Article
Zero Current Switching Switched-Capacitors Balancing Circuit for Energy Storage Cell Equalization and Its Associated Hybrid Circuit with Classical Buck-Boost

Xiaolin Wang, Ka Wai Eric Cheng * and Yat Chi Fong

Power Electronics Research Center, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China
* Correspondence: eeecheng@polyu.edu.hk

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Abstract: To overcome the problem of switching loss during the balancing process, a novel cell balancing circuit is proposed with the integration of a zero current switching technique. Moreover, the balancing circuit proposed can change between a classical buck-boost pattern and a resonant switched-capacitor pattern with flexible control to cater to the balancing requirements under different driving scenarios. The results of the simulation of field experiments demonstrate successful balancing, various balancing speed, and low energy loss. The proposed balancing circuit proves to be effective for a wide range of application and is the first attempt to integrate a dual balancing function in a single balancing circuit for cells.

Keywords: cell equalization; zero current switching; hybrid circuit

1. Introduction

The pursuit of better battery performance has become the top challenge for electric vehicle (EV) design, as it primarily determines the driving mileage and manufacturing cost [1–4]. With the fast development of a supercapacitor (SC), the battery and SC strings composed of a large number of series and parallel-connected cells are usually used to formulate a hybrid energy package for better power performance [5–8]. Moreover, increasing numbers of researchers are collecting retired batteries for second-life application, hoping to cut costs while maintaining a qualified driving performance. Due to non-uniform individual cell properties, a certain imbalance may be easily generated among voltages of different cells during charging and discharging processes. As the effect of imbalance is accumulative and leads to battery deterioration, voltage balancing is necessary to guarantee the safe operation of the hybrid energy package [9–11].

Researchers have done many state-of-the-art works on promoting the balancing efficiency and balancing speed and decreasing loss. The passive balancing method is the most commonly adopted technique. Resistors in parallel with the cell strings are switched on when the cells get close to the peak withstanding voltage or when they have a higher state-of-charge (SoC) than other cells. This method generates additional heating loss because the energy dissipates into resistors during balancing process [12]. For energy-saving purposes, an active balancing method is put forward so that the charging and discharging current of each cell can be controlled to keep the same SoC among all cell units for the higher energy to be transferred into the cells with lower energy using a power converter circuit, instead of wasting it as heat loss. This method has proven to be more efficient, hence, many advanced voltage equalizers have been designed based on the active method using converters [13,14], switched-capacitors [15–18], transformers [7] or switched inductors [19,20].
However, those methods are not flexible enough for changing scenarios. Furthermore, as a hard switching operation is adopted in a large number of cell balancing circuits [21-23], electromagnetic interference (EMI) and high switching energy loss will appear. On the other hand, the service life of energy sources will also be affected by a current spike in hard switching circuits. In this paper, a novel balancing circuit is proposed to realize zero-current switching (ZCS) similar to quasi-resonant [24,25] during the switched-capacitor mode and has been proven to further reduce energy loss [24-29].

Different states of EVs, such as the drive state, brake state, and park state, may have different requirements on the output power, balancing speed, and balancing loss. Many existing papers [22,23] do not take the real driving state into account and make a fixed cell balancing strategy, which decreases the overall balancing efficiency [30-33]. They are based on switched-capacitor techniques [34,35]. Some papers have realized the difference in energy management at different driving states and proposed specific energy controllers respectively. The energy saving controller for electric mining trucks is introduced in Reference [36], as it runs in high-frequency start-up processes. A predictive energy controller based on preceding vehicle movement management is designed in Reference [37] for lined up EVs on the road. A real-time energy controller for EVs in a charge-depletion mode is discussed in References [38-40] for adaptive energy consumption minimization.

In this paper, a novel and multi-functional balancing circuit is proposed with a ZCS technique to improve energy saving during the balancing process. The multi-functional circuit can easily change between a buck-boost pattern and switched-capacitor pattern with flexible switching frequency and duty ratios, i.e., the circuit can adapt to changing driving states. Figure 1 demonstrates six different operating modes with different cell balancing requirements for the corresponding driving states. Moreover, voltage sensors can be installed at each cell in order to collect the voltage signals for an intelligent control box. In the real-time feedback control, switching frequency and duty ratios are adjusted to accelerate voltage balancing process and decrease loss. This paper is the first attempt to use the ZCS technique in the integrated balancing circuit for rapid mode switching, accurate voltage tracking, and loss reduction. The circuit configuration, operation principle, and equations are presented in Sections 2 and 3. The results of the simulation and field experiment are presented in Sections 4 and 5. Section 6 concludes this paper.

2. Proposed Cell Balancing Circuits

2.1. Circuit Configuration

In this section, a series multi-functional balancing circuit is presented for analysis. Different states of EVs, such as the drive state, brake state, and park state, may have different requirements on the output power, balancing speed, and balancing loss. Figure 1 demonstrates six different operating modes and requirements.
modes with different cell balancing requirements for the corresponding driving states. For example, EVs in acceleration desire a high balancing speed and low loss while the park state does not have requirements on the balancing speed. The circuitry of Figure 2 shows the SC cells \((SC_1, SC_2, \ldots, SC_n)\) in series connection. In the \(n\)-cells voltage balancing system, there are \(n - 1\) switched-capacitors and \(4n - 4\) switches which are dominated by the main intelligent control box to operate the circuit in different modes. All the switches are named in two groups \(S_a\) and \(S_b\), the switches in each group are divided as \(S_{a2m-1}, S_{a2m}, S_{a2m+1}\) and \(S_{a2m+2}\), where \(m\) varies from 1 to \(n - 1\); In \(S_{b2m-1}, S_{b2m}, S_{b2m+1}\) and \(S_{b2m+2}\), \(m\) varies from 1 to \(n - 1\). This multi-functional balancing circuit has two operation states, buck-boost balancing and switched-capacitor balancing, under different control of inductors \((L_1, L_2, \ldots, L_{n-1})\) and switched-capacitors \((C_1, C_2, \ldots, C_{n-1})\). And the charge is transferred from a higher voltage SC to lower ones automatically. The proposed circuit changes its topology and parameters to cater to the operation requirements of different operation modes, such as the common drive mode, drive with air-conditioning mode, acceleration mode, brake mode, and park mode for EVs.

![Figure 2. Proposed balancing circuit.](image)

2.2. Balancing Circuit Operation Analysis

In an ideal case, the switching frequency \(f_s\) should be equal to the resonant frequency \(f_r\).

\[
    f_s = f_r = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \theta^2}
\]

where \(\theta = \frac{R}{2L}\); \(R\) is the equivalent resistance, \(L\) is the inductance of the inductor and \(C\) is the capacitance of the switched-capacitor.

However, it is arduous to precisely match the RLC parameters of different balancing branches in real implementation. To avoid a reverse current of the resonant inductor, the switching frequency in the proposed switched-capacitor circuit should be slightly higher than the resonant frequency with regards to the tolerances of the RLC parameters.

There are two clock phase \(\varphi_a\) and \(\varphi_b\) in one switching period \(T\), as shown in Figure 3. During the \(\varphi_a\), the switches \(S_{a2m-1}, S_{b2m-1}\) and \(S_{a2m+1}, S_{b2m+1}\) are turned on, the circuit forms the switched-capacitors resonant tanks series connecting with switched-capacitors as shown in Figure 4a,b. Meanwhile, Figure 4c,d are in a buck-boost mode state during the \(\varphi_b\), when \(S_{a2m-1}, S_{b2m-1}\) and \(S_{a2m}, S_{b2m}\) are turned on, there is only an inductor connect with SC. These two functioning modes operate alternatively with
a high frequency control signal. They are divided into ZCS mode state I, ZCS mode state II, buck-boost mode state I and buck-boost mode state II which will be discussed in Section 2.3.
2.3. Analysis of ZCS Operation

When the switches $S_{a2m-1}$, $S_{b2m-1}$, and $S_{b2m+1}$ are turned on, the circuit forms the switched-capacitors resonant tanks as shown in Figure 5. In the state of the ZCS-SC, charge will transfer from $SC_k$ to $C_k$ switched-capacitor tank when the voltage of $SC_k$ is higher than the initial voltage of $C_k$. Therefore, $C_k$ is charged and the control signal during the process is shown in the top curve of Figure 5 and Table 1. In a similar way, the charge will transfer from $C_j$ to $SC_j$ when the voltage of $SC_j$ is lower than the initial voltage of $C_j$. $C_j$ is discharged in this process and the control signal is shown in the bottom curve of Figure 5 and Table 1. $SC_k$, $C_k$, $L_k$ and $SC_j$, $C_j$, $L_j$ form the resonant loops. The $r_{SC}$, $r_C$, $r_S$, and $r_L$ internal resistors for $SCs$, switched-capacitors, ON-resistance of the switches, and inductors, respectively. In order to simplify the operation analysis, the internal resistance will first be ignored. All the components are ideal.
Table 1. Switches control logical signal.

| Function Mode | $S_{a2m-1}$ | $S_{a2m}$ | $S_{a2m+1}$ | $S_{a2m+2}$ | $S_{b2m-1}$ | $S_{b2m}$ | $S_{b2m+1}$ | $S_{b2m+2}$ |
|---------------|-------------|-----------|-------------|-------------|-------------|-----------|-------------|-------------|
| ZCS mode      | 1           | 0         | 1           | 0           | 1           | 0         | 1           | 0           |
| Buck boost mode | 1           | 1         | 0           | 0           | 1           | 1         | 0           | 0           |

(1) State I (See Figure 5 charging circle)

In the state when $S_{a2m-1}$ and $S_{a2m+1}$ are turned on and $S_{a2m}$ and $S_{a2m+2}$ are turned off. Assume that all the components here are ideal and there is zero internal resistance for the SCs, switched-capacitors, inductors, and switches in this analysis. The relationship between the current and the voltage are as shown below:

$$i_r = C_k \frac{dV_{C_k}}{dt}$$  \hspace{1cm} (2)

$$L_k \frac{di_r}{dt} + V_{C_k} = V_{SC_k}$$  \hspace{1cm} (3)

where $L_k$ is the inductance of inductor $L_k$; $V_{SC_k}$ is the voltage of SC$^k$.

Then, the variations of the $V_{C_k}$ and $i_r$ of the above are

$$V_{C_k} = V_{SC_k} - \frac{\Delta V_{C_k}}{2} \cos(\omega t)$$  \hspace{1cm} (4)

$$i_r = I_r \sin(\omega t)$$  \hspace{1cm} (5)

where $\Delta V_{C_k}$ is the peak-to-peak amplitude of $V_{C_k}$; $I_r$ is the amplitude of the $i_r$; $\omega$ is the resonant angular frequency which is $\omega = \frac{1}{\sqrt{L_k C_k}}$, $C_k$ is the capacitance of $C_k$.

In this resonant period, assume that the initial voltage $V_{C_{min}}$ across the capacitor $C_k$ is minimum voltage, which is lower than the voltage $V_{SC_k}$ across the SC$^k$. The initial voltage $V_{L_k}$ and the amplitude of the $i_r$ are:

$$V_{L_k} = L_k \frac{di_r}{dt} = V_{SC_k} - V_{C_{min}}$$  \hspace{1cm} (6)

$$I_r = \frac{V_{SC_k} - V_{C_{min}}}{\omega L_k} = \left( V_{SC_k} - V_{C_{min}} \right) \sqrt{\frac{C_k}{L_k}}$$  \hspace{1cm} (7)

After half a resonant period, the voltage of the $V_{C_k}$ could reach maximum $V_{C_{k,max}}$, which is shown below:

$$V_{C_{k,max}} = 2V_{SC_k} - V_{C_{min}}$$  \hspace{1cm} (8)

(2) State II (See Figure 5 discharging circle)

In the state when $S_{b2m-1}$ and $S_{b2m+1}$ are turned on and $S_{b2m}$ and $S_{b2m+2}$ are turned off, the switched-capacitor $C_j$ is discharging SC$^j$ and the resonant current $i_r$ is increasing in the opposite direction. Similarly as state I, the amplitude of the resonant current is

$$I_r = \frac{V_{C_{max}} - V_{SC_j}}{\omega L_j} = \left( V_{C_{max}} - V_{SC_j} \right) \sqrt{\frac{C_j}{L_j}}$$  \hspace{1cm} (9)

The voltage of $V_{C_j}$ could reach minimum $V_{C_{j,min}}$ at the end of this resonant period.

$$V_{C_{j,min}} = 2V_{SC_j} - V_{C_{max}}$$  \hspace{1cm} (10)

In fact, there are equivalent series resistance (ESR) for the components and the voltage drop across the switches that cannot be ignored. The $r_{SC}$, $r_C$, $r_S$, and $r_L$ internal resistors for SCs, switched-capacitors,
ON-resistance of the switches and inductors respectively should be considered in the following analysis. The total ESR $R_{ESR}$ in one resonant tank of the circuit is $R_{ESR} = r_{SC} + r_C + r_L + 2r_S$.

The resonant current of charging and discharging state should be revised as:

**State I:**

$$i_r = \frac{V_{SC_k} - V_{C_{min}}}{\omega_r L_k} e^{-\rho t} \sin \omega_r t$$  

**State II:**

$$i_r = \frac{V_{C_{max}} - V_{SC_j}}{\omega_r L_j} e^{-\rho t} \sin \omega_r t$$

where $\rho = \frac{R_{ESR}}{2\omega_r L_{k,j}}$, $\omega_r = \sqrt{\frac{1}{L_{k,j} C_{k,j}}} - \rho^2$.

$L_{k,j}$ refers to either $L_k$ or $L_j$ in each of their state I and II and hence $\rho$ and $\omega_r$ are calculated according to their respective $L_k$ or $L_j$ in State I and State II. The maximum and minimum voltage of $V_{C_{k,j}}$ are

$$V_{C_{max}} = V_{SC_k} + (V_{SC_k} - V_{C_{min}}) e^{-\rho \pi / \omega_r}$$  

$$V_{C_{min}} = V_{SC_j} - (V_{C_{max}} - V_{SC_j}) e^{-\rho \pi / \omega_r}$$

**3. Modeling for Balancing Mode**

**3.1. Modeling for ZCS Balancing Mode**

As it is shown in Figure 6, SC cells can be formulated to be charged or discharged between each other with the equivalent resistance. In the resonant circuit, $C_k$, $L_k$ and $C_j$, $L_j$ has the same value $C$ and $L$, respectively, and all the switches are the same. The voltage of $V_C$ could achieve the maximum $V_{C_{max}}$ at the end of the state I and be reduced to the minimum at the end of state II. The voltage ripple $\Delta V_C$ can be obtained by subtracting (14) from (13).

$$\Delta V_C = (V_{SC_k} - V_{SC_j}) \left[ 1 + e^{-\rho \pi / \omega_r} \right] \left[ 1 - e^{-\rho \pi / \omega_r} \right]$$  

In one switching cycle the quantity of electric charge is $C \Delta V_C$, flowing from higher voltage cell to lower voltage cell. The average current $I_{avg,t}$ of one cycle is

$$I_{avg,t} = f_s \cdot C \cdot \Delta V_C$$

When $\Delta V_C$ in (15) is substituted into (16), the equivalent resistance $R_{eq}$ of each resonant tank is

$$R_{eq} = \frac{1 - e^{-\rho \pi / \omega_r}}{f_s C \left( 1 + e^{-\rho \pi / \omega_r} \right)}$$
The power loss $P_{\text{loss},r}$ of the ZCS mode is shown below

$$P_{\text{loss},r} = I_{\text{avg},r}^2 \cdot R_{\text{eq}} = f_S C (V_{SCk} - V_{SCj})^2 \frac{1 + e^{-p\pi/\omega r}}{1 - e^{-p\pi/\omega r}}$$

(18)

### 3.2. Modeling for Buck-Boost Balancing Mode

During the progress of the buck-boost balancing mode, the charging/discharging varies in one cycle, the charge is transferred between $SC_k$ and $SC_j$. The equivalent model of the balancing circuit is shown in Figure 7, where the ESR and the on-state voltage for the diode are included to facilitate modeling.

![Figure 7. Model of the buck-boost mode circuit under charging and discharge.](image)

To illustrate the voltage conversion process for the inductor $L_1$, the mmf values of $M_{\text{ch}}$ and $M_{\text{disch}}$ to investigate the voltage conversion of the converter circuit for charging and discharging, respectively, during one cycle are

$$M_{\text{ch}} = \frac{V_{SCk} D_1 T}{L_1}$$

$$M_{\text{disch}} = \frac{V_{SCj} D_2 T}{L_1}$$

(19)

(20)

where $D_1$ and $D_2$ are the turn-on duty ratio of switches for charging and discharging, respectively, $D_1 + D_2 = 1$.

Considering volt-second balancing of $L_1$, the relationship between two cells is

$$V_{SCk} DT - R_1 \int_{i_1}^{i_2} i_{\text{ch}} dt = V_{SCj}(1 - D) T - R_2 \int_{i_2}^{i_3} i_{\text{disch}} dt$$

(21)

where $R_1 = 2r_S + r_L + r_{SCk}$, $R_2 = 2r_S + r_L + r_{SCj}$; $i_{\text{ch}}$ and $i_{\text{disch}}$ are instantaneous current across $L_1$ for charging and discharging, respectively. $I_{\text{avg},\text{ch}}$ and $I_{\text{avg},\text{disch}}$ are the average current across $L_1$ when it is charging or discharging.

When $\int_{i_1}^{i_2} i_{\text{ch}} dt \approx I_{\text{avg},\text{ch}} DT$ and $\int_{i_2}^{i_3} i_{\text{disch}} dt \approx I_{\text{avg},\text{disch}}(1 - D) T$, $I_{\text{avg},\text{ch}}$ could be obtained from (21) as:

$$I_{\text{avg},\text{ch}} = \frac{V_{SCj}(1 - D) + V_{SCk} D}{R_2 (1 - D) + R_1 D}$$

(22)

The average current $I_{\text{avg},b}$ of SC in this mode is

$$I_{\text{avg},b} = \frac{V_{SCj}(1 - D)D + V_{SCk}D^2}{R_2 (1 - D) + R_1 D}$$

(23)

In the balancing progress, all the energy transfers between each cell, from the higher voltage SC cell to lower voltage cell. During these states, the variation of the $i_{\text{ch}}$ is
\[ i_{ch}(t) = I_{avg,ch} + \Delta i_{ch}(t - \frac{DT}{2}) \]  

(24)

where \( \Delta i_{ch} \) is the current difference during charging state, \( T = \frac{1}{f_s} \).

The variation of the \( i_{disch} \) is

\[ i_{disch}(t) = I_{avg,disch} + \Delta i_{disch}(t - \frac{DT}{2}) \]  

(25)

where \( \Delta i_{disch} \) is the current difference during discharging state.

The energy discharged \( E_{disch} \) from \( SC_k \) and the energy charged \( E_{ch} \) to the \( SC_j \) throughout one cycle are:

\[ E_{disch} \approx V_{SCk} \int_{t_1}^{t_2} i_{ch} dt \]  

(26)

\[ E_{ch} \approx V_{SCj} \int_{t_2}^{t_3} i_{disch} dt \]  

(27)

The energy transferred in the inductor \( L_1 \) is

\[ \int_{t_1}^{t_2} (V_{SCk} - i_{ch} R_1) i_{ch} dt \approx \int_{t_2}^{t_3} (V_{SCj} - i_{disch} R_2) i_{disch} dt \]  

(28)

The energy loss \( E_{loss} \) could be obtained by subtracting Equation (27) from (26).

\[ E_{loss} \approx V_{SCk} \int_{t_1}^{t_2} i_{ch} dt - V_{SCj} \int_{t_2}^{t_3} i_{disch} dt \]

\[ = R_1 \int_0^{\frac{DT}{2}} i_{ch}^2 dt + R_2 \int_0^{(1-D)T} i_{disch}^2 dt \]

\[ = T \left( I_{avg,ch}^2 + \frac{3\Delta i_{ch}^2}{4} \right) \left[ R_1 D + R_2 (1-D) \right] \]  

(29)

where \( \Delta i_{ch} \approx \frac{D V_{SCk}}{2 L_1 f_s} \).

The power loss \( P_{loss,b} \) of the buck-boost mode is

\[ P_{loss,b} = \left[ \frac{V_{SCk}[1-D] + V_{SCj} D}{R_2(1-D) + R_1 D} \right]^2 + \frac{3}{4} \frac{D V_{SCk}^2}{L_1 f_s} \left[ R_2[1-D] + R_1 D \right] \]  

(30)

4. Simulation Results of the Multi-Function Voltage Equalizer

In PSIM software, the proposed circuit is simulated. The circuit topologies of three series connected SCs with initial voltages of 2.0, 2.4, 2.6 V, respectively, and with the same capacitance 1F are built in the simulation shown in Figure 8. Switched-capacitors C = 22 µF are used in simulation while \( f_s = 15, 20, 25 \) kHz and 90, 100, 110 kHz of the control signals are used to operate the circuit. The above configurations are the same with practical application, except the capacitance of the SCs.

Table 2 illustrates the comparison of the waveforms in the simulation varied with a different switching frequency \( f_s \) for ZCS and buck-boost mode. It is observed that \( V_{SC1}, V_{SC2}, \) and \( V_{SC3} \) finally converge to the same voltage level in all circumstances. For the ZCS mode, when \( f_s \) is larger, the switching speed is faster that accelerates the equalization process.

Figure 9 shows the simulation results of the ZCS mode under 20 kHz frequency with 350 F SCs. At 32 s the balancing progress was about 10%, the voltage between \( V_{SC1} \) and \( V_{SC2} \) are 0.18 V at this moment. The balancing progress reached approximately 90% at 290 s when the difference reduces to 0.02 V. And the variations of the voltage of the switched-capacitor \( C_1 \) and current \( I_1 \) are shown in this figure.
Figure 8. Multi-functional equalizer built in laboratory.

Table 2. Simulation results of the switched-capacitor voltage equalizer.

| Mode        | $f_s = 15$ kHz | $f_s = 20$ kHz | $f_s = 25$ kHz |
|-------------|----------------|----------------|----------------|
| ZCS mode    |                |                |                |
| $f_s = 15$ kHz |                |                |                |
| $f_s = 20$ kHz |                |                |                |
| $f_s = 25$ kHz |                |                |                |
| Buck-boost mode |              |                |                |
| $f_s = 90$ kHz |                |                |                |
| $f_s = 100$ kHz |               |                |                |
| $f_s = 110$ kHz |               |                |                |
The balancing phenomenon conforms to the principles in Equation (16). When the switching frequency $f_s$ is the same as the resonant frequency $f_r$, the balancing progress could reach zero current when switches are turn on and off, this conforms to the principle in Equation (1). But the variation of the $f_s$ could not affect the balancing speed for buck-boost mode which is illustrated in Equation (23).

5. Experimental Results of the Multi-Function Circuit

The proposed circuit has advantages in performing balancing for different EV driving modes so that it is more flexible for an energy storage system which has different working conditions. To verify the mathematical derivation and software simulation, energy storage strings composed of three SCs were formulated with the multi-functional balancing circuit controlled by different switching signals. The topology is shown in Figure 8 and the list of components is recorded in Table 3. Figure 10 is the supercapacitor test platform used in the laboratory.

The voltage balancing process for the ZCS mode of the experiment is shown in Figure 11. The initial voltages of the SCs are 2.6 V, 2.31 V, and 1.88 V, respectively. After the voltage balancing was conducted, $V_{SC1}$, $V_{SC2}$ and $V_{SC3}$ were all finally balanced to the same voltage magnitude, which coincides with the...
results in the above theoretical analysis. The integrated voltage magnitude after balancing was 2.23 V. Figure 12 depicts the voltage and current variations of $C_1$, $C_2$, and $L_1$. It is clearly shown that when the switch turns on/off, the instantaneous current of the resonant loop is close to zero, which conforms to the principles of ZCS and loss reduction.

The voltage balancing process for the buck-boost mode of the experiment is shown in Figure 13. The initial voltages of the SCs were set as 2.42 V, 2.29 V and 2.03 V, respectively. After conducting voltage balancing, $V_{SC1}$, $V_{SC2}$ and $V_{SC3}$ were also balanced to the same voltage magnitude, as expected. The integrated voltage magnitude after balancing operation was 2.17 V. Figure 14 depicts the voltage and current variations of $L_1$. The energy loss of ZCS mode decreased 35% compared with that in buck-boost mode.

**Table 3. Parameters in the experiment.**

| Units                                      | Quantity |
|--------------------------------------------|----------|
| Supercapacitor (DRL357S0TQ60SC)            | 3        |
| Capacitance of SCs                         | 350 F    |
| MOSFET(IRFR3607PBF) 75 V 7.34 mΩ           | 8        |
| ON-resistance of MOSFETs                   | 7.34 mΩ  |
| Switched-capacitor (RNS1E220MDN1KX)        | 2        |
| Capacitance of Switched-capacitors         | 22 µF    |
| ESR of Switched-capacitors                 | 28 mΩ    |
| Inductor (WE-HCF)                          | 2        |
| Inductance of the inductor                 | 3.3 µH   |
| ESR of Inductor                            | 1.31 mΩ  |
| Switching frequency                        | 20 kHz, 100 kHz |

**Figure 10.** The supercapacitor test platform.

**Figure 11.** The ZCS mode balancing waveform from the experiment in the laboratory.
The experimental results demonstrate that the variations of both voltage and current in the proposed circuit conform to the charging/discharging principles analyzed in each phase.

6. Conclusions

A novel zero-current switching cell balancing circuit is proposed in this paper to decrease switching loss during balancing process. Furthermore, in order to adjust to different requirements of EV operation states, the multi-functional circuit was able to easily change between buck-boost and switched-capacitor pattern with flexible switching frequency and duty ratios. Simulation and field experiment were conducted to demonstrate its loss reduction effect and flexibility in various situations. The energy loss of the ZCS mode decreased 35% compared with that in the buck-boost mode. Future works may include voltage feedback control during the balancing process to further increase speed and decrease loss.

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