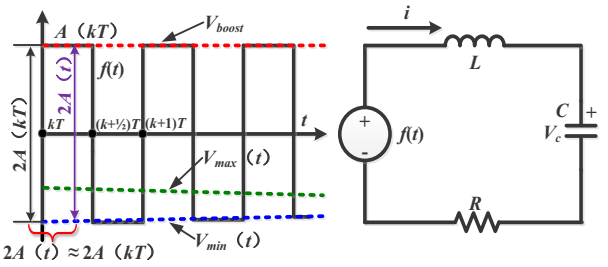


Fig. 9. Series resonant equivalent circuit of the proposed topology with the AC square wave power source.

charge current into $B_6$ is zero (see the state I in Fig. 8).

Working state II: $M_1$, $M_2$ are turned OFF, and $M_3$, $M_4$ are turned ON. The QRLCC is connected in parallel with $B_6$ through $M_3$, $D_3$ and $M_4$, $D_4$, as shown in Fig. 7 (b). *L*, *C*, and $B_6$ form a resonant loop. The current path from the QRLCC into $B_6$ is constructed. $B_6$ is charged by the capacitor *C*. Then, $V_c$ begins to decrease. Simultaneously, the BDDC acts as an open path, so the discharge current out of $B_1$ is zero (see the state II in Fig. 8).

### C. Circuit Analysis

For a sake of simplicity, it is assumed that the equalization is carried out in the battery pack with two cells. The output voltage of the BDDC is regulated to a constant value, and the voltages of the pack cells can also be viewed as constant values in a very short time. Therefore, the proposed equalization circuit can be simplified as shown in Fig. 9, and the following notations are to be used.

*1) R:* the equivalent resistance of the QRLCC. For the working state I as shown in Fig. 7 (a), *R* is the sum of the internal resistances of LC filter plug converter and the on-resistances of MOSFETs $M_1$ and $M_2$. In terms of the working state II as shown in Fig. 7 (b), *R* is the sum of the internal resistances of LC filter plug converter and the on-resistances of MOSFETs $M_3$ and $M_4$. Generally speaking, the on-resistances of MOSFETs $M_1$-$M_4$ are considered to be equal. Therefore, the resistance *R* in Fig. 9 can be expressed as

$$R = R_{LC} + 2R_{DS(on)} \tag{4}$$

where $R_{LC}$ is the internal resistance of LC filter plug converter. $R_{DS(on)}$ is the static drain-source on resistance of a MOSFET switch.

*2) T:* the switching period of the MOSFET switches, satisfying:

$$T = 2\pi\sqrt{LC}. \tag{5}$$

*3) $\omega_0$:* the characteristic angular frequency, satisfying:

$$\omega_0 = \frac{2\pi}{T} = \frac{1}{\sqrt{LC}}. \tag{6}$$

*4) m:* the harmonic number, and

$$m = \frac{\omega}{\omega_0} \tag{7}$$

where $\omega$ is the angular frequency.

*5) $V_{max}(t)$:* the maximum cell voltage.

*6) $V_{min}(t)$:* the minimum cell voltage, which can be approximate to a constant value in a switching period *T*.

*7) $V_{boost}$:* the output voltage of the BDDC, satisfying:

$$V_{boost} > V_{\max}(t). \tag{8}$$

*8) $f(t)$:* the AC square wave input of the QRLCC, whose amplitude is denoted by $A(t)$.

In our process, $f(t)$ can be expressed as

$$f(t) = \begin{cases} \frac{V_{boost} - V_{\min}(t)}{2} = A(t), & t \in (kT, (k+\frac{1}{2})T) \\ \frac{V_{\min}(t) - V_{boost}}{2} = -A(t), & t \in ((k+\frac{1}{2})T, (k+1)T) \end{cases} \tag{9}$$

where $k$=$[\frac{t}{T}]$, and $[\cdot]$ is Gaussian function. The Fourier transform of $f(t)$ can be expressed as

$$f(t) = a_0 + \sum_{m=1}^{\infty} a_m \cos(\frac{2\pi mt}{T}) + \sum_{m=1}^{\infty} b_m \sin(\frac{2\pi mt}{T}) \tag{10}$$

where $a_0$, $a_m$, $b_m$ are determined by

$$a_0 = \frac{1}{T}\int_0^T f(t)dt \tag{11}$$

$$a_m = \frac{2}{T}\int_0^T f(t)\cos\frac{2\pi mt}{T}dt, m = 1, 2, 3, ... \tag{12}$$

and

$$b_m = \frac{2}{T}\int_0^T f(t)\sin\frac{2\pi mt}{T}dt, m = 0, 1, 2, .... \tag{13}$$

As the period $T$ in our process is very small, $A(t)$, $t\in(kT,(k+\frac{1}{2})T))\cup((k+\frac{1}{2})T,(k+1)T)$ can be simplified as $A(kT)$ for a sake of simple calculation. With this knowledge in hard, the Fourier coefficient can be calculated as

$$a_m = 0, m = 0, 1, 2, ... \tag{14}$$

$$b_m = (1^m - (-1)^m)\frac{2A(kT)}{m\pi}, m = 0, 1, 2.... \tag{15}$$

After determining all coefficients of (10), the series of $f(t)$ ($kT < t < (k+1)T$, $t \neq (k+\frac{1}{2})T$) can be rewritten as

$$f(t) \approx \frac{4A(kT)}{\pi}(\sin(\omega_0 t) + \frac{\sin(3\omega_0 t)}{3} + \frac{\sin(5\omega_0 t)}{5} + \ldots). \tag{16}$$

The input AC impedance of the series resonant circuit shown in Fig. 9 can be expressed as

$$Z = R + j(\omega L - 1/\omega C). \tag{17}$$

By (16) and (17), the $mth$ harmonic wave amplitude in the resonance current is shown as

$$I_m = \frac{4A(kT)}{m\pi R\sqrt{1 + Q^2(m - \frac{1}{m})^2}} \tag{18}$$

where $Q$ is the quality factor, and

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}. \tag{19}$$

With (18), one can get the maximum of $I_m$, $m \in N$, i.e.,

$$I_1 = \frac{4A(kT)}{\pi R}. \tag{20}$$

It can be seen from (20) that $I_1$ is proportional to $A(kT)$, while is inversely proportional to the equivalent resistance $R$, but has no relationship with $L$ or $C$ values.

Under the reasonable assumptions of $R$=0.3 Ω and $A(kT)$=0.1 V, $I_m$ in (18) is represented in Fig. 10 for $Q$=1, 3, and 5, respectively. Compared $I_1$ with $I_m$ ($m \neq 1$), if $Q$ is large enough, the harmonic component in $i$ is far less than the fundamental component with the increase of the harmonic order $m$. It follows that the current $i$ in the QRLCC is very close to a sine wave, and can be approximatively represented by

$$i \approx \frac{4A(t)}{\pi R}\sin\omega_0 t. \tag{21}$$

A reasonable simplification on the transferred charge $\Delta q_T$ from one cell to another in one switching cycle can be obtained from (21), given by the following equation:

$$\Delta q_T \approx \int_0^{\frac{T}{2}} \frac{4A(t)}{\pi R}\sin\omega_0 t dt \approx \frac{8A(kT)\sqrt{LC}}{\pi R}. \tag{22}$$

Through dividing (22) by $T$, the transferred charge in unit time can be derived from

$$\frac{\Delta q}{\Delta t} = \frac{\Delta q_T}{T} = \frac{4A(kT)}{\pi^2 R} = \frac{I_1}{\pi} \tag{23}$$

where $\Delta q$ is the transferred charge in the time period $\Delta t$. (23) shows that the amplitude of the resonance current decides the balancing speed, which is not affected by $L$ or $C$ values.

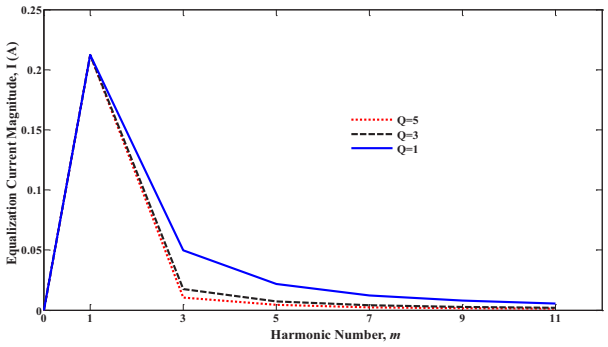


Fig. 10. Output current magnitudes of series resonant circuit with different harmonic order $m$ under the assumptions of $R$=0.3 Ω and $A(kT)$=0.1 V.

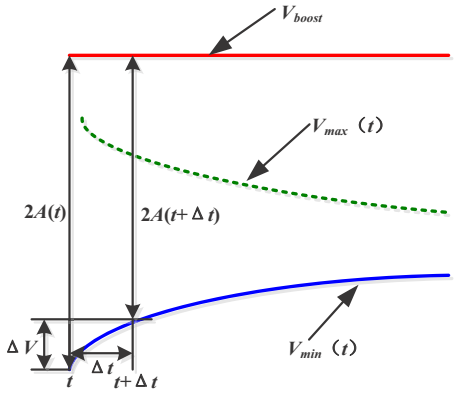


Fig. 11. Balancing process schematic diagram.

The relationship between the cell voltage and SOC is piecewise linear [15], which can be given by the following equation:

$$\Delta V = \lambda \Delta SOC = \lambda \frac{\Delta q}{C_{B,C}} = \frac{4\lambda A(kT)}{\pi^2 R \cdot C_{B,C}}\Delta t \tag{24}$$

where $\Delta V$ is the variation of the cell voltage according to the SOC variation $\Delta SOC$ within the time period $\Delta t$. $\lambda$ is the proportionality coefficient between the voltage and SOC in one approximate linear segment, and $\lambda$ can be viewed as a constant in the balancing process for relatively small SOC variation. $C_{B,C}$ represents the whole charge stored in the battery by converting nominal battery capacity in Ah to charge in Coulomb, and its value is defined as

$$C_{B,C} = 3600 \cdot C_{B,Ah} \cdot f_1(Cyc) \cdot f_2(Temp) \tag{25}$$

where $C_{B,Ah}$ is the nominal capacity in Ah. $f_1(Cyc)$ and $f_2(Temp)$ are cycle number-dependent and temperature-dependent correction factors. In general, the cycle number can be viewed as a constant in the balancing process, and a thermostat is used to keep the battery temperature constant, so all battery parameters are independent of the cycle number and temperature, i.e., $f_1(Cyc)$ and $f_2(Temp)$ are set to 1.

Fig. 11 shows the balancing process schematic diagram. It can be seen that the variation of the minimum cell voltage

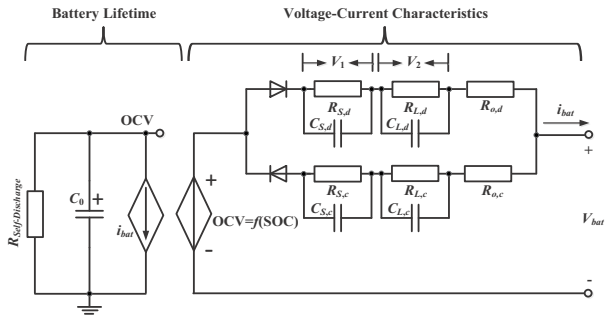


Fig. 12. Two-order RC equivalent circuit model of a battery cell. The *d* index is used for discharge, and *c* is used for charge.

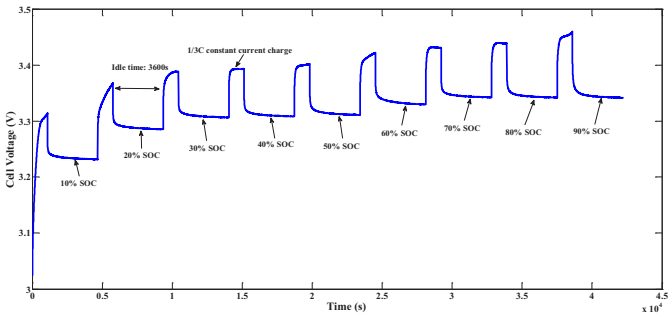


Fig. 13. Typical voltage response curve with pulse charge.

$\Delta V$ in the time period $\Delta t$ can be represented as

$$\begin{aligned}\Delta V &= 2A(t) - 2A(t+\Delta t) = -2\Delta A(t) \\ &= \frac{4\lambda A(t)}{\pi^2 R \cdot C_{B,C}} \Delta t\end{aligned} \tag{26}$$

where $\Delta A(t)$ is the variation of AC square wave amplitude in the time period $\Delta t$.

By solving (26), the relationship between $A(t)$ and the equalization time $t$ can be obtained as

$$A(t) = A(0) e^{-\frac{2\lambda}{\pi^2 R \cdot C_{B,C}} t} \tag{27}$$

where $A(0)$ is the amplitude of AC square wave at the beginning of the balancing process.

By (27), the expression of the equalization time $t$ can be represented as

$$\begin{aligned}t &= \frac{\pi^2 R \cdot C_{B,C}}{2\lambda} \ln \frac{A(0)}{A(t)} \\ &= \frac{\pi^2 R \cdot C_{B,C}}{2\lambda} \ln \frac{V_{boost} - V_{min}(0)}{V_{boost} - V_{min}(t)}\end{aligned} \tag{28}$$

where $V_{min}(0)$ is the initial value of the minimum cell voltage at the beginning of the balancing process.

As can be seen from (28), the equalization time $t$ is proportional to $R$ and $C_{B,C}$, and is inversely proportional to $V_{boost}$ and $\lambda$, having no relationship with $L$ or $C$ values. The larger the value of $R$, the longer the equalization time $t$. Therefore, the components, such as MOSFET switches, diodes, inductances, and capacitances with low equivalent resistances, can be selected accordingly to satisfy the equalizer fine requirement.

## IV. Simulation Result

### A. Battery Equivalent Circuit Model

Using the equivalent circuit model with two RC time constants shown in Fig. 12 is the best tradeoff between accuracy and complexity [47]. Therefore, this paper adopts the two-order RC circuit model for the proposed equalization system. This model comprises three parts: usable capacity ($C_B$), open-circuit voltage (OCV), and transient response (RC networks) [48]-[51].

1) Usable Capacity. The battery usable capacity can be modeled by a large capacitor $C_0$ and a self-discharge resistor $R_{Self-Discharge}$. The self-discharge resistor is used to characterize the self-discharge energy losses when the battery is stored for a long time. Theoretically, $R_{Self-Discharge}$ is a function of SOC, temperature, and cycle number. However, it can be simplified as a large resistor, or even ignored in practical application.

2) Open-Circuit Voltage. OCV, which changes depending on different capacity levels (SOCs), represents the potential difference between the two electrodes of battery in an open circuit. The nonlinear relationship between OCV and SOC, which can be represented by the voltage-controlled voltage source OCV=*f*(SOC), as shown in Fig. 12, is important to be included in the second-order RC circuit model. The OCVs at different SOCs can be obtained by measuring the battery terminal voltage after a long standing time. Through fitting the measured OCVs and the SOCs using a nonlinear function or lookup table, the nonlinear relationship between OCV and SOC is achieved for the second-order RC circuit model.

3) Transient Response. The electrical network consists of series resistor $R_o$ and two RC parallel networks, which are composed of $R_{S,c}$, $C_{S,c}$ and $R_{L,c}$, $C_{L,c}$ for charge, and $R_{S,d}$, $C_{S,d}$ and $R_{L,d}$, $C_{L,d}$ for discharge. $R_o$ determines the instantaneous voltage drop of the step response and the ohmic losses related to the physical nature of the electrodes and the electrolyte. The two RC networks determine the short-time and long-time constants of the step response, which represents the effects of the double-layer capacity and the diffusion phenomenon in the electrolyte, respectively.

To extract all the parameters in the second-order RC model at various SOC points, two experimental procedures, i.e., the pulse charge shown in Fig. 13 and the pulse discharge, need to be designed to measure the voltages and currents of cells at various SOC points. By using the measured data, the parameters of the second-order RC circuit model can be identified based on the nonlinear least-squares method, which can minimize the error between the experimental results and the model outputs.

### B. Simulation Analyses

In order to facilitate analyses, a PSpice simulation of the QRLCC is performed for a battery stack with two cells, whose initial voltages are set as 3.6 V and 3.4 V, respectively. The switching period for the QRLCC is determined by (5) and the duty ratio is set as 0.5.

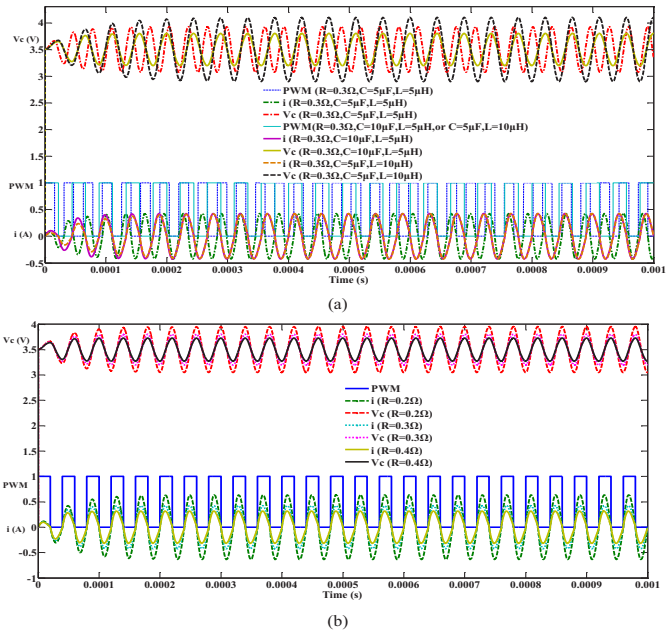


Fig. 14. Simulation results of resonant currents and capacitor voltages under resonant state. (a) Simulation waveforms with $R$=0.3 Ω and different $L$, $C$ values. (b) Simulation waveforms with $L$=5 $\mu$H, $C$=10 $\mu$F, and different $R$ values.

Fig. 14 show the simulation results of resonant currents and capacitor voltages with different $L$, $C$, and $R$ values. We observe that the resonant current $i$ is sinusoidal. The capacitor voltage $V_c$ is also a sinusoidal waveform lagging $90^o$ phase from the resonant current $i$, and the peak value of $V_c$ will occur at zero-crossing point of the resonant current. The MOSFETs are switched at the near-zero-current state, thus reducing switching losses.

Fig. 14 (a) shows the simulation results of resonant currents and capacitor voltages under the conditions of $R$=0.3 Ω and different $L$, $C$ values, which are set as $L$=5 $\mu$H, $C$=5 $\mu$F, or $L$=5 $\mu$H, $C$=10 $\mu$F, or $L$=10 $\mu$H, $C$=10 $\mu$F, respectively. We can observe that the resonant current magnitude remains invariant even though $L$ and $C$ values are changed. This verifies (20) in which the magnitude of the resonant current is not affected by $L$ or $C$ values. However, the capacitor voltage oscillation amplitude increases with $L/C$ ratio increasing.

Fig. 14 (b) shows the simulation waveforms with $L$=5 $\mu$H, $C$=10 $\mu$F, and different $R$ values, which are set as 0.2 Ω, 0.3 Ω, or 0.4 Ω, respectively. We can observe that when the equivalent resistance $R$ changes from 0.2 Ω to 0.3 Ω and then to 0.4 Ω, the oscillation amplitudes of the resonant current and capacitor voltage become smaller every time. This fact is in accord with (20) in which the magnitude of the resonant current is inversely proportional to the equivalent resistance $R$. Consequently, the choice of MOSFET switches, diodes, inductances, and capacitances with different equivalent resistances will affect the balancing settling time.

Fig. 15 shows the balancing simulation results of the proposed scheme for eight battery cells with different $V_{boost}$, $C$, $L$, and $R$ values. The initial voltages of the eight battery cells are set as 3.63 V, 3.60 V, 3.61 V, 3.59 V, 3.62 V, 3.58 V, 3.64 V, and 3.57 V, respectively. Figs. 15 ($a$) and ($b$) show that the equalization time gets shorter with a higher $V_{boost}$. Figs. 15 ($b$) and ($c$) show that the larger $R$ results in a longer equalization time. Figs. 15 ($a$) and ($d$) show that the variations of $L$ and $C$ values have less effect on the equalization time when $R$ and $V_{boost}$ remain the same.

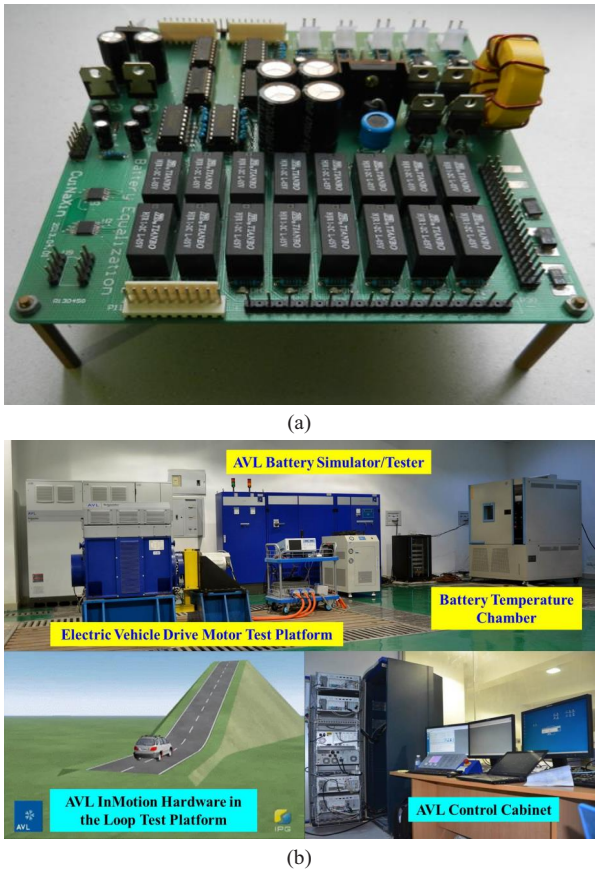


Fig. 16. The proposed eight-cell balancing system and experimental platforms. (a) Photograph of the implemented prototype. (b) Test platforms.

## V. Experimental Results

In order to verify the operation principles and to show the balancing performance of the proposed equalizer, a prototype of 8 lithium-ion cells, as shown in Fig. 16 (a), is implemented and tested. The battery tests, e.g., the constant-current charge/discharge and Urban Dynamometer Driving Schedule (UDDS) test cycles, can be achieved with the AVL test platforms, as shown in Fig. 16 (b). It mainly includes the AVL battery simulator/tester, the electric vehicle drive motor test platform, and the AVL InMotion hardware in the loop test platform. The InMotion hardware in the loop test platform can simulate well enough the characteristics of EVs and the real road conditions.

Table I summarizes the parameters of the QRLCC, the BDDC, and the selection switch modules in Fig. 6. The inductances, capacitances, and resistances in Table I are measured by an Agilent 4263B LCR Meter. The cell voltages are monitored by LTC6802-1 (made by Linear Technology), and are recorded every second.

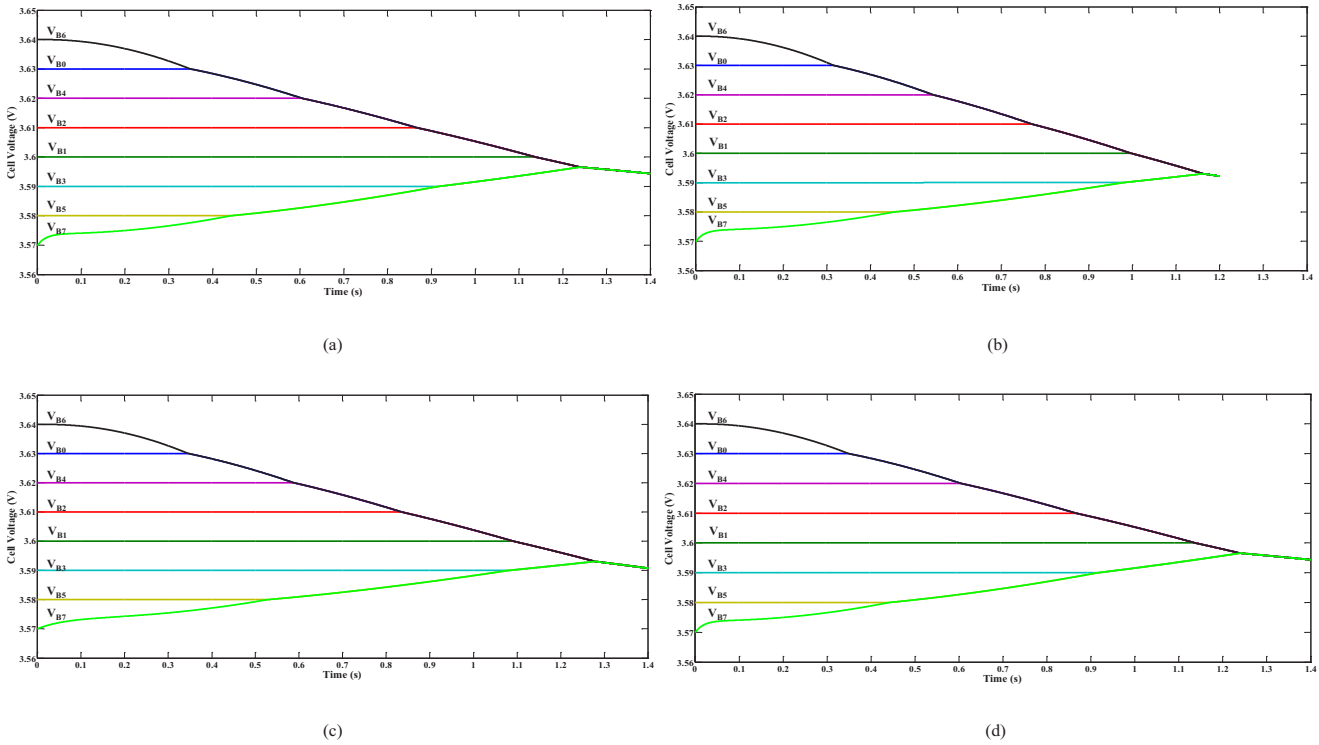


Fig. 15. Balancing simulation results of the proposed scheme for eight battery cells with different $V_{boost}$, $C$, $L$, and $R$. (a) $V_{boost}$= 7.5 V, $R$= 0.01 Ω, $C$=10 $\mu$F, and $L$=10 $\mu$H. (b) $V_{boost}$= 15 V, $R$= 0.01 Ω, $C$=10 $\mu$F, and $L$=10 $\mu$H. (c) $V_{boost}$= 15 V, $R$= 0.1 Ω, $C$=10 $\mu$F, and $L$=10 $\mu$H. (d) $V_{boost}$= 7.5 V, $R$= 0.01 Ω, $C$=20 $\mu$F, and $L$=5 $\mu$H.

### *A. Experimental Waveforms of Resonant Current and Capacitor Voltage*

Fig. 17 shows the experimental waveforms of resonant current $i$ and capacitor voltage $V_c$ with various $L$, $C$, and $R$ values, where the minimum cell voltage $V_{min}$ and the output voltage of the BDDC $V_{boost}$ are set to 3.343 V and 7.5 V, respectively. We can observe clearly from the results that the resonant current $i$ and the capacitor voltage $V_c$ are sinusoidal, and the peak value of the capacitor voltage $V_c$ occurs at zero-crossing point of the resonant current. The MOSFET switches are turned ON and OFF at near zero current state, thus effectively reducing the switching losses. We can observe from Figs. 17 (*a*)-(*c*) that if the influence of different $L$, $C$ values resulting in different equivalent resistances can be ignored, the amplitudes of the resonant current can be considered to be essentially consensus, and this verifies that the balancing current amplitude has no relationship with $L$ or $C$ values. Figs. 17 (*a*), (*d*), and (*e*) show that when the equivalent resistor $R$ in the resonant converter is changed from 0.317 Ω to 1.397 Ω and then to 2.407 Ω, the magnitude of the resonant current changes from 0.86 A to 0.64 A and then to 0.48 A. This demonstates the balancing current amplitude is inversely proportional to the equivalent resistance $R$. Therefore, the experimental results are the same as the theoretical analyses and simulations.

### *B. Static Equalization*

In order to evaluate the consistency of the cells, the consistency coefficient $\rho$ is introduced by

$$\rho = \sigma / \overline{V} \tag{29}$$

TABLE I
COMPONENT VALUES USED FOR THE PROTOTYPE

| Parameters | | | Value |
|---|---|---|---|
| Equalizer | The BDDC | MOSFET, $M_b$ | 80NF70, $R_{DS(on)}$[1]≤0.0098 Ω |
| | | Diode, $D_b$ | IN5819, $V_F$[2]=0.6 V |
| | | Inductance, $L_b$ | 100 $\mu$H |
| | | Capacitance, $C_b$ | 4700 $\mu$F |
| | The QRLCC | MOSFETs, $M_1$-$M_4$ | 80NF70, $R_{DS(on)}$[1]≤0.0098 Ω |
| | | Diodes, $D_1$-$D_4$ | IN5819, $V_F$[2]=0.6 V |
| | | Inductances, $L$ | (9.5 $\mu$H, 0.010 Ω), (50.3 $\mu$H, 0.088 Ω), (200.8 $\mu$H, 0.040 Ω) |
| | | Capacitances, $C$ | (10.9 $\mu$F, 0.288 Ω), (51.2 $\mu$F, 0.106 Ω), (93.6 $\mu$F, 0.158 Ω) |
| | The Switch Module | $(S_1, Q_1)$-$(S_n, Q_n)$, $(S'_1, Q'_1)$-$(S'_n, Q'_n)$ | HJR 1-2C L-05V |
| Battery Pack | | $B_0$-$B_{n-1}$ | $LiFePO_4$, IFR26650, 6.2 Ah |

[1] $R_{DS(on)}$. Static drain-source on resistance.
[2] $V_F$. Forward voltage.

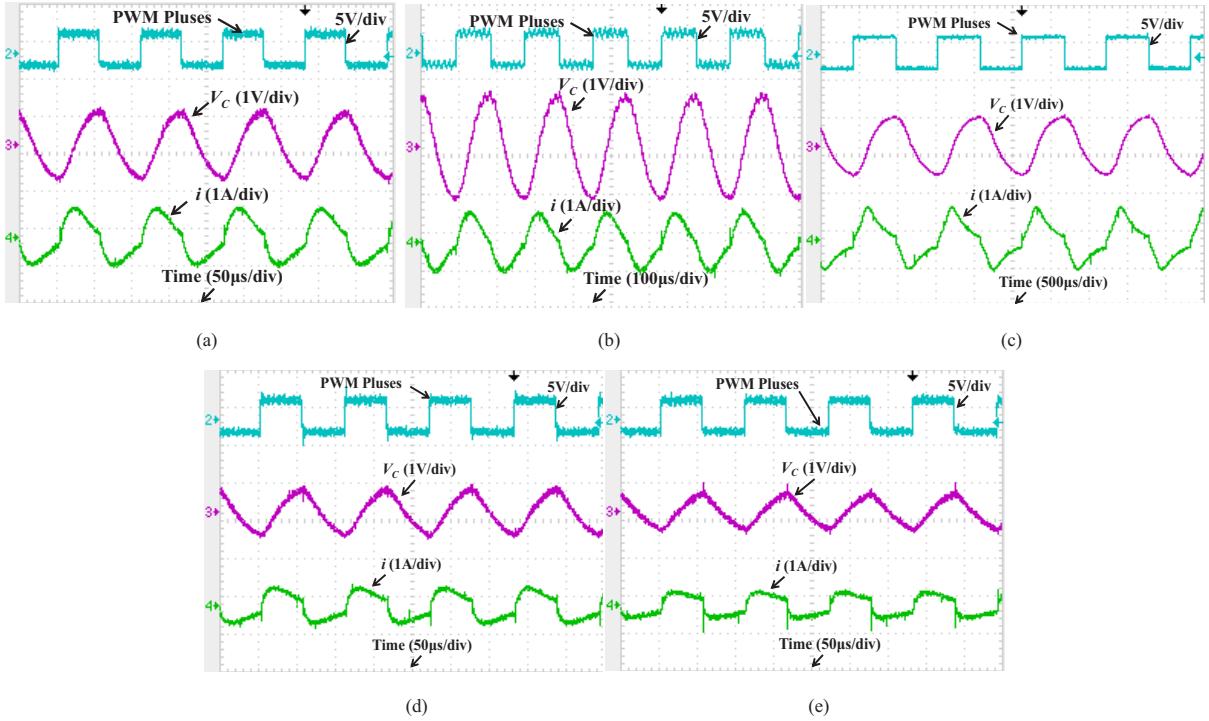


Fig. 17. Experimental waveforms of resonant current $i$ and capacitor voltage $V_C$ with various $L$, $C$, and $R$ values. (a) $C$=10.9 $\mu$F, $L$=9.5 $\mu$H, and $R$=0.317 Ω. (b) $C$=9.5 $\mu$F, $L$=50.3 $\mu$H, and $R$=0.395 Ω. (c) $C$=93.6 $\mu$F, $L$=200.8 $\mu$H, and $R$=0.217 Ω. (d) $C$=10.9 $\mu$F, $L$=9.5 $\mu$H, and $R$=1.397 Ω. (e) $C$=10.9 $\mu$F, $L$=9.5 $\mu$H, and $R$=2.407 Ω.

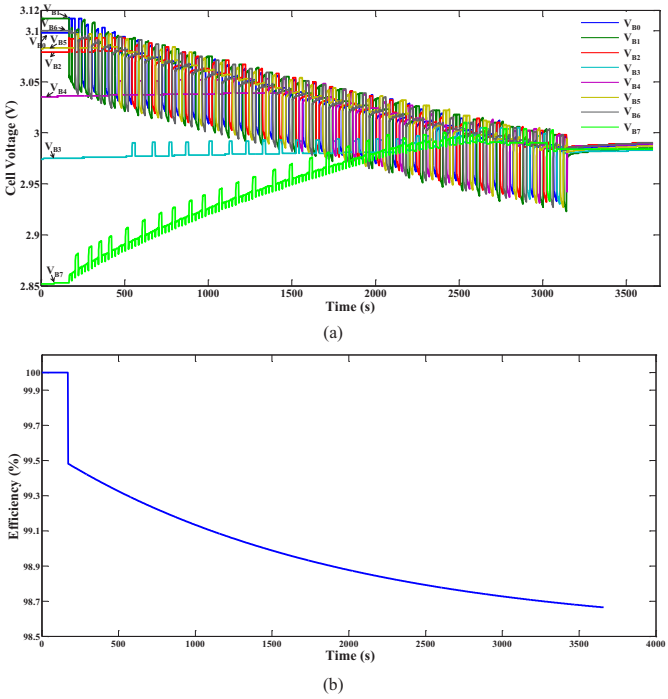


Fig. 18. Static equalization for 8 lithium-ion cells during an idle period. (a) The 8-cell voltage trajectories. (b) Energy conversion efficiency during an idle period.

where $\overline{V}$ and $\sigma$ are the average value and the standard deviation of cell voltages, respectively.

Fig. 18 presents the voltage equalization results of 8 lithium-ion cells during an idle period with the initial voltages of $V_{B0}$=3.098 V, $V_{B1}$=3.112 V, $V_{B2}$=3.079 V, $V_{B3}$=2.975 V, $V_{B4}$=3.036 V, $V_{B5}$=3.083 V, $V_{B6}$=3.1 V, and $V_{B7}$= 2.853 V. We can observe from Fig. 18 (a) that the most undercharged cell and the most overcharged voltage cell are $B_7$ and $B_1$, respectively. The maximum voltage difference between them is 0.259 V. By (29), the initial consistency coefficient of the battery stack can be obtained as 0.0884. At about 3200 s, ZVG between cells is achieved, and the consistency coefficient is greatly reduced to approximately 0. As shown in Fig. 18 (b), during the balancing process, the energy conversion efficiency varies from 99.5% to 98.6%, keeping at a high level.

### C. Dynamic Equalization

The equalization during the charge or discharge process of battery, i.e., the dynamic equalization, is more complex but necessary than that during the idle period. This is due to the serious imbalance in cell voltages that is usually generated during the fast charge or discharge process of battery. Furthermore, the cell voltage should not go below the discharge cut-off voltage (∼2 V) in order to prevent overdischarge, and the cell voltage cannot exceed the end-of-charge voltage (∼3.65 V) in order to prevent overcharge. Once one cell voltage in the battery string either exceeds the end-of-charge voltage or reaches the discharge cut-off voltage, the charge or discharge process will have to stop. This fact reduces enormously the available capacity of the battery pack. Consequently, the

dynamic equalization performance is a significant issue need to verify.

The lithium-ion battery offers a relatively flat open circuit voltage within a broad range of SOC from 20% to 80%. In other words, even though the SOC difference between cells is large, the corresponding voltage difference still remains small. Moreover, in practice the resolution limit of the analog-to-digital converter is about 0.001V-0.002V. Therefore, it would be counterproductive to carry out the voltage-based equalization during the SOC range of 20%-80%, because this may enlarge the cell inconsistency due to the voltage measurement errors. Thus, in order to improve the balancing performance, it is optimum to carry out the voltage-based equalization across the SOC range of 0%-20% or 80%-100%. Fig. 19 shows the experimental results during the constant current discharging and charging without the equalization (see Figs. 19 (a) and (c)) and with the equalization (see Figs. 19 (b) and (d)).

As shown in Fig. 19 (a), the discharging process without equalization has to stop when the cell $B_1$ reaches the discharge cut-off voltage, although the other cells still have energy left. The maximum voltage difference between cells from 80% SOC to 20% SOC is more than 0.5 V. As shown in Fig. 19 (b), the maximum voltage difference between cells from 80% SOC to 20% SOC is less than 0.02 V, showing a good consistency of the cell voltages with the proposed equalization. Almost the whole energy (i.e., 6.0 Ah) in the battery stack is used, and is significantly larger than that (i.e., 5.3 Ah) without the equalization. The available capacity of the battery stack with the proposed equalizer is increased by 13.2% compared with that without equalization.

As shown in Figs. 19 (c) and (d), a similar situation occurs when this battery stack is charged. Table II summarizes the consistency coefficients and the available capacities of the battery pack with and without equalization. We can observe that the consistency and the available capacity of the battery stack are greatly improved by the proposed equalization scheme.

TABLE II
A COMPARISON OF THE CONSISTENCY COEFFICIENT AND AVAILABLE PACK CAPACITY BETWEEN WITH AND WITHOUT BALANCING DURING CONSTANT-CURRENT DISCHARGE AND CHARGE

| Performance Indicators | Constant-Current Discharge | | Constant-Current Charge | |
|---|---|---|---|---|
| | Without Balancing | With Balancing | Without Balancing | With Balancing |
| $\rho$ at 30% SOC | 0.0156 | 0.0013 | 0.0024 | 0.0005 |
| $\rho$ at 70% SOC | 0.0122 | 0.0014 | 0.0025 | 0.0013 |
| Available Capacity | 5.3 Ah | 6.0 Ah | 6.0 Ah | 6.3 Ah |

In order to further prove the validity of the proposed scheme in terms of the dynamic equalization, Fig. 20 further presents the test results under UDDS test cycles. As shown in Fig. 20 (a), the discharging process without equalization has to stop when the cell $B_3$ reaches the discharge cut-off voltage, and the maximum voltage difference is over 0.8 V. As shown in Fig. 20 (b), all the cells are almost identically discharged with the proposed equalization, and the maximum voltage difference is about 0.6 V when the cell $B_7$ reach the discharge cut-off voltage. Fig. 20 (c) presents the energy conversion efficiency varies from 99.3% to 98.2% during UDDS test cycles, showing a high dynamic equalization efficiency of the proposed equalizer. Hence, the proposed equalizer is also appropriate for UDDS test cycles.

### *D. SOC-Based Equalization*

Voltage-based equalization, which targets the consistent cell voltages, is the most feasible to realize due to the direct measured cell voltages. But the voltage-based equalization is more challenging because of the relatively flat open circuit voltage. To solve this dilemma, a SOC-based equalization algorithm is proposed and shown in Fig. 21. SOC-based equalization targets the consistent cell SOCs rather than the cell voltages, hence this method is not limited to the SOC range of 20%-80%.

The initial SOCs of the battery cells are established from a lookup table, which consists of the OCVs and the corresponding SOC information. The ampere-hour integration approach is used to count how many coulombs of charge being pumped into or out of a battery cell, which provides higher accuracy than most other SOC estimation methods [51]-[54], since it computes directly the integral of the current with respect to time.

In the proposed method, the SOC-based balancing test is operated in an idle battery pack. As shown in Fig. 21, the balancing test begins with the initial SOCs of $SOC_0$=93.7%, $SOC_1$=100%, $SOC_2$=98.5%, $SOC_3$=91.3%, $SOC_4$=92.4%, $SOC_5$=92%, $SOC_6$=98.8%, and $SOC_7$=93.2%, whose corresponding initial voltages are $V_{B0}$= 3.348 V, $V_{B1}$=3.425 V, $V_{B2}$=3.407 V, $V_{B3}$= 3.280 V, $V_{B4}$= 3.363 V, $V_{B5}$=3.346 V, $V_{B6}$= 3.396 V, and $V_{B7}$= 3.346 V, respectively. We can observe from Fig. 21, that after about 2400 s the proposed equalizer reduces the maximum SOC difference from 8.7% to 0.9%, and reduces the corresponding maximum voltage difference from 0.145 V to 0.012 V, which proves the validity of SOC-based equalization of the proposed scheme.

### *E. Over-Equalization Prevention*

The energy in the proposed topology is transferred in real time from the cell with the highest voltage at any position to the one with the lowest voltage at any position in the stack. Therefore, an appropriate equalization switching period and equalization current are important for the consistency of the battery pack. The equalization switching period is composed of the equalization time $t_e$ and the standing time $t_s$, as shown in Fig. 22 (a). A long equalization time or a large equalization current is ample in equalization capability but might lead to over-equalization, while a short equalization time or a small equalization current can efficiently prevent over-equalization but leads to a long infant stage and high switching frequency. Hence, a fuzzy logic controller (FLC) is employed to regulate the equalization switching period ($t_e$ and $t_s$) and the equalization current of the proposed equalization scheme. The input of the FLC is the maximum voltage difference between cells in the battery pack, and the output are the equalization switching period and the duty cycle of the BDDC. It can be seen from (20) that the amplitude of the equalization current is proportional to the difference between the BDDC output

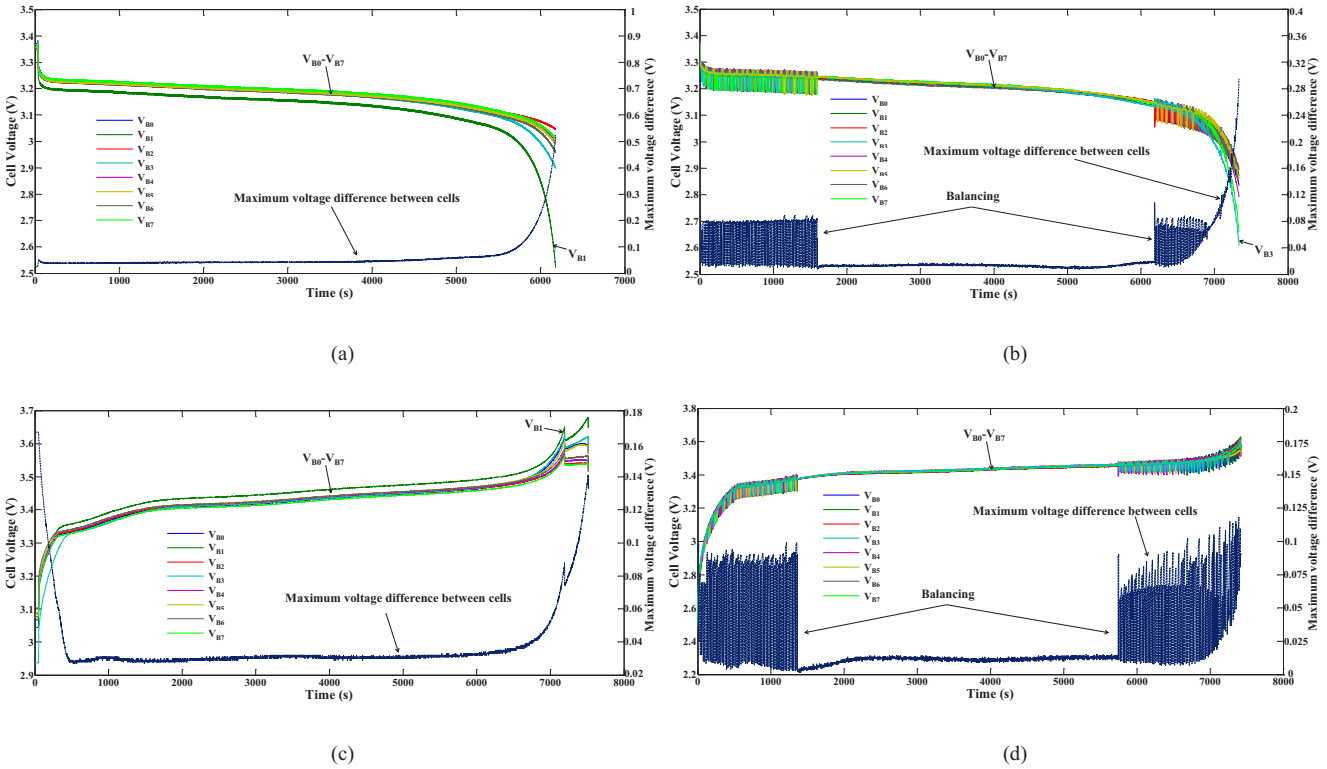


Fig. 19. Dynamic equalization during discharge and charge at a constant current of 0.5 C. (a) Discharge without voltage balancing. (b) Discharge with the proposed balancing. (c) Charge without voltage balancing. (d) Charge with the proposed balancing.

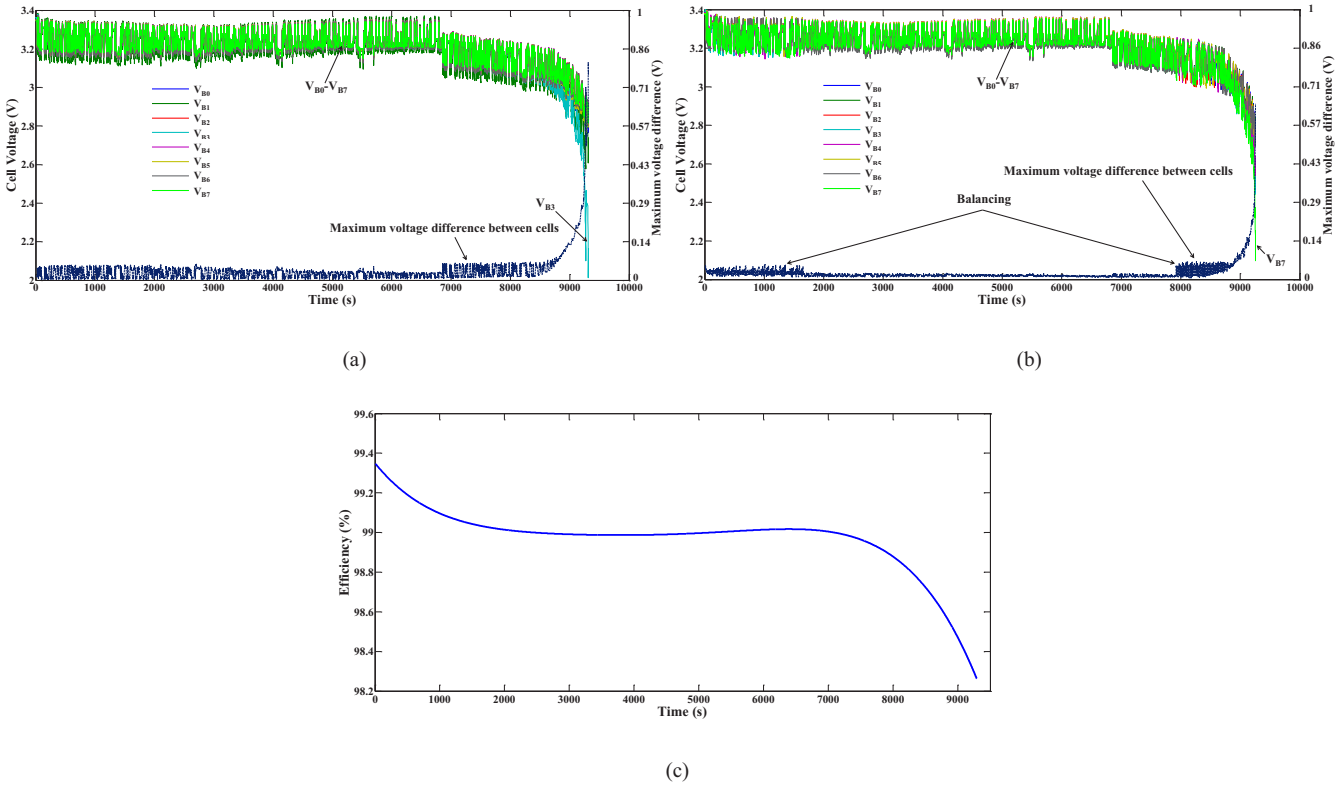


Fig. 20. Dynamic equalization during UDDS test cycles. (a) Cells' voltages and maximum voltage difference between cells without equalization. (b) Cells' voltages and maximum voltage difference between cells with the proposed equalization. (c) Energy conversion efficiency during UDDS test cycles.

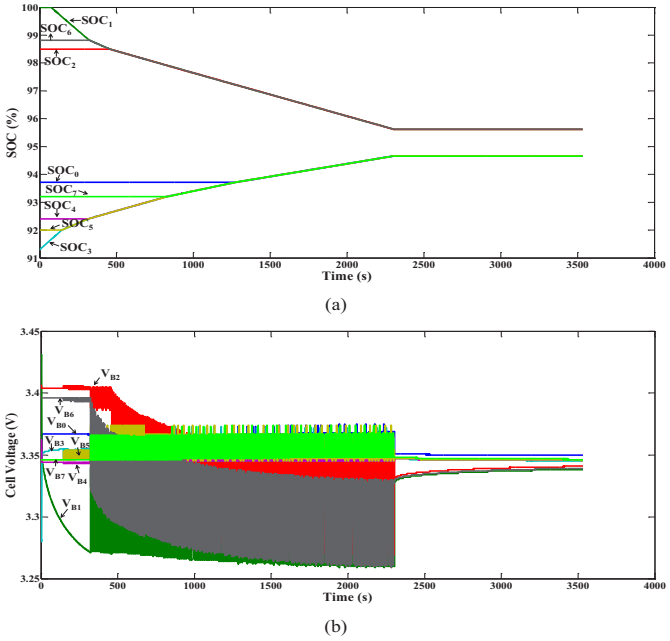


Fig. 21. SOC-based balancing for eight lithium-ion cells during an idle period. (a) The eight-cell SOC trajectories. (b)The eight-cell voltage trajectories.

voltage and the minimum cell voltage. Hence, the proposed equalizer can regulate the equalization current by directly controlling the duty cycle of the BDDC.

Fig. 22 shows the experimental results with the FLC. As shown in Fig. 22 (a), the equalizing time $t_e$ and the standing time $t_s$ are adjusted according to the voltage difference between the two cells (see the switching pots in Fig. 22 (a)). The larger the voltage difference, the longer the equalizing time $t_e$, and the shorter the standing time $t_s$. Fig. 22 (b) presents the changing process of the equalizing currents at the times $t_0$-$t_9$ marked in Fig. 22 (a). It can be observed that the equalizing current is online adaptively regulated according to the voltage difference. The proposed equalizer with the FLC effectively prevents over-equalization compared with the balancing result without the FLC in Fig. 23, where over-equalization happens due to the constant equalization switching period and the fixed duty cycle of the BDDC. Fig. 22 (c) further shows the eight-cell voltage trajectories with the FLC, whose initial voltages are the same as that in Fig. 18. We can observe that the total equalization time is abbreviated about 50% compared with the experimental result without the FLC in Fig. 18.

## VI. Comparison with Conventional Equalizers

In this section, the proposed equalizer is compared with the typical solutions of each traditional balancing method. In order to make a systematic evaluation of the proposed scheme, it is assumed that the battery pack consists of $n$ cells connected in series.

Equalization speed is one of the major design parameters for a battery balancing scheme, because the serious imbalance in cell voltages is usually generated during the fast charge or discharge of battery, which reduces enormously the available capacity of the battery pack. In general, the equalization speed

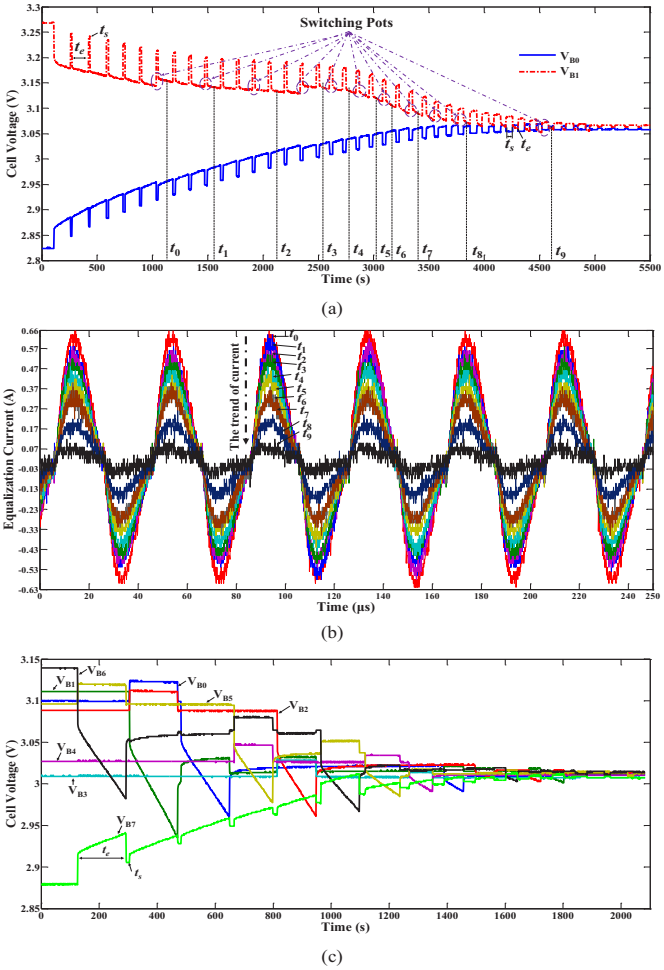


Fig. 22. Balancing results with the FLC. (a) Balancing results for two cells. (b) Equalizing currents during the two-cell balancing process. (c) Balancing results for eight cells.

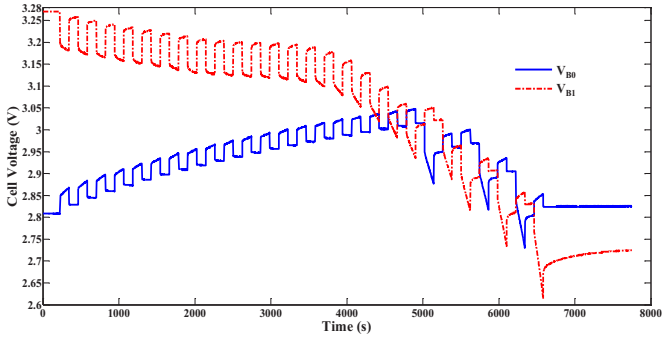


Fig. 23. Over-equalization for two cells without the FLC.

is determined by the maximum equalization current and the average switching cycle. The maximum equalization current decides the transferred power among the cells in one switching cycle, and the average switching cycle to complete the charge transportation from the source cell to the target one decides the equalization speed and efficiency.

Table III gives a quantitative comparison of the proposed equalizer with the existing typical solutions in terms of the maximum equalization current $I_E$, the average switching cycle $Cyc_{ave}$, and the average energy conversion efficiency $\eta_{ave}$. Since the proposed scheme belongs to DCTCM, the energy can be transferred directly from the source cell at any position to the target one at any position in the stack. Theoretically, it only takes one switching cycle to complete the charge transportation, which makes the cell balancing faster and more effective. As shown in Table III, the presented topology offers a 0.86 A equalization current, which is comparable to many existing solutions. In conclusion, the proposed equalizer offers a better equalization speed.

In terms of the circuit size, weight, and cost, the presented solution has also some advantages compared with the typical solutions due to the absence of transformers and a small number of MOSFETs. In the proposed topology, MOSFET switches $M_1$, $M_2$, $M_3$, and $M_4$ require a single floating drive circuit, whereas the drive circuits of the relays $(S_1, Q_1)$-$(S_n, Q_n)$, $(S'_1, Q'_1)$-$(S'_n, Q'_n)$ are powered by a common power source. Therefore, the drive circuitries of this topology are simpler. Moreover, only one LC filter plug converter and one BDDC are shared by all cells, leading to great size and cost reduction for the circuit.

Based on the above analyses, Table IV further gives a systematically comparative study in terms of component, cost, size, speed, efficiency, ZCS, ZVG, and over-equalization. "Components" defines what components are utilized and the number of them. A fuzzy scale is employed to evaluate each parameter, for which "−" is the minimum value, "+" is the maximum one, and "=" is the mean one between "+" and "−". It can be concluded from Table IV that the proposed topology has the advantages of low cost, low size, high efficiency, high speed, ZCS, and ZVG, which give the proposed topology very good implementation possibility for a long series-connected battery string.

## VII. Conclusion

In this paper, a novel direct cell-to-cell equalizer based on QRLCC and BDDC is proposed. The operation principle, the equalization time prediction, the cell balancing performance, and the comparative studies with previous contributions are presented. The proposed scheme obtains ZCS due to the QRLCC, and achieves ZVG between cells because of the BDDC. Moreover, by sharing connection of the QRLCC and the cell selection switches, the proposed equalizer solves the dilemma of equalization implementation with small size and low cost for a long series-connected battery string. On the one hand, the outstanding equalization performance (e.g., ZCS, ZVG between cells, over-equalization prevention, good equalization speed, and high equalization efficiency) of the proposed equalizer is certified by the experimental results with eight lithium-ion battery cells. On the other hand, a systematic and quantitative comparison for $n$ cells has been presented to further show the superiorities of the proposed topology in terms of circuit size, weight, and cost compared with the existing ones. As a future work, this topology will be extended for the battery pack with more than hundred cells to be used in EVs or HEVs.

## References


[1] J. Cao and A. Emadi, "A new battery/ultra-capacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles," *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp.122-132, Jan. 2012.

[2] N. M. L. Tan, T. Abe, and H. Akagi, "Design and performance of a bidirectional isolated dc-dc converter for a battery energy storage system," *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1237-1248, Mar. 2012.

[3] Y.-S. Lee, Y.-P. Ko, M.-W. Cheng, and L.-J. Liu, "Multiphase zero-current switching bidirectional converters and battery energy storage application," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 3806-3815, Aug. 2013.

[4] C. Park and S. Choi, "Quasi-resonant boost-half-bridge converter with reduced turn-off switching losses for 16 V fuel cell application," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 4892-4896, Nov. 2013.

[5] J. Park and S. Choi, "Design and control of a bidirectional resonant DC-DC converter for automotive engine/battery hybrid power generators," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3748-3757, Jul. 2014.

[6] W. C. Lee and D. Drury, "Development of a hardware-in-the-loop simulation system for testing cell balancing circuits," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5949-5959, Dec. 2013.

[7] Mini E [Online]. Available: http://en.wikipedia.org/wiki/Mini E.

[8] J. G.-Lozano, E. R.-Cadaval, et al., "Battery equalization active methods," *J. Power Sources*, vol. 246, pp. 934-949, 2014.

[9] H.-S. Park, et al., "Design of a charge equalizer based on battery modularization," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3216-3663, Sep. 2009.

[10] M. Uno and K. Tanaka, "Single-switch multioutput charger using voltage multiplier for series-connected lithium-ion battery/supercapacitor equalization," *IEEE Trans. Ind. Electron.*, vol. 60, no. 8, pp. 3227-3239, Aug. 2013.

[11] A. Manenti, A. Abba, A. Merati, S. Savaresi, and A. Geraci, "A new BMS architecture based on cell redundancy," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4314-4322, Sep. 2011.

[12] T. Stuart and W. Zhu, "Fast equalization for large lithium ion batteries," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 24, no. 7, pp. 27-31, Jul. 2009.


TABLE III
A Comparison of the Proposed Equalizer With the Existing Typical Solutions in Terms of the Equalization Speed and Efficiency

| Topology | | Equalization Speed | | Equalization Efficiency | |
|---|---|---|---|---|---|
| References | Type | $I_E$ | $Cyc_{ave}$ | $\eta$ | $\eta_{ave}$ |
| [12], [13] | CBM | 0.7 A | $\frac{n}{2}$ | 0% | 0% |
| [15] | ACTCM | 0.18 A | $\frac{n+1}{3}$ | 98% | $(98\%)^{\frac{n+1}{3}}$ |
| [22] | DCTCM | 0.8 A | 1 | 90% | 90% |
| [32] | CTPM | 0.3 A | $\frac{n}{2}$ | 88% | $88\% - \frac{1}{n}$ |
| [36] | PTCM | 0.49 A | $\frac{n}{2}$ | 61.5% | $61.5\%\frac{n-1}{n}$ |
| [40] | CTPTC | 1.96 A | $\frac{4}{3}$ | 81.6% | $(81.6\%)^{\frac{4}{3}}$ |
| Proposed Topology | DCTCM | 0.86 A | 1 | 98% | 98% |

$n$. The number of cells connected in series in a battery pack.
$I_E$. The maximum equalization current.
$Cyc_{ave}$. The average switching cycle to complete the charge transportation.
$\eta$. The conversion efficiency in one equalization cycle.
$\eta_{ave}$. The average conversion efficiency.

[13] Y. Zheng, M. Ouyang, L. Lu, J. Li, X. Han, and L. Xu, "Online equalization for Lithium-Ion battery packs based on charging cell voltages: part 2. fuzzy logic equalization," *J. Power Sources*, vol. 247, pp. 460-466, Feb. 2014.

[14] V. L. Teofilo, L. V. Merritt, and R. P. Hollandsworth, "Advanced lithium ion battery charger," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 12, no. 11, pp. 30-36, Nov. 1997.

[15] Y. Yuanmao, K. W. E. Cheng, and Y. P. B. Yeung, "Zero-current switching switched-capacitor zero-voltage-gap automatic equalization system for series battery string," *IEEE Trans. Power Electron.*, vol. 27, no. 7, pp. 3234-3242, Jul. 2012.

[16] A. Baughman and M. Ferdowsi, "Analysis of the double-tiered three-battery switched capacitor battery balancing system," *in Proc. IEEE Vehicle Power Propulsion Conf.*, 2006, pp. 1-6.

[17] R. Ugle, Y. Li, and A. Dhingra, "Equalization integrated online monitoring of health map and worthiness of replacement for battery pack of electric vehicles," *J. Power Sources*, vol. 223, pp. 293-305, Feb. 2013.

[18] Y.-S. Lee and M.-W. Cheng, "Intelligent control battery equalization for series connected lithium-ion battery strings," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1297-1307, Oct. 2005.

[19] T. H. Phung, J. C. Crebier, A. Chureau, A. Collet, and T. Van Nguyen, "Optimized structure for next-to-next balancing of series-connected lithium-ion cells," *in Proc. Appl. Power Electron. Conf.*, pp. 1374-1381.

[20] Y.-S. Lee and M.-W. Cheng, "Quasi-resonant zero-current-switching bidirectional converter for battery equalization applications," *IEEE Trans. Power Electron.*, vol. 21, no. 5, pp. 1213-1224, Sep. 2006.

[21] S.-H. Park, K.-B. Park, H.-S. Kim, G.-W. Moon, and M.-J. Youn, "Single-magnetic cell-to-cell charge equalization converter with reduced number of transformer windings," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2900-2911, Jun. 2012.

[22] F. Baronti, G. Fantechi, R. Roncella, and R. Saletti, "High-efficiency digitally controlled charge equalizer for series-connected cells based on switching converter and super-capacitor," *IEEE Trans. Ind. Informat.*, vol. 9, no. 2, pp. 1139-1147, May 2013.

[23] S.-H. Park, T.-S. Kim, J.-S. Park, G.-W. Moon, and M.-J. Yoon, "A new buck-boost type battery equalizer," *in Proc. IEEE Appl. Power Electron. Conf.*, 2009, pp. 1246-1250.

[24] L. F. L. Villa, X. Pichon, F. Sarrafin-Ardelibi, B. Raison, J. C. Crebier, and A. Labonne, "Toward the design of control algorithms for a photovoltaic equalizer: choosing the optimal switching strategy and the duty cycle," *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1447-1460, Mar. 2014.

[25] S. Yarlagadda, T. T. Hartley, and I. Husain, "A battery management system using an active charge equalization technique based on a DC/DC converter topology," *in Proc. IEEE Appl. Power Electron. Conf.*, Sep. 2011, pp. 1188-1195.

[26] F. Mestrallet, L. Kerachev, J.-C. Crebier, and A. Collet, "Multiphase interleaved converter for lithium battery active balancing," *IEEE Trans. Power Electron.*, vol. 29, no. 6, pp. 2874-2881, Jun. 2014.

[27] G. Jin-hui, J. Li-feng, L. Ying-ying, and T. Jing, "The design of a non-energy-consuming balance system for lithium-ion batteries," *in Proc. Electr. Control Eng. Conf.*, 2010, pp. 4403-4405.

[28] C. Moo, Y. Hsieh, and I. Tsai, "Charge equalization for series-connected batteries," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 39, no. 2, pp. 704-710, Apr. 2003.

[29] M. Einhorn, W. Guertlschmid, T. Blochberger, et al., "A current equalization method for serially connected battery cells using a single power converter for each cell," *IEEE Trans. Veh. Technol.*, vol. 60, no. 9, pp. 4227-4237, Nov. 2011.

[30] A. Imtiaz, F. Khan, and H. Kamath, "A low-cost time shared cell balancing technique for future lithium-ion battery storage system featuring regenerative energy distribution," *in Proc. IEEE Vehicle Power Propulsion Conf.*, 2011, pp. 792-799.

[31] C.-S. Lim, K.-J. Lee, N.-J. Ku, D.-S. Hyun, and R.-Y. Kim, "A modularized equalization method based on magnetizing energy for a series-connected Lithium-ion battery string," *IEEE Trans. Power Electron.*, vol. 29, no. 4, pp. 1791-1799, Apr. 2014.

[32] A. M. Imitiaz and F. H. Khan, ""Time shared flyback converter" based regenerative cell balancing technique for series connected li-ion battery strings," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5960-5975, Dec. 2013.

[33] M. Uno and A. Kukita, "Double-switch equalizer using parallel or series-parallel-resonant inverter and voltage multiplier for series-connected supercapacitors," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 812-828, Feb. 2014.

[34] C.-M. Young, N.-Y. Chu, L.-R. Chen, Y.-C. Hsiao, and C.-Z. Li, "A single-phase multilevel inverter with battery balancing," *IEEE Trans. Ind. Electron.*, vol. 60, no. 5, pp. 1972-1978, May 2013.

[35] M. Daowd, N. Omar, P. Van Den Bossche, et al., "Passive and active battery balancing comparison based on MATLAB simulation," *in Proc. IEEE Vehicle Power Propulsion Conf.*, 2011, pp. 1-7.

[36] C.-H. Kim, M.-Y. Kim, H.-S. Park, et al., "A modularized two-stage charge equalizer with cell selection switches for series-connected lithium-ion battery string in an HEV," *IEEE Trans. Power Electron.*, vol. 27, no. 8, pp. 3764-3774, Aug. 2012.

[37] N. Kutkut, H. Wiegman, D. Divan, and D. Novotny, "Design considerations for charge equalization of an electric vehicle battery system," *IEEE Trans. Ind. Appl.*, vol. 35, no. 1, pp. 28-35, Jan. 1999.

[38] Y.-H. Hsieh, T.-J. Liang, S.-M. Chen, W.-Y. Horng, and Y.-Y. Chung, "A novel high-efficiency compact-size low-cost balancing method for series-connected battery applications," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5927-5939, Dec. 2013.

[39] G. Altemose, P. Hellermann, and T. Mazz, "Active cell balancing system using an isolated share bus for li-ion battery management: Focusing on satellite applications," *in Proc. IEEE Systems, Applications and Technology Conf.*, 2011, pp. 1-7.

[40] C.-H. Kim, M.-Y. Kim, and G.-W. Moon, "A modularized charge equalizer using a battery monitoring IC for series-connected Li-Ion battery strings in electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 3779-3787, Aug. 2013.

[41] S. Li, C. Mi, and M. Zhang, " A high-efficiency active battery-balancing

TABLE IV
A COMPARISON BETWEEN THE PROPOSED EQUALIZER AND THE EXISTING TYPICAL SOLUTIONS IN TERMS OF THE COMPONENT NUMBER AND THE WORK PERFORMANCE

| Topology | | Components | | | | | | | Performance Indicators | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| References | Type | M | RE | L | C | D | T | R | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ |
| [12], [13] | CBM | $n$ | 0 | 0 | 0 | 0 | 0 | $n$ | + | + | + | − | − | + | − |
| [15] | ACTCM | $2n$ | 0 | $n-1$ | $n-1$ | 0 | 0 | 0 | − | − | − | − | + | + | + |
| [22] | DCTCM | $4n$ | 0 | 0 | 1 | 0 | 0 | 0 | = | = | + | + | − | − | + |
| [32] | CTPM | $n+1$ | 0 | 0 | 0 | $2n-1$ | 1 | 0 | − | − | − | = | − | + | − |
| [36] | PTCM | $2n+9$ | 0 | 0 | 9 | 9 | 9 | 0 | − | − | − | − | − | + | − |
| [40] | CTPTC | $2n+2$ | 11 | 0 | 2 | 2 | 2 | 0 | − | − | + | = | − | + | − |
| Proposed Topology | DCTCM | 5 | $2n$ | 2 | 2 | 5 | 0 | 0 | = | = | + | + | + | + | + |

Components. M (MOSFETs), RE (Relays), L (Inductors), C (Capacitors), D (Diodes), R (Resistors).
$P_1$. Cost (−: expensive, +: cheap).
$P_2$. Size (−: big, +: small).
$P_3$. Speed (−: low, +: high).
$P_4$. Efficiency (−: low, +: high).
$P_5$. Whether be ZCS or not? (−: no, +: yes).
$P_6$. Whether be ZVG or not? (−: no, +: yes).
$P_7$. Whether can prevent over-equalization or not? (−: no, +: yes).

circuit using multiwinding transformer," *IEEE Trans. Ind. Appl.*, vol. 49, no. 1, pp. 198-207, Jan. 2013.
[42] J.-H. Kim, J.-W. Shin, C.-Y. Jeon, and B.-H. Cho, "Screening process of li-ion series battery pack for improved voltage/SOC balancing," *in Proc. IEEE Power Electron. Conf.*, 2010, pp. 1174-1179.
[43] J.-H. Kim, J.-W. Shin, C.-Y. Jeon, and B.-H. Cho, "Stable configuration of a li-ion series battery pack based on a screening process for improved voltage/SOC balancing," *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 411-424, Jan. 2012.
[44] F. Deng and Z. Chen, "A control method for voltage balancing in modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 29, no. 1, pp. 66-76, Jan. 2014.
[45] Y. Zheng, M. Ouyang, L. Lu, J. Li, X. Han, and L. Xu, "On-line equalization for lithium-ion battery packs based on charging cell voltages: part 1. equalization based on remaining charging capacity estimation," *J. Power Sources*, vol. 247, pp. 676-686, Feb. 2014.
[46] Liebig's law of the minimum [Online]. Available: http://en.wikipedia.org/wiki/Liebig's_law_of_the_minimum.
[47] C. Min and G. R.-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 504-511, Jun. 2006.
[48] M. Einhorn, F. V. Conte, C. Kral, and J. Fleig, "Comparison, selection, and parameterization of electrical battery models for automotive applications," *IEEE Trans. Power Electron.*, vol. 28, no. 3, pp. 1429-1437, March 2013.
[49] B. Hredzak, V.G. Agelidis, and M. Jang, "A model predictive control system for a hybrid battery-ultracapacitor power source," *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1469-1479, March 2014.
[50] S. Ben-Yaakov, "Behavioral average modeling and equivalent circuit simulation of switched capacitors converters," *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 632-636, Feb. 2012.
[51] R. Priewasser, M. Agostinelli, C. Unterrieder, S. Marsili, and M. Huemer, "Modeling, control, and implementation of DC-DC converters for variable frequency operation," *IEEE Trans. Power Electron.*, vol. 29, no. 1, pp. 287-301, Jan. 2014.
[52] J. Kim, S. Lee, and B. H. Cho, "Complementary cooperation algorithm based on DEKF combined with pattern recognition for SOC/capacity estimation and SOH prediction," *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 436-451, Jan. 2012.
[53] J. C. Alvarez Anton, P. J. Garcia Nieto, F. J. de Cos Juez, F. Sanchez Lasheras, C. Blanco Viehjo, and N. Roqueni Gutierrez, "Battery state-of-charge estimator using the MARS technique," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 3798-3805, Aug. 2013.
[54] J. C. Alvarez Anton, P. J. Garcia Nieto, C. Blanco Viejo, and J. A. Vilan Vilan, "Support vector machines used to estimate the battery state of charge," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5919-5926, Dec. 2013.

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