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A Cell Equalization Method Based on Resonant Switched Capacitor Balancing for Lithium Ion Batteries

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Abstract—**This paper presents the concept of a cell balancing method for Lithium Ion (Li-ion) batteries for Electrical Vehicles (EV), based on Resonant Switched Capacitor Converter (RSCC) balancing technique. It equalizes eight number of cells in a series. In Li-ion batteries, voltage differences always exist between cells due to charging and discharging process, therefore a battery management system (BMS) is required to ensure that all cells are equally charged or discharged and it also increases the life cycle of the battery. An equalizing method is essential to achieve the best performance. A number of cell balancing method have been presented. Among them, Switched Capacitor Converter (SCC) is more effective compared to other methods because it can be implemented easily. Low volume, low cost, high power density are its features. However, low balancing speed is an important problem of the SCC. In this paper, a resonant switching capacitor is proposed to reduce the balancing time and reduce the energy loss. The simulation results are performed to verify the feasibility of the system.**

Keywords-BMS; EV; Li-ion; RSCC; SCC

I. INTRODUCTION

Nowadays, the world is being confronted with the incomparable problems such as global warming; sea level rising and depletion of fuels, thus the demand for electrical vehicles are increasing during last decades. They can achieve low pollution, low noise compared to gasoline powered vehicles. The cost of electrical vehicles depends on many aspects, but the most expense in it, is the cost of the batteries. Lithium Ion batteries are widely used in many application, for instance, electrical vehicles, motor bikes [1]–[3] due to their advantages such as high density, low self discharge rate, lower weight, higher safety, no memory effect [4]–[7]. The open circuit voltage of the battery is low, thus in many application Li-ion batteries are connected in series [8], [9]. However, due to the charging and discharging cycles, the voltages of the cells will differ.

These unavoidable differences are due to the chemical and electrical characteristics, such as asymmetrical degradation with aging, production tolerance, internal impedance [7], [10]. These imbalances reduce the life cycle and utilization rate of the battery [11], [12]. Battery management system is used to increase the life cycle and available capacity of the battery system and plays an important role in electrical vehicle. It monitors and manages battery modules and provides early warning protection. It detects battery voltage, battery charge, battery temperature, discharge current and has over voltage protection, under voltage protection, over current protection, over temperature protection and short circuit protection.

Many battery equalization methods have been proposed in the literature [13]–[15]. These are divided into a passive balancing methods and active balancing methods. The shunting cell balancing method is a passive method that removes the excess charge from fully charged cell through resistor until the charge matches those of the lower cells in the pack. The advantages are, low cost, easy implementation, however, the disadvantages are, energy dissipation and the heat problem, thus the efficiency is low [16]–[18].

Active cell balancing techniques are divided into two categories, such as switched capacitor converters (SCC) and inductor based converters. It transfers excessive energy from over charged cells to the uncharged cells by using switched capacitor [19]–[22], inductor [23]–[25] and multi-winding transformers [26]–[28]. The most important disadvantage of a switched capacitor converter is long balancing time and low speed compared to inductor based balancing method.

The inductor based converters may have smaller balancing time but has disadvantages such as high cost and magnetic losses. Therefore, the switched capacitor methods are suitable due to easy implementation, small size and low cost. The disadvantage of (SCC) is low balancing time. In this paper the problem of (SCC) method is improved by using resonant switched capacitor converter.

The conventional switched capacitor converter circuit with two batteries is shown in Fig. 1. It consists four number of switches S_1 to S_4. All switches are controlled to be turned on and turned off simultaneously with a desired switching frequency with duty cycle of 50%. According to the switching connection, this circuit can be divided into two modes. In the first mode, the switches S_1 and S_3 are tuned on while the switches S_2 and S_4 are kept turned off. In the second mode, the switched S_2 and S_4 will be turned on, while the switches S_1 and S_3 are kept turned off. To analyze the circuit assume that the voltages of the adjacent battery cells are different, thus, the charge will be transferred between adjacent cells through the common capacitor. The common capacitor connected between the two cells is connected to the upper cell and the lower cell with the same duty ratio of 50%.

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The voltage of the common capacitor is equal to the average voltage of the two adjacent cells. In the conventional switched capacitor converters circuits, the equalizing speed is low, especially when the number of cells increases. In this paper a resonant switched capacitor converter is proposed to increase the equalization time and total energy loss. The resonant tanks include the resonant inductor L, capacitor C and consist of eight number of cells (Fig. 2).

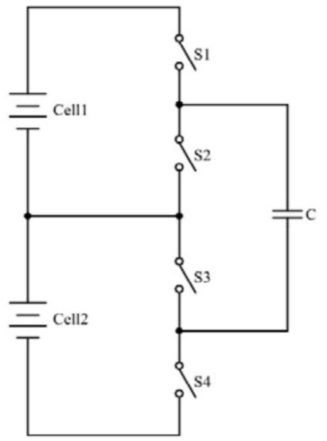

Figure 1. The conventional capacitor based balancing circuit.

II. The Proposed Circuit Based on Resonant Switched Capacitor Converter Balancing

In Fig. 2 the block diagram of the proposed circuit is presented. All switches are MOSFETs with body diodes and controlled by a pair of complementary signal in synchronous trigger pattern with the duty cycle of 50%. The operational principle of the circuit can be divided into two stages.

A. Stage one

In stage one, the odd switches S_1-S_{15} are turned on to store energy to the resonant tanks while the even switches S_2-S_{16} are kept turned off. When the switches S_1-S_{15} are turned on the energy of the cell 1, cell 3, cell 5 and cell 7 will be transferred to the resonant tanks, thus the resonant tank will be connected in parallel with odd cells, cell number 1 to cell number 7. Therefore, the capacitor C_1 to C_7 will be charged. The voltage of the capacitors will be increased and resonant current increases. The resonant current for the first resonant tank L_1C_1 in parallel with cell 1 can be expressed as

$$i_{(resonant)} = C_1 \frac{dV_{C_1}}{dt} \quad (1)$$

$$\varepsilon + \frac{\varphi}{C_1} = V_{\text{cell1}} \quad (2)$$

$$L_1 \frac{di_{(resonant)}}{dt} + V_{C_1} = V_{\text{cell1}} \quad (3)$$

where ε is the inductor voltage of L_1, and $\frac{\varphi}{C_1}$ is the capacitor voltage of C_1. The initial angle of resonant is

$$\varphi = \varphi_0(\cos\omega t + \varphi) \quad (4)$$

The resonant angular frequency can be driven as

$$\omega = \frac{1}{\sqrt{LC}} \quad (2)$$

Therefore, the solution for Eq. 3 can be expressed as

$$V_{C_1} = V_{\text{cell1}} + V\cos(\omega t + \varphi) \quad (3)$$

$$i_{(resonant)} = I_{max}\sin(\omega t + \varphi) \quad (4)$$

where I_{max} is the amplitude of the resonant current, V is the amplitude of the V_{C1} and ω is the resonant angular. The resonant current for the other resonant tanks can be expressed as the same Eq. 7.

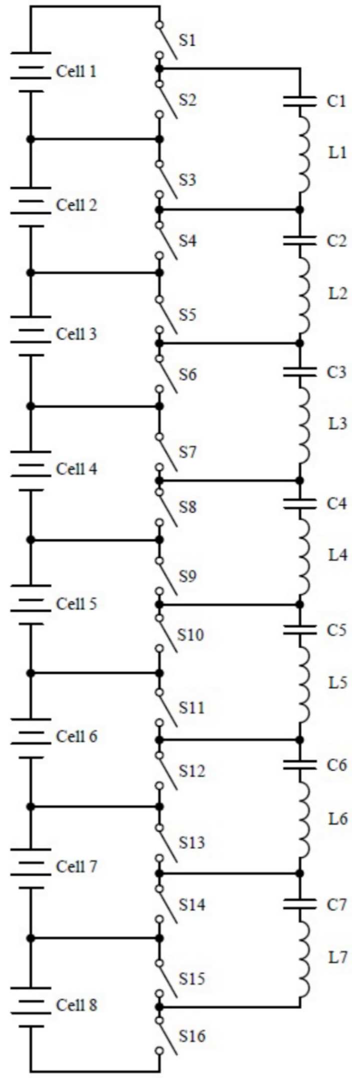

Figure 2. The proposed resonant switched capacitor balancing circuit.

B. Stage two

In stage two, the even switches S_2-S_{16} will be turned on while the odd switches S_1-S_{15} are kept turned off. Therefore, the resonant tanks will be connected in parallel with the even cells, cell number 2 to cell number 16. Thus the even cells will be charged and resonant current will increase, but this time in the opposite direction. Similarly as discussed in the previous state, the resonant current for the first resonant tank L_1C_1 also can be expressed as

$$i_{(resonant)} = -I_{max}\sin(\omega t + \varphi) \quad (5)$$

$$V_{C_1} = V_{\text{cell2}} - V\cos(\omega t + \varphi) \quad (6)$$

The resonant current for the other resonant tasks will be expressed as the same as Eq. 8. In order to have maximum current, $\sin(\omega t + \varphi) = 1$ should be equal to one. I_{max} can be expressed as $(I_{max} = \omega\varphi_0)$. Therefore, in order to get the maximum current the equation for the maximum current, I_{max} can be expressed as

$$I_{max} = \frac{\varphi_0}{\sqrt{LC}} \quad (7)$$

III. Simulation Results

In order to verify the feasibility of the proposed circuit the simulation results are expressed. To model the proposed circuit in MATLAB, the cells are modeled with the capacitors with the value of 50mF and the resonant tanks are molded with the 10μH inductors and 10μF capacitors. All the switches are MOSFETs with the body diodes and they are triggered with the synchronous pulse, generated by a pulse generator with the duty ratio of 50% and 45% to investigate different conditions. The battery voltages are chosen to be from 3V to 3.6 V inappropriately to present the significant voltage difference of the cells. The resonant frequency is calculated 15.915kHz, originated from the pulse generator. The resonant current changes from zero at the beginning of each state. Therefore, in order to have zero current the resonant frequency should be multiple of switching frequency. The resonant frequency with the inductor value of L=10μH and capacitor values of C=10μF can be calculated as

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

In order to control the MOSFETs a synchronous pulse with the duty ratio of 50% is applied to the gate of the MOSFETs with the switching frequency of fs=15.915kHz. (fs=fresonant). Fig. 3 and Fig. 4 illustrate the gate to source voltage to the odd and even switches with 50% duty ratio respectively.

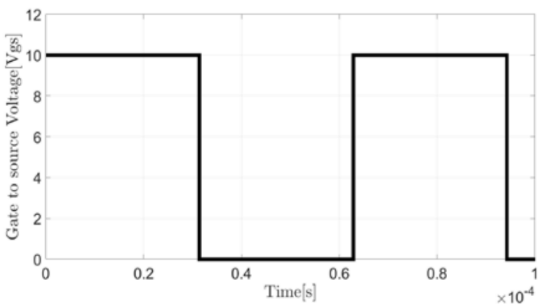

Figure 3. Gate to Source Voltage (Vgs) to the odd switches.

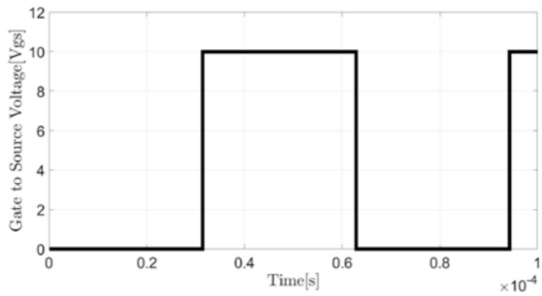

Figure 4. Gate to Source Voltage (Vgs) to the even switches.

To compare between the conventional switched capacitor converter (SCC) shown in Fig.1 and the proposed resonant switched capacitor converter (RSCC) circuit shown in Fig. 2, the simulation result of the conventional switched capacitor converter is presented in Fig. 5. To analyze the circuit, the conventional SCC is modeled with eight number of cells in series. The cell voltage is chosen to be from 3V to 3.6 V to have significant voltage difference between the cells. The capacitor values are 10μF, the switching frequency is15.915kHz with 50% duty ration. The switches are MOSFETs with body diodes and are controlled with the synchronous pulse. As it can be observed in Fig. 5, the equalization time is very slow compared to the proposed (RSCC) circuit as shown in Fig. 6.

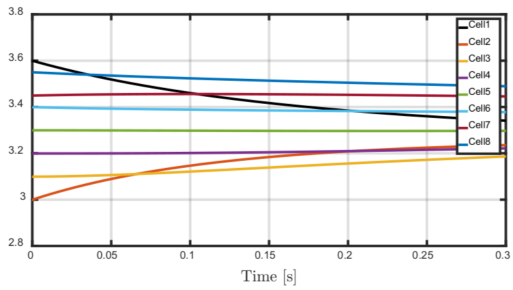

Figure 5. Cell Voltages of the conventional switched capacitor converter.

In Fig.6 the cell voltages of the proposed (RSCC) circuit is shwon. All the parameters for the components are the same with the conventional circuit in order to consider the difference between the two methods.

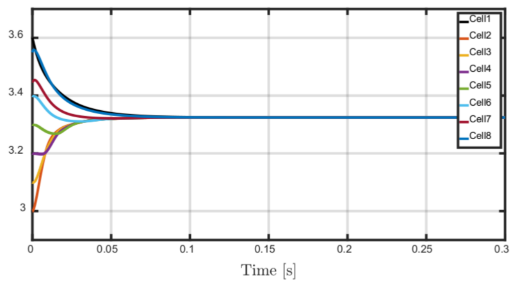

Figure 6. Cell Voltages of the proposed (RSCC) circuit.

To examine the response of the system to the switching time, the switching frequency of fs=15.915kHz with 45%

duty ratio is applied to the switches. As shown in Fig. 7, with a dead time of 5%, the equalization time increase barely.

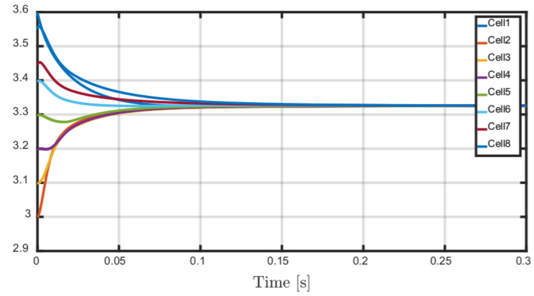

Figure 7. Cell Voltages of the proposed (RSCC) circuit with 5% dead time.

The resonant currents of the resonant tanks L1C1 to L1C7 is presented in Fig. 8. It can be seen that in transient period when the cell are equalizing the current is oscillation, then after the cells are balanced equally the resonant current becomes zero. Fig. 9 shows the resonant current of the resonant tanks in detail in transient period when the cells are not equalized.

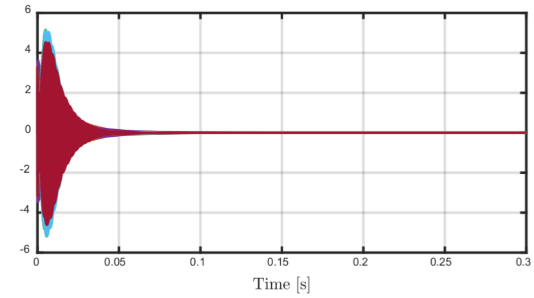

Figure 8. The resonant current of the resonant tank 1-7.

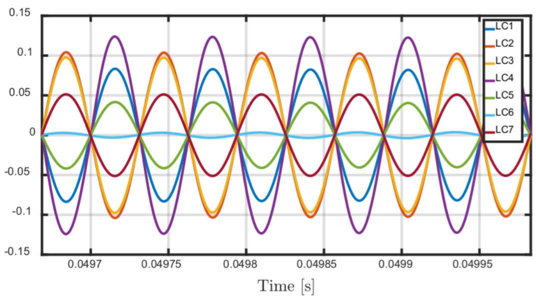

Figure 9. The resonant current of the resonant tank 1-7 in detail.

In the proposed circuit as explained before, the switching frequency and the resonant frequency are chosen to be the same in order to obtain zero current, when the cells are totally equalized. To consider the difference response, the switching frequency fs is chosen to be half of the resonant frequency fresonant (fs=1/2fresonant). Fig. 10 shows the resonant current when the switching frequency is half of the resonant frequency. It can be observe that the current is not equal to zero in steady state because of the resistor in resonant circuit which causes oscillation. In Fig. 11 the resonant current in detail is expressed.

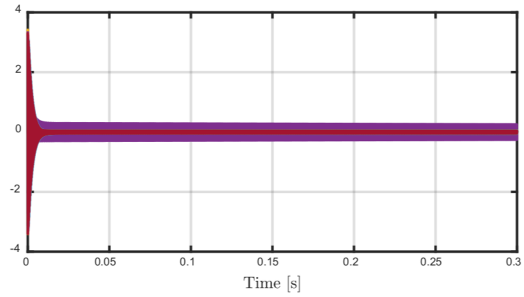

Fig. 10. The resonant current of the resonant tank 1-7 ($f_{resonant}$=2f)

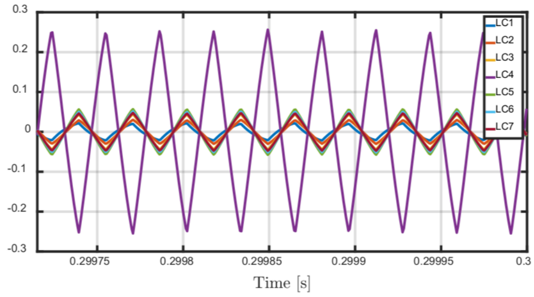

Figure 11. The resonant current of the resonant tank 1-7 ($f_{resonant}=2f_s$) in closer view.

IV. CONCLUSIONS

In this paper, the concept of cell equalization technique based on resonant switched capacitor converter (RSCC) is investigated. The switched capacitor based equalizer has many advantages, such as easy implementation, low volume, low cost and high power density compared to other equalization method. The conventional switched capacitor balancing method has a disadvantage of long equalization time. In order to overcome this problem, the proposed topology shown in Fig. 2 improves the balancing time compared to conventional method shown in Fig. 1. This method uses the resonant tank includes the resonant inductor and capacitor to equalize the cells. It equalizes eight number of cells in a one battery pack, faster compared to the conventional topology due to zero current turn-on and off, thus less switching loss is achieved. To verify the feasibility of the system the simulation results are performed.

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