Constant Current and Constant Voltage Hybrid Bidirectional String-to-Cell Equalizer Based on C2L3 Resonant Topology

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***Abstract*—Key performance metrics in battery equalization systems include equalization speed, energy flow path length and control complexity. In this paper, we propose a string-to-cell equalizer based on the C2L3 resonant topology to achieve a good comprise among those metrics. The proposed equalizer hybridizes constant current (CC) and constant voltage (CV) balancing in different stages of equalization, ensuring both fast speed and high accuracy. Moreover, we adopt direct String-to-Cell (S2C) and Cell-to-String (C2S) connections to minimize energy flow path length. Besides, open loop control is analyzed and adopted, which can significantly reduce the control complexity. Simulations are conducted to verify feasibility of the proposed equalizer. An experimental prototype of C2L3 converter is designed. Experiment shows that it has a good ZVS ability.**

***Index Terms*—Battery Equalization, Battery management system (BMS), C2L3 converter, ZVS.**

I. Introduction

Lithium-ion battery is a widely used energy storage component for its advantages of high energy density, low self-discharge rate and no memory effect [1]. However, imbalances in lithium-ion battery strings can occur due to various internal and external operations. Such imbalances can lead to significant performance degradation, cell damage and safety issues [1]–[4]. Battery equalizers can effectively mitigate this issue.

As Fig. 1 shows, equalizer structures can be classified based on their energy flow paths: Cell-to-Cell (C2C) (Fig. 1 (a)) [5]–[8], String-to-Cell (S2C) (Fig. 1 (b)) [1], [9]–[11], Cell-to-String (C2S) (Fig. 1 (c)) [9], [11], [9], [11] and hierarchical module equalizer (HME) (Fig. 1 (d)) [5].

The simplest structure is C2C, it directly transfers energy from strong cell to weak cell. Equalizer maintains simple structure, but its equalizing speed is slow due to the small voltage gap between weak and strong cell. To make the matter worse, energy flow path length depends on the distance between strong and weak cells, if there are too many intermediate cells, energy flow path is long, which degrades the efficiency. To solve this problem, Any-Cell-to-Any-Cell (AC2AC) structure based on multi-winding transformer is proposed in [8]. All cells are connected to a common transformer, energy can directly be transferred from strong cells to weak cell via the

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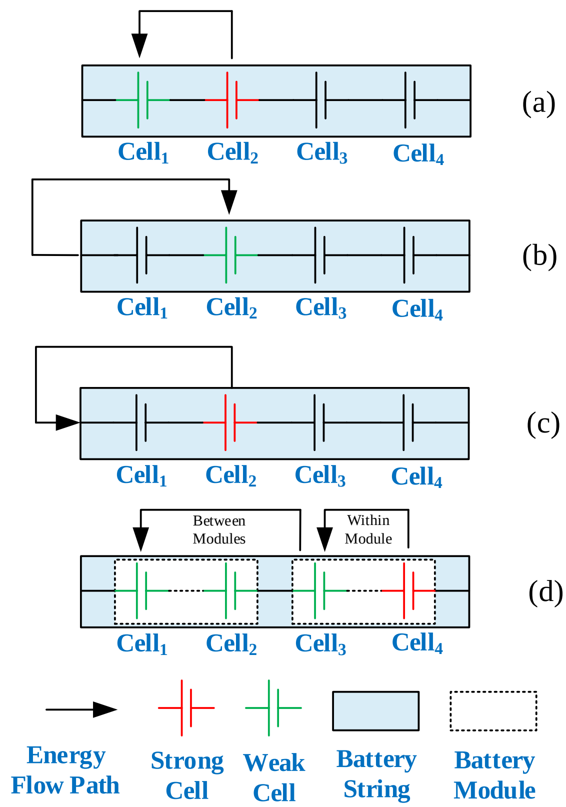

Fig. 1. Equalizers sorted by energy flow pathes: (a) C2C, (b) S2C, (c) C2S, (d) HME.

transformer. The energy flow path is constant no matter how many cells are there between strong and weak cell. However, a multi-winding transformer is needed, if cell number scales up, transformer design and manufacture can become challenging.

HME is another structure to shorten energy flow path when there is a long distance between strong cell and weak cell. In [5], a long battery string is divided into different modules, they use buck-boost converter to equalize cells within a group and adopt LLC converter to achieve equalization among groups. However, adopting different topologies can lead to an increase of system and control complexity. To make the matter worse, this structure still adopt C2C structure to equalize cells within a group, which inherits the slow equalizing issue.

To improve, S2C structure can accelerate the equalizing speed since there is a large voltage gap between the entire battery string and a single cell. In [1], a S2C equalizer based on LCC converter is proposed. This method maintains a high equalizing speed. However, if the string has only one strong cell, this structure needs to transfer energy from the string to all other weak cells, which increases equalization complexity and degrades the efficiency.

To make up the drawback of S2C, C2S is proposed. In C2S structure, energy is transferred directly from strong cell to the entire string, which is contrary to S2C. Since S2C and C2S are two symmetrical structures, they can be combined together. In [9], a bidirectional L2C3 equalizer is proposed. S2C and C2S are realized by a bidirectional dc/dc converter. However, L2C3 converter can only achieve constant current equalization. If the equalization stop point and recovery immune time is not properly adjusted at first, the equalizing accuracy can not be ensured.

In this paper, a novel equalizer based on C2L3 resonant topology is proposed. S2C and C2S can be realized by one bidirectional converter. Both Constant Current (CC) and Constant Voltage (CV) equalization are adopted to ensure fast equalizing speed and high accuracy. These innovations can solve these drawbacks mentioned above.

The main contributions of the proposed equalizer are outlined:

1) Achieving bidirectional equalization with a single converter, which significantly reduces system complexity;
2) Implementing CC and CV mode to ensure both fast equalization speed and high accuracy;
3) ZVS is realized in the proposed converter topology;
4) Open-loop control is analyzed and adopted, which can significantly reduce control complexity.

II. Operation Principles

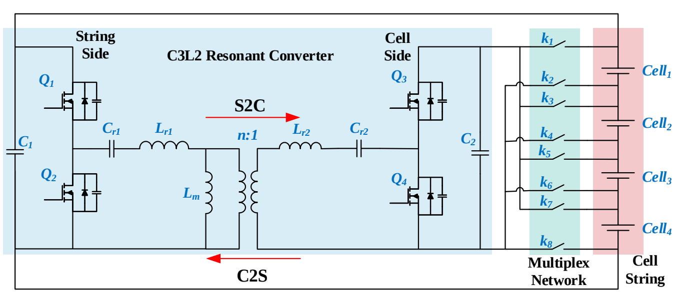

Fig. 2. Schematic of proposed equalizer.

Fig. 2 shows schematic of the proposed equalizer. As shown, one side of the converter is connected to the battery string, which is the string side; the other side is connected to a multiplex network used to select cell to be equalized, which is the cell side. The typical waveform of C2L3 converter is shown in Fig. 3. Dead time between two gate signals need to be enforced to facilitate the ZVS of MOSFETs.

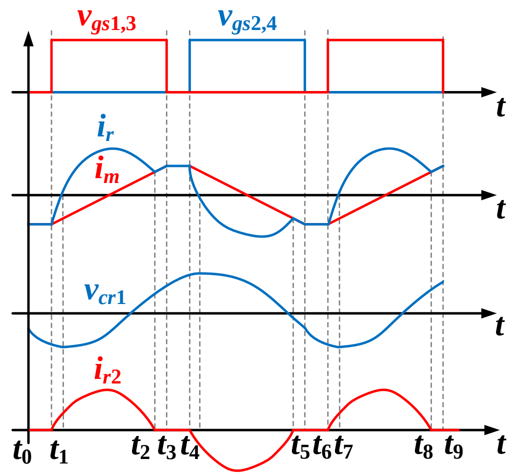

Fig. 3. Typical waveforms of the proposed equalizer.

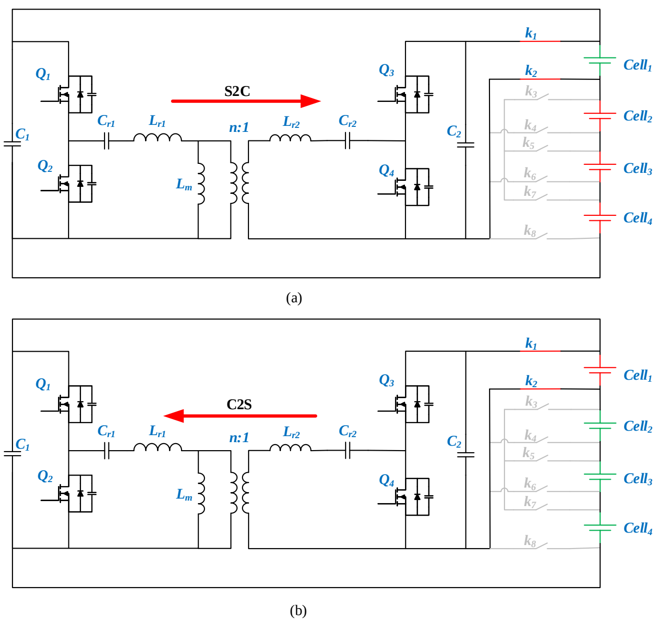

Fig. 4. Operation principles of (a) S2C and (b) C2S modes.

A. S2C Mode

When a weak cell is located, S2C mode will be enabled. As Fig. 4 (a) shows, if $cell_1$ is a weak cell in the string, in order to equalize it, switch k_1 and k_2 will be turned on. Then, S2C mode is enabled, as the red arrow shows, energy flows from string to cell. There are two major switching frequencies in this mode. At the beginning stage, a lower frequency is selected, which facilitates a CC fast equalization. In the ending stage, a higher frequency (equals to resonant frequency) is selected, which facilitates a CV equalization.

B. C2S Mode

When a strong cell is located, C2S mode will be enabled. As Fig. 4 (b) shows, if $cell_1$ is a strong cell in the string, in order to equalize it, switch k_1 and k_2 will firstly turned on. Then, C2S mode is enabled, as the red arrow shows, energy flow from cell to string. The circuit operation also maintains CC and CV modes, which are similar to S2C. There are also two major switching frequencies in this mode. At the beginning stage, the lower frequency is selected, which facilitates a CC fast equalization. In the ending stage, the higher frequency (equals to resonant frequency) is selected, which facilitates a CV equalization, which is same as S2C mode.

III. Design Considerations

A. Parameter Design

To simplify the analysis of the C2L3 converter, first harmonics approximation (FHA) [12], [13] is adopted. Equivalent circuit of the resonant tank is plotted in Fig. 6. The corresponding equivalent L_{r2} and C_{r2} can be derived as Eq. (1)

$$\begin{cases} L_{r2} = L_{r1}/n^2 \\ C_{r2} = C_{r1} \times n^2 \end{cases} \tag{1}$$

where n is the turns ratio of transformer.

The normalized voltage gain can be derived as Eq. (2)

$$\begin{cases} G_n = \frac{{\omega_n}^3}{\sqrt{a+b}} \\ a = {\omega_n}^2\left({\omega_n}^2\left(\frac{1}{L_n}+1\right) - \frac{1}{L_n}\right)^2 \\ b = Q^2\left({\omega_n}^4\left(\frac{1}{L_n}+2\right) - {\omega_n}^2\left(\frac{2}{L_n}+2\right) + \frac{1}{L_n}\right)^2 \end{cases} \tag{2}$$

where L_n is the inductance ratio, ω_n is the normalized angular frequency, and Q is the quality factor of the resonant tank, which shows as Eq. (3).

$$\begin{cases} L_n = \frac{L_m}{L_r} \\ \omega_n = \frac{\omega_s}{\omega_r} \\ Q = \frac{\sqrt{L_r/C_r}}{R_{ac}} \end{cases} \tag{3}$$

According to the gain curve shown in Fig. 5, a larger Q is preferred to get a higher equalization speed at CC mode. In CV mode, the equalizer work at the resonant frequency. At that time, the output voltage is constant even if the load changes. Besides, as analyzed in [12], to achieve ZVS, L_m should meet the requirement of Eq. (4).

$$L_m \leq \frac{T_0 t_d}{16 C_{oss}} \tag{4}$$

B. Open Loop Control

The designed equalization current in S2C mode is $500mA$. Cell voltage variation range is $3.6V - 3.7V$, Dc equivalent resistance can be calculated by Eq. (5), which is $R_{eq\_dc} = 7.2\Omega - 7.4\Omega$.

$$R_{eq\_dc} = \frac{V_{cell}}{I_{balance}} \tag{5}$$

The ac equivalent resistance R_{ac} can be derived as Eq (6).

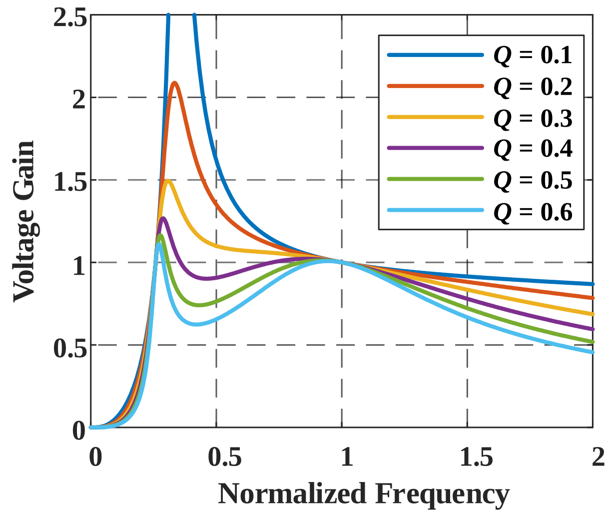

Fig. 5. Voltage gain of different Q.

$$R_{ac} = \frac{2R_{eq\_dc}}{\pi^2} \tag{6}$$

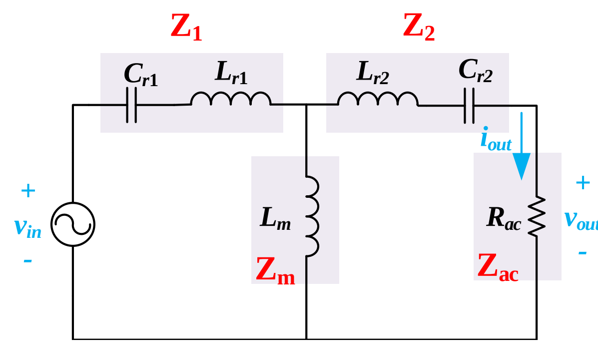

Fig. 6. AC equivalent circuit.

The expression of output voltage is derived as Eq. (7) and is plotted in Fig. 7 (a).

$$V_{out} = V_{in}\frac{Z_{ac}Z_m}{\left(Z_1 + \frac{Z_m(Z_2+Z_{ac})}{Z_2+Z_{ac}+Z_m}\right)(Z_2+Z_{ac}+Z_m)} \tag{7}$$

The expression of output current is derived as Eq. (8) and is plotted in Fig. 7 (b).

$$I_{out} = V_{in}\frac{Z_m}{\left(Z_1 + \frac{Z_m(Z_2+Z_{ac})}{Z_2+Z_{ac}+Z_m}\right)(Z_2+Z_{ac}+Z_m)} \tag{8}$$

As Fig. 7 shows, since the equivalent resistance only varies in a small range, at CC mode, constant current closed loop control can be replaced by constant frequency open loop control. This remarkably reduces the control complexity.

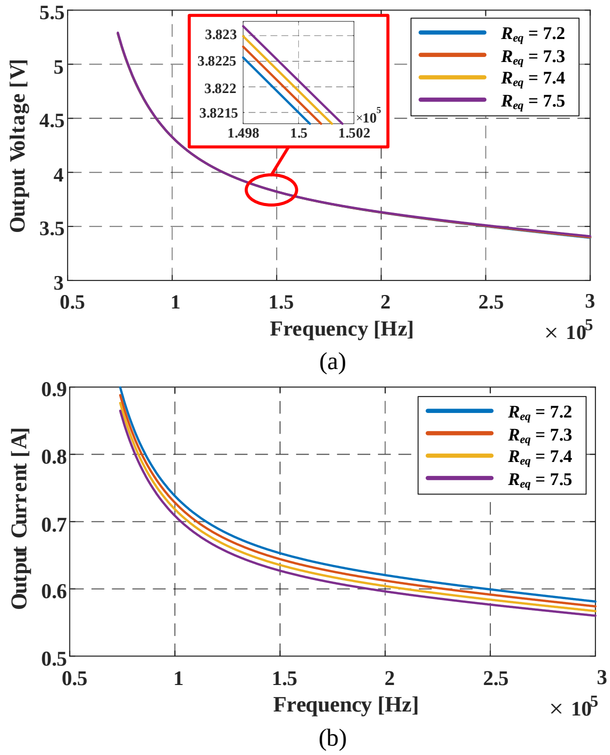

Fig. 7. (a) Output voltage versus f_s at different load conditions, (b) output current versus f_s at different load conditions.

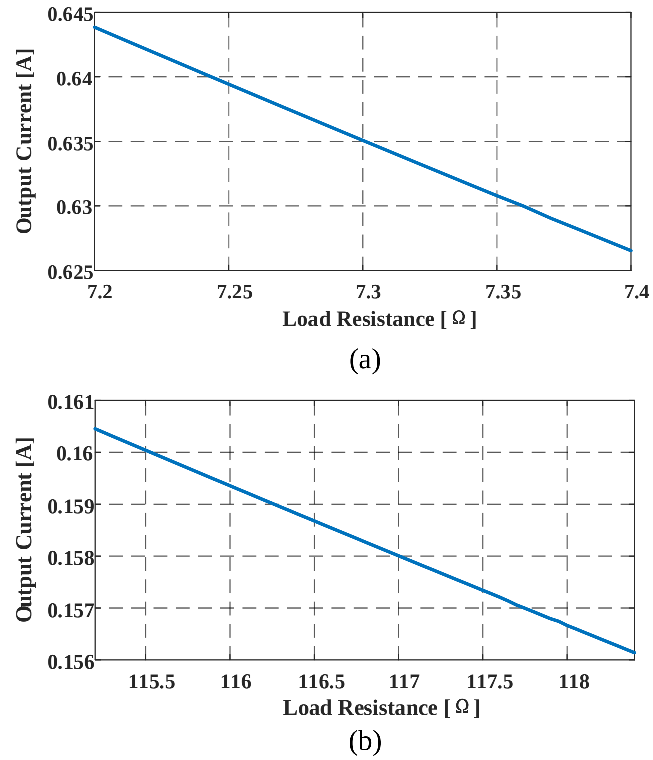

Fig. 8. Current variation in constant frequency control: (a) S2C Mode (b) C2S Mode.

IV. Results

A. Open Loop Feasibility Simulation

As mentioned earlier, open loop constant frequency control can replace close loop constant current control in battery equalization usage.

To verify this, a simulation is conducted in PSIM. In S2C mode, switching frequency is set as $100kHz$ which is lower than resonant frequency, when load resistance changes from 7.2Ω to 7.4Ω, output current changes from $0.644A$ to $0.627A$. In C2S mode, output current changes from $0.160A$ to $0.156A$. Current variation curves are plotted in Fig. 8. This current error is acceptable considering practical battery equalization.

B. Equalization Simulation

To validate the proposed equalizer, simulations are conducted in PSIM. Parameters adopted in simulation are summarized in Table I. To shorten simulation calculation time, four $1000mF$ capacitors with preset initial voltages are adopted to replace battery cells.

First simulation is CC in S2C mode, initial voltage of $cell_1$ is $3.8V$, others are $4.0V$. When equalization starts, as Fig.9 (a) shows, switching frequency is set to be lower than resonant frequency, voltage of $cell_1$ is increases and other cells decrease. CC mode can provide a high equalizing speed. If CC mode keeps equalizing without a ending point, weak cell will be over equalized. The ending point is marked as a red line. In actual equalization, when the voltage gap between average voltage and weak cell voltage is smaller than $0.05V$, CV equalization will be enabled.

Second simulation is CV in S2C mode, switching frequency is set equals to resonant frequency, initial voltage of $cell_1$ is $3.90V$, others are $3.97V$, which is the ending point of CC mode. When equalization starts, as Fig. 9 (b) shows, the voltage of $cell_1$ continues to increase until it meets the average voltage line. In CV mode, C2L3 can output a constant voltage without being influenced by load variation, this mode can ensure equalization accuracy.

C2S equalization simulation is also conducted, initial voltage of $Cell_1$ is set as $4.0V$, others are $3.8V$. Simulation procedure is same as S2C mode, voltage variation curve of CC mode is shown in Fig. 9 (c), CV mode is shown in Fig. 9 (d).

C. Experiments

A prototype of C2L3 converter is designed to verify the bidirectional energy transformation ability. The designed parameters are summarized in Table I. Typical waveform of the converter is shown in Fig. 10. It can be observed that ZVS is realized.

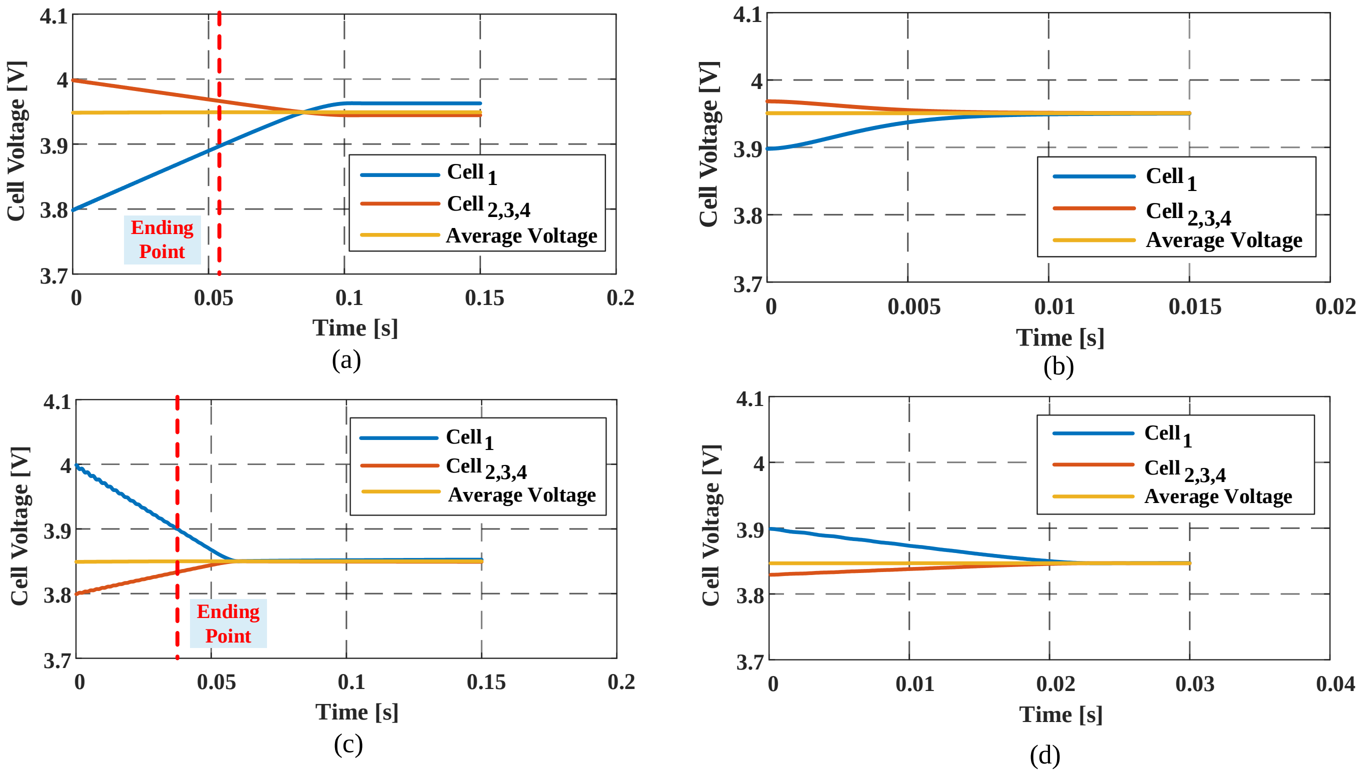

Fig. 9. Voltage variation curve during equalization process with different path: (a) CC in S2C mode, (b) CV in S2C mode, (c) CC in C2S mode, (d) CV in C2S mode.

TABLE I
DESIGNED PARAMETERS OF THE EQUALIZER

Component Type	Parameters
Micro controller	TMS320F28335
MOSFET	BSC059N04LS
MOSFET Driver	2EDS8565H
Turns Ratio(n)	4:1
Resonant Inductor 1 (L_{r1})	2.62 μH
Resonant Inductor 2 (L_{r2})	163.75 nH
Magnetizing Inductor (L_m)	18.34 μH
Resonant Capacitor 1 (C_{r1})	625 nF
Resonant Capacitor 2 (C_{r2})	10 μF
Resonant Frequency (f_{sw})	124.37kHz

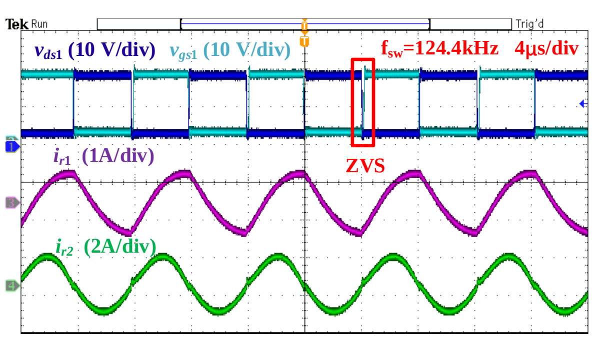

Fig. 10. Typical waveform of C2L3 resonant converter.

V. CONCLUSION

This paper proposes a novel battery equalizer which combines S2C and C2S energy flow paths. In the proposed equalizer, bidirectional C2L3 resonant topology is adopted, which can realize two equalization structures by one converter. CC and CV equalizations can be realized depending on the voltage gap, which can realize high speed and good accuracy; constant frequency open loop control is analyzed and adopted to replace close loop control, which can significantly reduce the control complexity. Simulation shows that the proposed equalizer topology is feasible. Experiments show that ZVS can be realized, which can reduce switching loss and get a higher efficiency. The proposed equalizer have a great potential, equalization experiments will be conducted in future work.

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