A String-to-Cell Battery Equalizer Based on Fixed-Frequency LCC Resonant Converter

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Abstract—Battery equalization technology can effectively mitigate inconsistency in battery strings. In this paper, an LCC resonant converter based string-to-cell (S2C) battery equalizer is proposed to achieve easy-control battery equalization. This equalization scheme utilizes a common equalizer shared by each unbalanced cell to transfer energy from the entire string to a single cell. The proposed equalizer achieves a constant balancing current with simple fixed-frequency open-loop control. The constant balancing current facilitates a fixed equalization speed. The design considerations of the proposed equalizer are analyzed in detail, which ensures zero-voltage switching (ZVS) among all MOSFETs during the equalization process. An experimental platform to balance four Lithium-Ion battery cells is designed to verify the system performance. Experimental results validate the functionality and analysis of this battery equalizer.

Keywords—Battery equalizers, battery management system, LCC converter, electric vehicles, ZVS.

I. INTRODUCTION

Lithium-ion batteries are widely utilized in energy storage systems due to their high energy density, low self-discharge rate, and no memory effect. Since the terminal voltage of each Lithium-ion battery is usually low, in order to meet the power requirement, a large number of battery cells are usually connected in series [1]. However, the differences in battery capacity and internal resistance lead to the mismatch among the series-connected batteries, which might incur over-charge and depletion induced hazards [2],[3]. To address this issue, battery equalizers are required to mitigate these mismatches. In general, fast equalization speed and simplified control are desired features of battery equalization systems.

The balancing schemes are divided into passive and active methods. Passives methods transduce excess energy from cells into heat with shunting resistors [4]. The energy dissipation leads to zero efficiency and heat management problems. The active methods are mainly divided into four balancing structures: cell-to-cell (C2C) [5], cell-to-string (C2S) [6], string-to-cell (S2C) [7]–[11] and hierarchical module equalizer (HME) [12].

C2C method transfers energy from a higher voltage cell to a lower voltage cell. Its advantages include small size and easy implementation. However, its equalization speed is usually slow because of the trivial voltage gap [13]. C2S method [6] presents a flexible energy flow. However, in this structure, each cell requires a separate transformer winding. This leads to bulky magnetics when the number of cells scales up. As discussed in [12], HME method employs a multi-winding transformer to achieve energy transfer between cell packs. This structure can decrease the number of switches. However, HME requires multi-level equalizers to balance single cells in sub-module which increases control complexity.

In [7]–[11], S2C structures are investigated to solve cell voltage difference issues. S2C equalizers are mainly applied to

Fig. 1. Schematic of the proposed equalizer to balance 4 cells.
scenarios when certain cells are undercharged. Typically, this structure uses a fly-back unit as the equalization circuit. Its size is usually large because of the multi-winding transformer. Balancing speed is a crucial parameter to evaluate the performance of the battery equalizer. Indeed, it is mainly determined by the balancing current. In [7], LLC resonant converter is employed to achieve a closed-loop controlled constant current balancing. Whereas, the switching frequency of LLC converter needs to swing over a wide range to achieve constant current balancing. This increases control and circuit complexity. In [14] and [15], different active equalization structures are compared. Among them, S2C structure can obtain large balancing current because of large voltage differences between the string and unbalanced cells [8]. Thus, these structures are suitable in scenarios with the voltage of single-cell lower than the average voltage.

This paper proposes an LCC resonant converter based equalizer. It is able to achieve the energy transfer from the cell string to a single cell. In addition, the high voltage battery cell can transfer its charge to the low voltage battery cell via the battery string. Compared with the conventional S2C method, the proposed equalizer is featured with a reduced number of balancing cycles. On the other hand, the proposed equalizer has good constant current characteristics [16]. The current can be customized by properly designing the circuit parameters. Due to the output characteristic of LCC resonant converter, only a pair of complementary driving signals with fixed switching frequency are required. This simplifies the circuit design and reduces the control complexity. Moreover, both MOSFETs can realize ZVS turn-on, and both diodes can realize ZCS turn-off. This reduces the switching loss remarkably. The proposed equalization structure can be easily configured in the hierarchical structure to improve circuit extensibility.

Fig. 2. Key waveforms of LCC based equalizer.

II. PROPOSED EQUALIZER AND OPERATION PRINCIPLES

The schematic of the proposed equalizer to balance four series-connected batteries is plotted in Fig. 1. As shown, it is based on a shared LCC resonant converter. The multiplexer facilitates both shared transformer and the hierarchical structure. Fig. 2 demonstrates the corresponding key waveforms of the LCC based equalizer. The operation of the equalization unit can be divided into four modes. Their equivalent circuits are illustrated in Fig. 3. Each mode can be described briefly as follows:

**Mode 1:** As shown in Fig. 3 (a), at \( t = t_0 \), \( Q_1 \) is turned ON with ZVS, and \( Q_2 \) remains OFF. At this time, \( i_{Lr} \) dose not return to zero, and the resonant tank discharges to the battery string through \( Q_1 \). The terminal voltage of \( C_p \) is clamped at \(-n(V_o+V_D)\).

**Mode 2:** As shown in Fig. 3 (b), at \( t = t_1 \), \( i_{Lr} \) increases to zero. Meanwhile, the parallel resonant capacitor \( (C_p) \) begins to be discharged. The terminal voltage on \( C_p \) \((V_{cp})\) decreases and then increases. Whereas, \( V_{cp} \) is lower than \(-n(V_o+V_D)\) in this...
mode. Thus, two rectifier diodes on the secondary side of the transformer are reversely biased.

**Mode 4:** As shown in Fig. 3 (d), at \( t = t_4 \), \( Q_4 \) is turned OFF, \( C_{eq2} \) starts to be charged, \( C_{eq2} \) starts to be discharged. During the dead band, \( i_{o1} \) commutes to \( Q_2 \) and flows through its body diode. This means that the body diode conduct before \( Q_2 \) turns on. This creates the condition of the soft-switching for \( Q_2 \).

Starting at \( t_4 \), the resonant converter starts to work in the other half cycle, which is similar to the first half cycle.

### III. BALANCING CURRENT AND DESIGN CONSIDERATIONS

#### A. Balancing Current

First harmonics analysis (FHA) method is used to analyze the circuit. In order to simplify the analysis, the circuit is assumed to operate in an ideal working state and the transformer is ideal [17].

The fundamental component of \( v_{ab} \) (\( v_{ab1} \)) is expressed as,

\[
v_{ab1} = \frac{2V_{string}}{\pi} \sin(2\pi f_s t)
\]  

(1)

The output current of the resonant network can be derived as,

\[
i_o = \frac{v_{ab1}}{Z_r[Q_o(1+C_r)(1-f_s^2)+j(f_s - \frac{1}{f_s^2} - 1)C_r]}
\]  

(2)

Where \( f_s \) is the normalized angular frequency \( (f_s = f_o/f_0) \); \( C_o \) is capacitance ratio \( (C_o = C_{eq}/C_r) \); \( Z_r \) is the resonant network impedance \( (Z_r = \sqrt{L_o/C_r + 1/C_r}) \); \( Q_o \) is resonant circuit quality factor \( (Q_o = R_{eq}/Z_r) \);

#### B. Open Circuit Voltage Estimation

Based on equation (1), when \( f_n = 1, f_s = f_o = \sqrt{2} \), and the output current can be derived as,

\[
i_o = \frac{V_{string}(1+C_o)}{Z_r}
\]  

(3)

The output current is normalized as,

\[
i_{o,N} = \frac{I_o}{V_{string}/Z_r}
\]  

(4)

\[
i_{o,N} = \frac{1}{\sqrt{Q_o^2(1+C_o)(1-f_o^2)+\left(f_o - \frac{1}{f_o^2} - 1\right)C_o}}
\]  

(5)

The curves of current gain versus normalized frequency under different load conditions are depicted in Fig. 4. As shown, the curves converge to a point at \( f_o = 1 \). According to equation (3), the output current is determined by the input voltage and resonant tank parameters while it is independent of load.

#### C. Design Considerations

- **Balancing Current:**
  - Thevenin model;
  - Simplified battery model;
  - Equivalent circuit of the basic equalizer unit with two cells.

**Fig. 4. Current gain curves versus normalized \( f_n \).**
Due to the existence of internal resistance, the open-circuit voltage (OCV) is not equal to the measured terminal voltage \(V_{\text{cell}}\). Therefore, equalization judgment may not be accurate. In order to improve equalization accuracy, the Thévenin-based electrical model [18] is used in the Li-ion battery model [19]. Its schematic is illustrated in Fig. 5 (a), where the dc voltage source represents OCV, \(V_{\text{cell}}\) is the terminal voltage, \(R_0\) is the ohmic resistance, \(R_1, \ldots, R_n\) are dynamic resistances, and \(C_1, \ldots, C_n\) are the corresponding dynamic capacitances, and \(i_{\text{cell}}\) is the terminal current. The equivalent internal resistance \(R_{\text{eq}}\) can be measured experimentally based on a further simplified model, as shown in Fig. 5 (b).

In order to simplify the analysis, the equivalent circuit diagram of the proposed voltage equalizer with two cells is shown in Fig. 5 (c), the basic LCC resonant converter can be modeled as a DC transformer, and the cell pack (Cell1 and Cell2) is source and the single cell (Cell2) is the target cell. \(L_s\), \(I_{\text{cell1}}\) and \(I_{\text{cell2}}\) represent average output current, input current and equalization current, respectively. Thus, OCV can be

**Table I**

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Fig. 6. Open circuit voltages with different equalization stages. (a) Without recovery effect compensation, (b) With recovery effect compensation.

Fig. 7. The photo of experiment setup

![Fig. 7](image)

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can accurately characterize the end of balancing. This is when the proposed equalizer output compensates for the recovery effect. Therefore, the equalization process needs to be extended to compensate for the voltage change after the equalization stops.

The equivalent internal resistance ($R_{eq}$) can be measured experimentally by the pulse-current discharge method [13]. The voltage drop across the battery internal resistance affects the accuracy of balancing judgment. Compensating the impact of $R_{eq}$ can capture $OCV$ curves to improve the accuracy of equalization.

### C. Recovery Effect Compensation

Generally, batteries have recovery effect, and the open-circuit voltage can be stable only after a certain idle time. Then, the open-circuit voltage can accurately characterize SOC[20]. However, practically in the equalization process, the effect affects the judgment of the end of balancing. The recovery effect can be clearly observed in the experimental results as shown in Fig. 6 (a). In order to improve the accuracy of equalization, battery recovery should be considered in the process of equalization. The voltage of the battery falls after the charging and rises after discharging.

Therefore, the equalization process needs to be extended to compensate for the voltage change after the equalization stops [21]. As shown in Fig. 6 (b), when certain over-balance is enforced, the open-circuit voltage converges eventually after the equalization. This is due to the battery recovery effect. Using this method, more accurate balancing can be achieved.

### IV. EXPERIMENTAL VERIFICATION

In order to validate the analysis of the proposed equalizer, an experimental prototype to balance four series-connected Lithium-ion cells is implemented. Fig. 7 showcases the test bench. The circuit parameters are listed in Table I. NCR18650PF Lithium-ion cells are employed in the prototype. The module multiplex network is implemented by relays (SRD05VDC).

Fig. 8(a) shows the key waveforms of $Q_1$ and $v_{OC2}$. Fig. 8 (b) shows the waveforms of $v_{O2s2}$, secondary winding voltage $v_{os}$, diode current $i_{O3}$ and $i_o$. Both $Q_1$ and $Q_2$ are turned on with ZVS, which verifies the theoretical analysis.

As shown in Fig. 9, when the proposed equalizer output voltage is equal to the change of load in the real process of single cell battery balancing, the output balancing current is
approximately 505 mA. When the load range is equal to three batteries, the change range of the output current is less than 5%. It indicates that the proposed equalizer achieves a good open-loop constant current performance.

Figs 10 and 11 show the experimental terminal voltages ($V_{\text{cell}}$) and open-circuit voltage of every single cell during two different working scenarios. The voltage data is recorded by Keysight 34972A. In Fig. 10, three cells have identical initial voltages (3.882 V), while the target cell has its initial voltage lower than the average voltage (3.678 V). This setting emulates the scenario when a cell has its voltage is obviously lower than the average voltage of the string. As demonstrated, when the balancing stops, a recovery phenomenon of each cell is observed. Therefore, the balancing time needs to be extended to ensure that the voltage converges. The experimental results show that when the voltage of a certain battery is lower than the threshold voltage, the equalization circuit reduces the voltage difference from 204 mV to 3mV in 4,100 seconds.

In Fig. 11, three series-connected lithium-ion cells in the string have identical initial cell voltages (3.647 V), while the source cell has its initial voltage higher than the average voltage (3.789 V) This setting emulates the scenario when a cell has its voltage is obviously higher than the average voltage of the string. The experimental results show that when the voltage of a certain battery is higher than the overall voltage, the equalization circuit reduces the voltage difference from 142 mV to 7 mV in 3,000 seconds.

V. CONCLUSION

This manuscript proposes a novel battery equalizer based on LCC resonant converter. This equalizer utilizes the constant current characteristic of LCC resonant circuit at the resonance frequency. The proposed structure can achieve a direct path for charge transfer between the cell string and the single cell. In addition, simple control complexity can be achieved. The experimental results are presented to validate the analysis. Both MOSFETs operate with ZVS to reduce the switching loss. An experiment platform to balance four Lithium-Ion battery cells is designed to verify system performance.

ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China under Grant 51607113.

REFERENCES