

Active Clamped Forward based Active Cell Balancing Converter

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Abstract

This paper proposes an active cell equalizing technology by an active clamped forward converter in which the stored energy in the transformer is recycled to the battery pack. This cell balancing circuit prevents the transformer from saturation which may result in power loss. In addition, the clamp capacitor of the proposed cell equalizer can protect active switches from voltage spikes because of the charge balance of the clamp capacitor. Therefore, the proposed balancing circuit has higher efficiency and lower voltage stress than the previous RCD reset circuit based forward-type cell balancing circuit in the literature. In addition, this active cell equalizing circuit operates for all cells to be equilibrated simultaneously. Therefore, the cell balancing speed is faster than the previous balancing circuit in the literature. The operational principle of the proposed circuit in this paper was analyzed and simulated by PSIM software.

Keywords: Active Clamp, Cell Balancing Circuit, Forward Converter, Transformer Saturation

1. Introduction

This paper presents an active cell balancing circuit based on a Forward Active Clamp (FAC) circuit which transfers each energy cell to be balanced in the battery string. The high voltage battery system with a multi-cell battery group has recently studied and used for the secondary cell battery system in the industrial applications such as energy storage systems and electric vehicles. This FAC is one of the most widespread topologies to attain high efficiency for low and medium power applications at higher frequencies¹. This FAC circuit is composed of the auxiliary switch and the clamp capacitor used to repress voltage stress at the active switch in the magnetizing inductance of the transformer^{2,3}. The cell balancing circuit for n_s cells of which capacities of the voltage were diverse was connected with the multi-windings transformer T_m ^{4,5}. However, the transformer in this cell balancer cannot be prevented from its saturation because this circuit had not

the reset circuit. A snubber circuit can be used to reset the core in the resonant forward converter. The RCD clamp method has been proposed and analyzed to reduce the voltage stress of the switch devices. However, the energy stored in the magnetizing inductance is dissipated on the resistor and the conversion efficiency is limited^{6,7}.

This paper proposes an active cell balancing circuit with a multi-winding transformer based on FAC. In the proposed circuit, the auxiliary switches are used to drive the active clamp switches. The advantage of the proposed cell balancing circuit is that the transformer can be prevented from saturation⁸. The simulation results have been shown to verify the validity of the presented method for cell balancing. This paper is organized as follows: the proposed cell balancing circuit and its operational principle are described in the Section 2. The simulation results of the proposed active cell balancing circuit are presented in the Section 3. Lastly, this paper concludes with a summary and findings in the Section 4.

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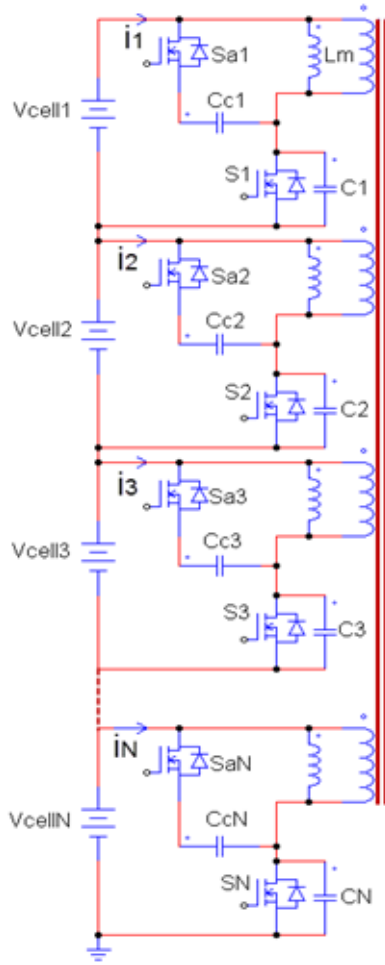


Figure 1. Proposed cell balancing circuit topology.

2. Proposed Cell Balancing Circuit and its Operational Principle

2.1 Proposed Cell Balancing Circuit

Figure 1 shows the proposed active cell balancing circuit. The proposed circuit includes N series-connected cells in which each cell connects a power switch S_k , the FAC reset circuit and a multi-windings transformer T_m to balance the voltage of each cell in the battery string. Because of the simplicity for a circuit operational analysis, it was assumed that a cell string consists of four cells in the rest of the paper; the relationship among the battery cell voltages was defined as $V_{cell1} < V_{cell2} < V_{cell3} < V_{cell4}$, and the average voltage was $V_{aver} = (V_{cell1} + V_{cell2} + V_{cell3} + V_{cell4})/4$.

In this proposed balancing circuit with FAC, the currents were transmitted from the highest voltage cell to the lowest voltage cell by selectively working the power switches S_k and the auxiliary switches S_{ak} .

For the proposed switching method for the FAC, all power switches connected to each battery cell are turned on or turned off with the fixed duty cycle (D) simultaneously.

2.2 Operational Principles and Mode Analysis

The operational mode of the proposed cell balancing circuit consists of six different modes in one switching period T_s . The theoretical waveforms and operating modes are shown in Figures 2 and 3 respectively. Figure 2 shows the waveforms of a voltage across the k_{th} of power switch (V_{swk}) and auxiliary switch (V_{swak}), a voltage across the capacitor (V_{Cck}), a discharging current of the lowest cell (i_{sw1}), a discharging current of the highest cell (i_{sw4}), and current through the magnetizing inductance (i_{Lm}). The V_{gs} and V_{gsa} are the pulse-width modulated gate driving signal of power and auxiliary switches, respectively.

Mode 1 [t_0, t_1] (see Figure 3(a)): At t_0 , four power switches S_k (S_1, S_2, S_3 , and S_4) are turned on, while four auxiliary switches S_{ak} (S_{a1}, S_{a2}, S_{a3} , and S_{a4}) are turned off simultaneously as shown in Figure 2. Thus, the voltage of these power switches S_k are zero. The magnetizing inductance L_m current increases linearly with a slope of V_{cellk}/L_m where V_{cellk} is the voltage of the k_{th} cell. Figure 4 describes the equivalent circuit with the Laplace transformation for the purpose of analysis in this mode. Based on the Laplace transformed circuit analysis in Figure 4, the following time domain switch currents can be calculated as follows:

$$i_1(t) = \frac{3V_{Cell1} - (V_{Cell2} + V_{Cell3} + V_{Cell4})}{4R_{ds(on)}} e^{-\frac{t}{R_{ds(on)} \cdot C}}, \quad (1)$$

$$i_2(t) = \frac{3V_{Cell2} - (V_{Cell1} + V_{Cell3} + V_{Cell4})}{4R_{ds(on)}} e^{-\frac{t}{R_{ds(on)} \cdot C}}, \quad (2)$$

$$i_3(t) = \frac{3V_{Cell3} - (V_{Cell1} + V_{Cell2} + V_{Cell4})}{4R_{ds(on)}} e^{-\frac{t}{R_{ds(on)} \cdot C}}, \quad (3)$$

$$i_4(t) = \frac{3V_{Cell4} - (V_{Cell1} + V_{Cell2} + V_{Cell3})}{4R_{ds(on)}} e^{-\frac{t}{R_{ds(on)} \cdot C}}, \quad (4)$$

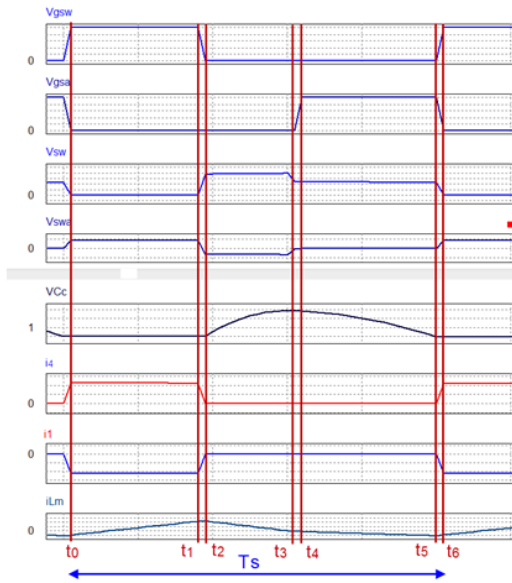


Figure 2. Operational waveforms of the proposed cell balancing circuit.

where $i_1(t)$, $i_2(t)$, $i_3(t)$ and $i_4(t)$ are the currents coming out from voltage cell V_{cell1} , V_{cell2} , V_{cell3} and V_{cell4} , respectively, and $R_{ds(on)}$ is the in resistance of an active power switch.

Equations (1)-(4) describe that the cell currents $i_3(t)$ and $i_4(t)$ are the positive value of cell currents that the related battery cell gives the energy to the other battery cells. On the other hand, $i_1(t)$ and $i_2(t)$ are the negative value of cell currents that the related battery cell receives the energy from the other battery cells. In this mode, the energy is transmitted from highest voltage cell (V_{cell4}) to the lowest voltage cell (V_{cell1}) through the multi-winding transformer (T_m). The FAC reset circuit can be ignored in the circuit analysis as shown in Figure 3(a). At t_1 , these power switches begin to be turned off. Thus, the switch voltages increase.

For an N cell series-connected battery string, the proposed circuit in this mode can be considered as an N cell Laplace transformed equivalent circuit as depicted in Figure 5. From the Laplace transformed circuit analysis of Figure 5, the following generalized switch current in the mode 1 can be given as

$$\begin{bmatrix} i_1(t) \\ i_2(t) \\ \vdots \\ i_k(t) \\ \vdots \\ i_N(t) \end{bmatrix} = \begin{bmatrix} N-1 & -1 & \dots & -1 & \dots & -1 \\ -1 & N-1 & \dots & -1 & \dots & -1 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ -1 & -1 & \dots & N-1 & \dots & -1 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ -1 & -1 & \dots & -1 & \dots & N-1 \end{bmatrix} \begin{bmatrix} V_{cell1} \\ V_{cell2} \\ \vdots \\ V_{cellk} \\ \vdots \\ V_{cellN} \end{bmatrix} e^{-\frac{t}{NR_{ds(on)}C}} \quad (5)$$

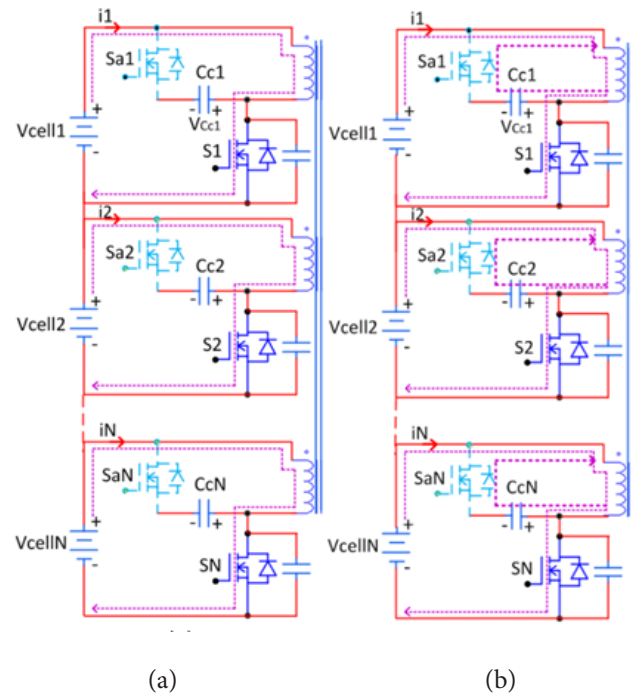
Mode 2 [t_1 , t_2] (see Figure 3(b)): At t_1 , all power switches (S_k) start to be turned off and all auxiliary switches (S_{ak}) are turned off, which causes the power switches voltage to increase as shown in Figure 2. In this mode, the stored energy in the magnetizing inductance L_m begins to be discharged through the diode.

Mode 3 [t_2 , t_3] (see Figure 3(c)): At t_2 , all power switches (S_k) are turned off as shown Figure 2. The magnetizing inductance (L_m) resets through the diode resulting in a reduction of the inductance current (i_{Lm}).

Mode 4 [t_3 , t_4] (see Figure 3(d)): At t_3 , all auxiliary switches (S_{ak}) start to be turned on.

Mode 5 [t_4 , t_5] (see Figure 3(e)): At t_4 , all auxiliary switches (S_{ak}) are turned on. The magnetizing inductance (L_m) keeps on resetting through the auxiliary switches. The discharging process of magnetizing inductance (L_m) energy is completed by the FAC circuit in this mode.

Mode 6 [t_5 , t_6] (see Figure 3(f)): At t_5 , all power switches (S_k) start to be turned on and all auxiliary switches (S_{ak}) start to be turned off. The magnetizing inductance current (i_{Lm}) increased. At t_6 , all power switch (S_k) turned on and all auxiliary switches (S_{ak}) turned off. A cycle is completed at this mode.



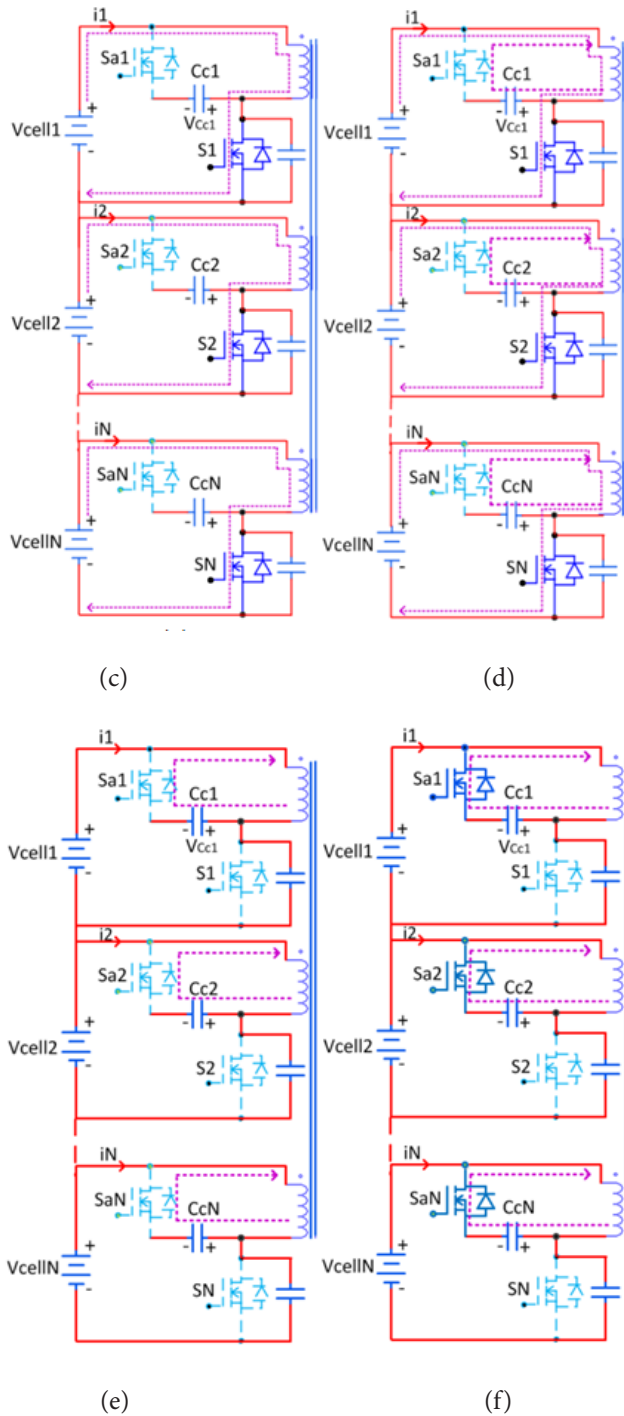


Figure 3. Operating modes of the proposed cell balancing circuit. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5. (f) Mode 6.

3. Simulation Results

Simulation studies were carried out to verify the feasibility of the proposed circuit using PSIM software.

For the simplicity of simulations, four cells were modeled by four series capacitors of which the capacitance (C) was set 40mF and of which initial voltages are: $V_{cell1} = 3.5V$, $V_{cell2} = 3.6V$, $V_{cell3} = 3.7V$ and $V_{cell4} = 3.8V$. To illustrate the operation of the FAC reset circuit, Figures 6, 7 and 8 show the simulation results of the voltage, the current and the current of magnetizing inductance (L_m) waveforms, respectively, as shown in Figure 1. The circuit parameters used in the simulation using PSIM software are as follows: $L_m = 2.5mH$, $C_c = 22nF$, the duty ratio (D) of PWM signals to power switches is 0.375, a switching frequency is $f = 40kHz$, the duty ratio of PWM signals to auxiliary switches is $1-D$ with switching frequency $f_a = 40kHz$. In this research, the cell balancing criterion for the completion disparity between the maximum and minimum cell voltage is less than or equal to 8mV. In other words, the cell balancing operation is completed if the maximum and minimum cell voltages of the battery string are satisfied condition as follows:

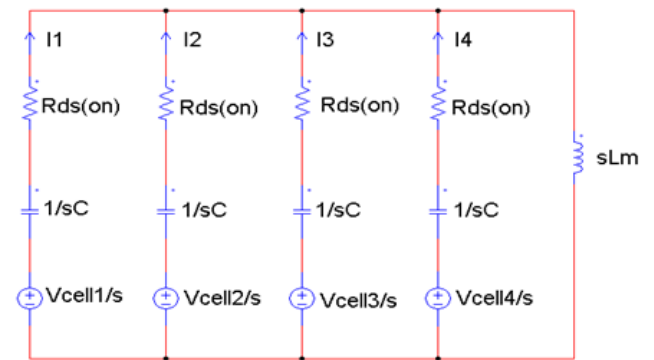


Figure 4. Laplace transformed equivalent circuit of the proposed four-cell active balancer in mode 1.

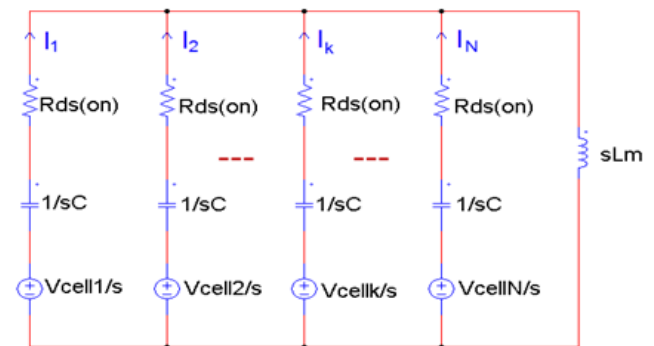


Figure 5. Laplace transformed equivalent circuit of the proposed N-cell active balancer in mode 1.

$$V_{max} - V_{min} \leq 8 \text{ mV}, \quad (6)$$

where V_{max} and V_{min} are the voltage of the highest

energy cell and the lowest energy cell of the battery string, respectively.

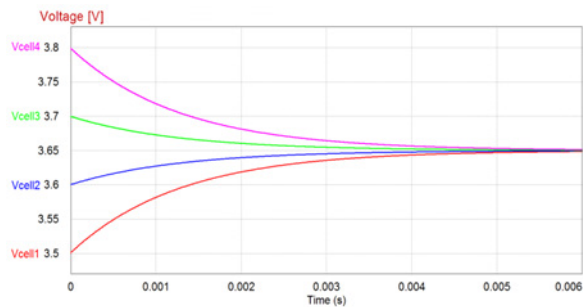


Figure 6. Simulation voltage waveforms of the proposed balancer.

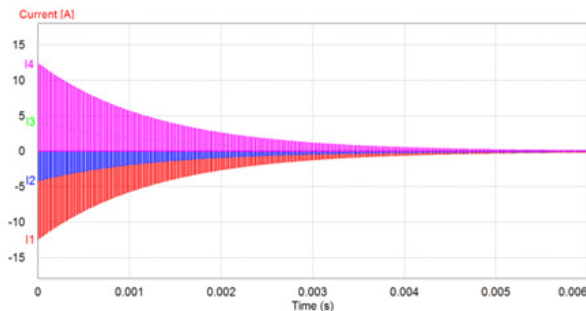


Figure 7. Simulation current waveforms of the proposed balancer.

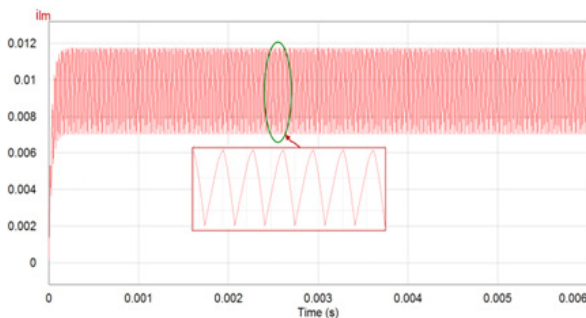


Figure 8. Simulation current waveform of the magnetizing inductance L_m .

Table 1 shows the simulation circuit parameters of proposed cell equalizer shown in Figure 1. Figure 6 shows the cell equalizer process that is completed at 6ms, which the voltage disparity between the highest voltage cell and the lowest voltage cell is less than or equal 8mV and Figure 8 shows that the current of magnetizing inductance (L_m) is stable, so that the transformer is not saturated.

Table 1. Simulation parameters

Parameter name	Value	Units
C (Cell model capacitance)	40	mF
V_{cell1}	3.5	V
V_{cell2}	3.6	V
V_{cell3}	3.7	V
V_{cell4}	3.8	V
C_C	22	nF
L_m	2.5	mH
f and f_a	40	kHz
D	0.375	
Balancing Time	6	ms

4. Conclusions

This paper proposed an active cell balancing circuit based on a Forward Active Clamping circuit (FAC). The proposed cell balancing circuit used the FAC circuit to preclude the transformer from being saturated. The proposed circuit operates as follows: all the power switches have the same PWM signal with a constant duty ratio (D) while the auxiliary switches operate with a constant duty ratio ($1-D$). The energy is transferred from the highest voltage cell to the lowest voltage cell. The simulation results were presented to prove the validity of the proposed cell balancing circuit by PSIM software. The balanced cell voltage with the cell balancing circuit in the simulation result was approximately 3.65V which is equivalent to the average cell voltage.

5. Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2014R1A1A1036384).

6. References

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