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Active cell balancing of Li-Ion batteries using single capacitor and single LC series resonant circuit

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ABSTRACT

In this paper a novel single series resonant tank and capacitor converter based voltage balancing circuit for series supercapacitor string and battery cells string is presented. It recognizes the balancing circuit which recovered the maximum energy and zero voltage gap between cells in a series supercapacitor system or battery system. This balancing circuit not only inherits the improvement of conventional single series resonant converter based balancing system, but also recovers the drawback of switching loss, conduction loss and voltage gap between cell strings. All MOSFET switches are controlled by a pair of complementary PWM signals. Also the resonant tank and parallel capacitor operate between the two mode of charging and discharging. This voltage balancing circuit has shown promising result to be used in battery management system.

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1. INTRODUCTION

Electric vehicles (EV) has become popular in last few years. In the transportation sector EVs are suitable alternative to gas or diesel engine vehicles because of ecological and economical issues [1]. Internal combustion engine (ICE) vehicles and industries are major source of carbon monoxide, nitrogen oxides, sulphur dioxide, and especially carbon dioxide, which are the major reasons for greenhouse effect. In transportation sector, ICE vehicles, including aircraft, cargos consumed one-third of fossil fuel energy. The transportation energy source is 1% by electricity, 2% by bio-fuels, 3% by natural gas and 94% by oil [2-3]. In EV, electricity is used to drive the motor without emitting any CO, CO2, nitrogen oxides, sulphur dioxide. For these reasons EV is called zero-carbon emission vehicle which will solve the energy and environmental issues [2].

Currently energy storage device such as rechargeable batteries or supercapacitors are widely used in UPS, satellites, hybrid electric vehicles (HEVs), EVs and plug-in HEVs. Rechargeable batteries such as NiCd, lithium battery (i.e., Lipo, Li-ion, and LiFePO4 etc.) are used in EVs [4]. Due to the high power density, high energy density, environmental friendliness, long lifetime, no memory effect and low self-discharge rate Li-ion batteries are widely used in automotive applications [5]. However, a single cell terminal voltage is 2-4.2 V, e.g., Li-ion battery cell is 3-4.2 V, LiFEPO4 battery cell is 2-3.65 V, Nickel Metal Hydride (NiMH) is 2-3.6 V. For EV application, supercapacitor is used as a particular energy source and can be engaged with battery. Generally EV battery pack consists of Li-ion battery cells which are connected in series and parallel to meet the required load voltage and power for traction motor in EV. Tesla Model S, in order to meet required voltage and power, uses 7616 Li-ion 18650 cells are connected in series and parallel combination [4, 6-7].

However, the rechargeable batteries or supercapacitors are electrochemical vessel, for that reason after some charging and discharging cycles their physical characteristics will change. Due to their internal resistance, in terms of capacity among the battery cells are slight different which causes imbalance in the cell voltage during charging and discharging time. Imbalanced cells voltage reduce the durability and overall performance of the energy storage devices. Over-charge can be the reason behind cell explosion and over-discharge might be cause for chemical digression that reduce life time of the battery cells. To protect the Li-ion battery cell from over-charging and under-charging, a battery management system (BMS) is very essential. A BMS can monitor the individual cell status on charging or discharging time, the charge balancing system could save the Li-ion cell from over-charging and over-discharging hazard and increase the performance of the rechargeable battery or supercapacitors to supply power effectively in EV [8-9].

Therefore, voltage balancing between different cells in a battery pack is very important to extend the battery life time and power supply range. Last few decades, many researcher worked on battery voltage balancing system and proposed many balancing topologies to improve the battery lifetime and safety issues. Battery voltage balancing topologies are classified into two group. One is called passive balancing system and another is active balancing system [10]. In passive balancing system resistances are connected in parallel with every cell and excess energy from higher cells are diminished by heat. The disadvantages of this system are heat problem and energy dissipation [11]. To overcome those problems, researchers have tried to transfer energy from one cell to another by using capacitor [12-17], inductor [18-21] and transformer [22-26]. The active balancing system have first balancing capacity, higher efficiency than passive balancing system. And it is also small in size, cost effective and can easily be controlled.

In this paper, a new single *LC* + parallel capacitor (Cs) based cell to cell active balancing topology is proposed. This balancing circuit works like as switched-capacitor balancing circuit. The switching frequency of this circuit is equal to the resonant frequency. This is how this balancing circuit achieved soft switching thus increased the balancing time. The rest contents of this paper are- proposed balancing circuit is described in Section 2. Operational principle of the balancing circuit is described in Section 3. Result of the balancing circuit is shown in Section 4 and conclusion highlighted in Section 5.

2. PROPOSED VOLTAGE BALANCING CIRCUIT

The proposed voltage balancing circuit connected to a single LC tank and a parallel capacitor is shown in Figure 1. In this circuit all cells are connected in a series string. Here cell$_1$ and cell$_2$ are connected with two MOSFET switches and cell$_2$ to cell$_{n-1}$ are connected with anti-series MOSFET switches. For voltage balancing, all MOSFET switches are controlled by the same PWM signal.

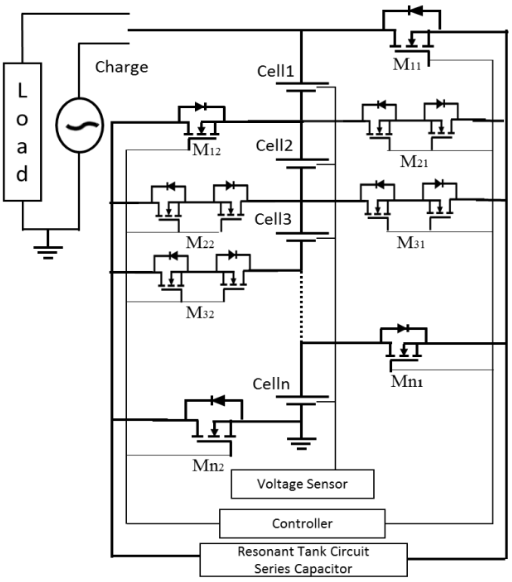


Figure 1. Proposed voltage balancing circuit

3. PRINCIPLE OF VOLTAGE BALANCING SYSTEM:

This balancing circuit can balance the highest voltage difference between two series energy storage (ES) cell in the ES cell string. The operation principle of the ES string have two mode and every mode has two step as shown in Figure 2. In operational mode, the MOSFET switch M_{11}, M_{12}, M_{21} and M_{22} are operated by a PWM signal.

3.1. Operational mode I: $Cell_1>Cell_2$

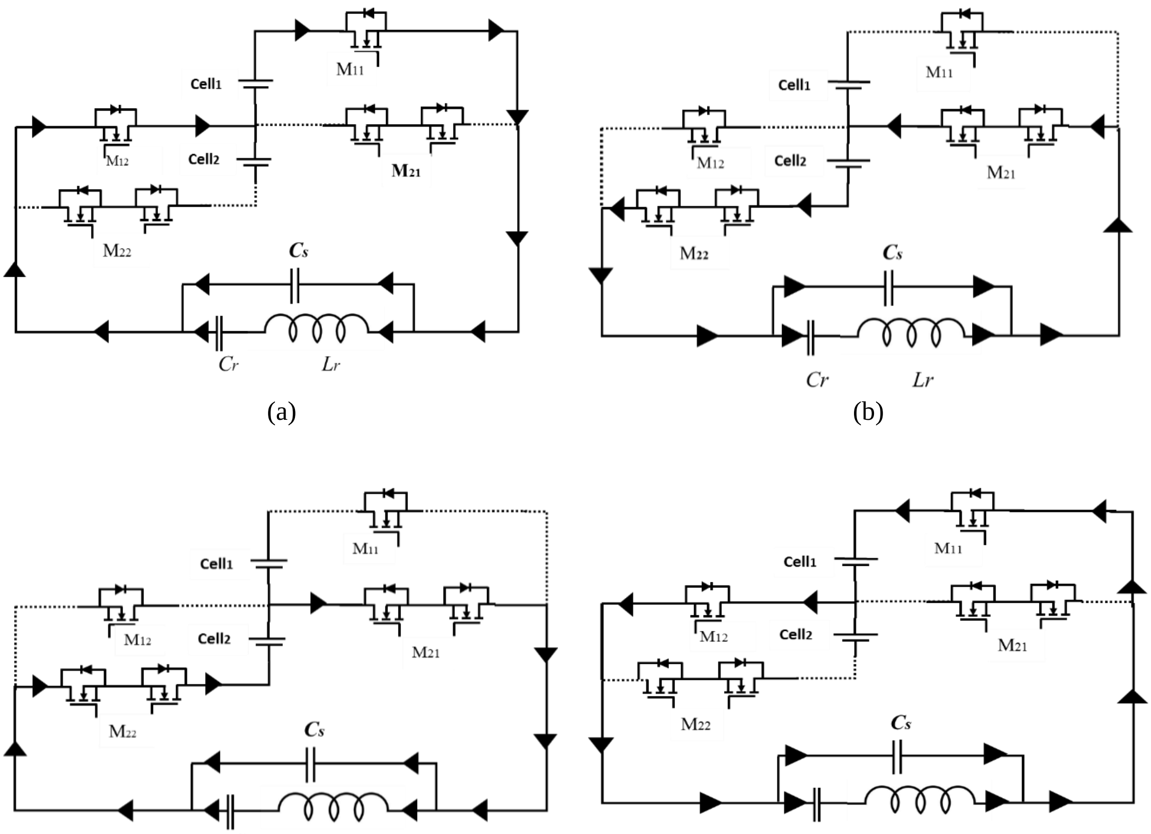
Charging state: M_{11} and M_{12} are turned ON in this state, on the other hand M_{21} and M_{22} are turned OFF. $Cell_1$, M_{11}, LC tank, Cs and M_{12} form a circle and the current flowing direction of the circle is clockwise, as shown in Figure 2(a). In this time *LC + Cs* are charged by $cell_1$.

Discharging state: M_{11} and M_{12} are turned OFF, on the other hand M_{21} and M_{22} are turned ON. $Cell_2$, M_{21}, M_{22}, LC tank and Cs form a circle. The resonant capacitor and series capacitor release all stored energy to $cell_2$, the direction of resonant inductor current is anti-clockwise, as shown in Figure 2(b). In this time $cell_2$ is charged by *LC + Cs*.

3.2. Operational mode II: $Cell_2>Cell_1$

Charging state: M_{21} and M_{22} are turned ON, on the other hand M_{11} and M_{12} are turned OFF. $Cell_2$, M_{21}, LC tank, Cs and M_{22} form a circle and the current flowing direction of the circle is clockwise, as shown in Figure 2(c). In this time *LC + Cs* are charged by $cell_2$.

Discharging state: M_{21} and M_{22} are turned OFF, on the other hand M_{11} and M_{12} are turned ON. $Cell_1$, M_{11}, M_{12}, LC tank and Cs form a circle. The resonant capacitor and series capacitor release all stored energy to $cell_1$, the direction of resonant inductor current is anticlockwise, as shown in Figure 2 (d). In this time $cell_1$ is charged by *LC + Cs*.



(a) (b)

(c) (d)

Figure 2. Current flowing path of the balancing circuit, (a) LC & Cs store energy from $cell_1$, (b) LC & Cs release the stored energy and $cell_2$ store that energy, (c) LC & Cs store energy from $cell_2$, (d) LC & Cs release the stored energy and $cell_1$ store that energy

3.3. Resonant analysis

When M_{11} and M_{12} are turned ON and M_{21} and M_{22} are turned OFF, then initial voltage of the switch capacitor (Cr) in resonant network is Vc_r. In [6], resonant voltage and current start to increase with time t from $Cell_1$ that should be equal to,

$$L_r \frac{di_r}{dt} + V_{C_r} + V_{C_s} = V_{Cell1} \tag{1}$$

At the resonant time,

$$V_{C_r} = V_{Cell1} + V_{C_s} + \Delta V_C (\cos \omega t + \theta) \tag{2}$$

$$i_r = \Delta I (\sin \omega t + \theta) \tag{3}$$

Here ΔV_C is the amplitude of Cr, resonant current amplitude is ΔI, angular frequency $\omega = 1/\sqrt{LC_r}$ and θ is the initial angle of the resonant. Capacitor initial voltage is assumed to be 0. Capacitor (Cr) of resonant circuit starts charging and amplitude of the resonant current is,

$$\begin{aligned} \Delta I &= \frac{V_{Cell1} - V_{C_S} - V_{Cr}}{\omega L_r} \\ &= \left(V_{Cell1} - V_{C_s} - V_{Cr}\right)\sqrt{\frac{C_r}{L_r}} \end{aligned} \tag{4}$$

In charging state, voltage across of the resonant capacitor (Cr) will reach to the maximum $V_{C_r \max}$, that is,

$$V_{C_{r\,max}} = 2V_{Cell1} - V_{C_s} - V_{Cr} \tag{5}$$

At discharging state, M_{21} and M_{22} are turned ON and M_{11} and M_{12} are turned OFF. Resonant voltage and current start to increase in opposite direction with time t and should be equal to,

$$L_r \frac{di_r}{dt} + V_{C_s} + V_{C_r} = V_{Cell2} \tag{6}$$

At the resonant time,

$$V_{C_r} = V_{Cell2} - V_{C_s} - \Delta V_C (\cos \omega t + \theta) \tag{7}$$

$$i_r = -\Delta I (\sin \omega t + \theta) \tag{8}$$

Capacitor (Cr) of resonant circuit starts discharging and amplitude of the resonant current is,

$$\begin{aligned} \Delta I &= \frac{V_{Crmax} + V_{C_S} - V_{Cell2}}{\omega L_r} \\ &= \left(V_{C_{rmax}} + V_{C_s} - V_{Cell2}\right)\sqrt{\frac{C_r}{L_r}} \end{aligned} \tag{9}$$

Voltage across the resonant capacitor (Cr) will reach to the minimum $V_{C_r \min}$, that is,

$$V_{C_{r\,min}} = 2V_{Cell2} - V_{C_s} - V_{Cr} \tag{10}$$

In operational state, allowing the standard voltage balance of the resonant capacitor V_c completed switching cycle,

$$i_L DT - i_L (1 - D) T = 0 \tag{11}$$

Here, D is the duty cycle, and T is the switching time.
The average current of the inductor can be expressed as,

$$i_L = [\frac{1}{2} (\frac{V_{C_r} + V_{C_S} + V_{cell1}}{L} D^2 + \frac{V_{C_r} + V_{C_S} - V_{cell1}}{L} (1 - D)^2] T \tag{12}$$

4. RESULTS AND DISCUSSION

The DC to DC active voltage balancing circuit is simulated in MATLAB SIMULINK-2016a. Here supercapacitors are used as an energy storage cells for this topology. In simulation 100F supercapacitors are used. All MOSFET switches are controlled by PWM signal with 50% of duty cycle. In the resonant tank, 100 µH inductor, 100 µF capacitor and 100 mF parallel capacitor are used. Figure 3 demonstrates the switching frequency of the MOSFET switches. It can be observed that the switching frequency is same as resonant frequency. Thus, soft switching has been achieved. Figure 4 shows the balanced result for cell$_1$ and cell$_n$. Initial voltages of two 100F supercapacitor are 2.7V for cell$_1$ and 2.4V for cell$_n$. The balancing circuit takes 102 seconds to balance the voltage difference of cell$_1$ and cell$_n$. The balancing result of two cell$_1$ and cell$_2$ is shown in Figure 5 which takes 125 seconds to balance the voltage difference.

Figure 6 shows that the multiple cell balancing result for cell$_1$, cell$_2$ and cell$_n$. In this analysis, different capacitances of supercapacitors are used. Here, cell$_1$ and cell$_2$ are 100F and cell$_n$ is 10F and the balancing circuit takes approximately 176 seconds to balance the voltage diffrence. Figure 7 shows the comparison of simulation result between [6] and currently proposed circuit for cell$_1$ & cell$_n$. The proposed topology takes 102 seconds to balance the cell voltage difference whereas the circuit in [6] takes 168 seconds. It is evident that the proposed balancing circuit takes less time to balance than the circuit in [6].

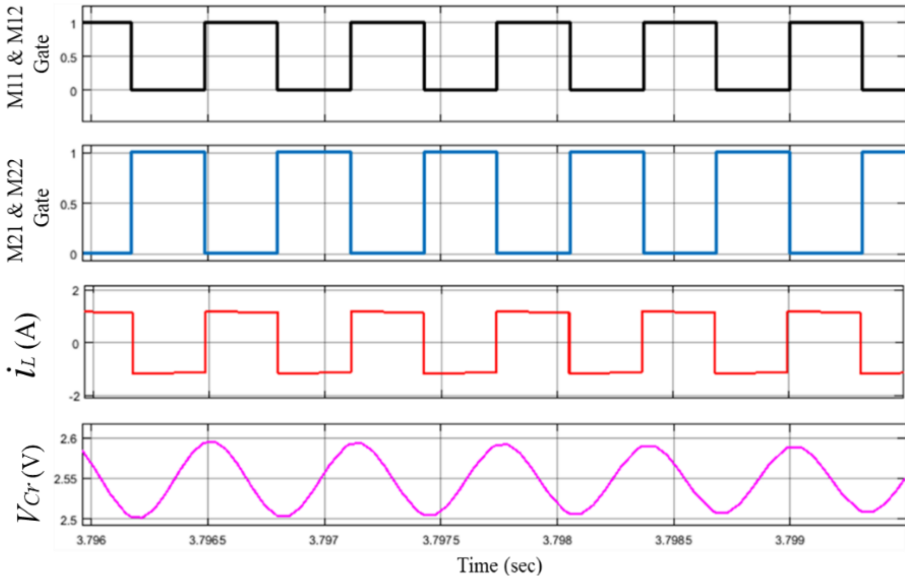


Figure 3. Simulation waveforms of the MOSFET switches gate pulse, inductor current and resonant capacitor voltage

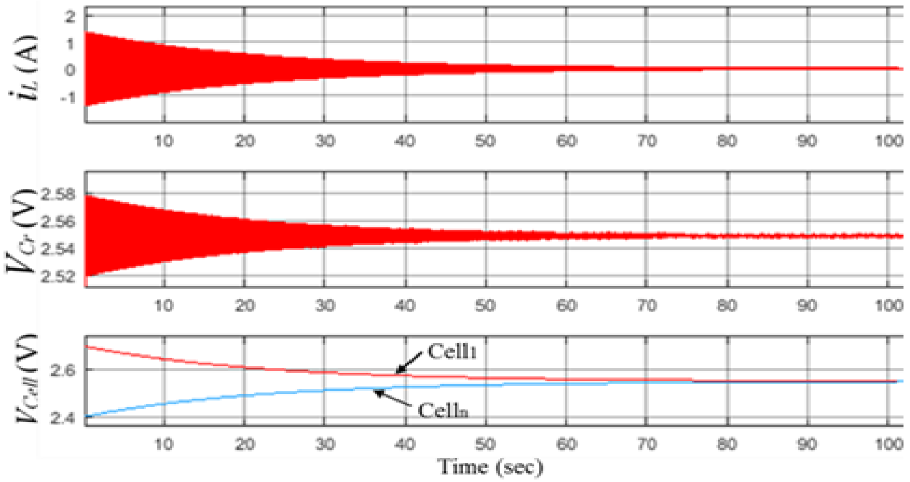


Figure 4. Balanced result for cell$_1$ and cell$_n$

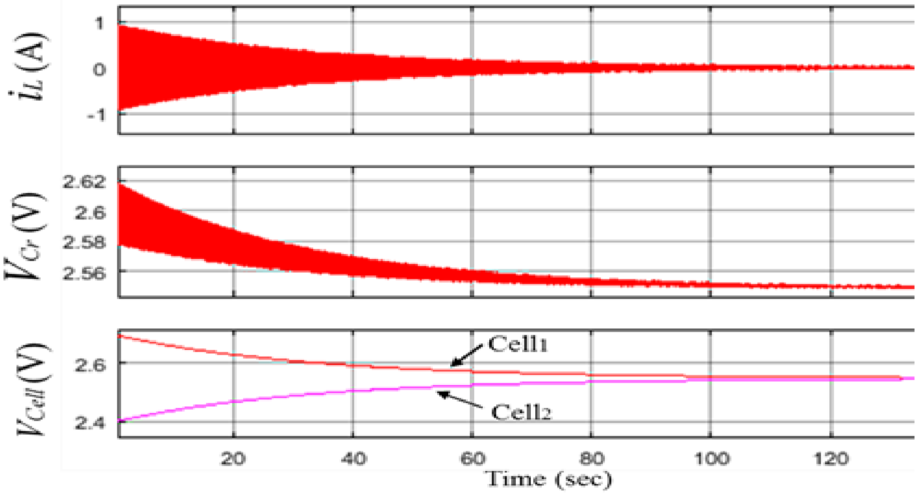


Figure 5. Balanced result for cell$_1$ and cell$_2$

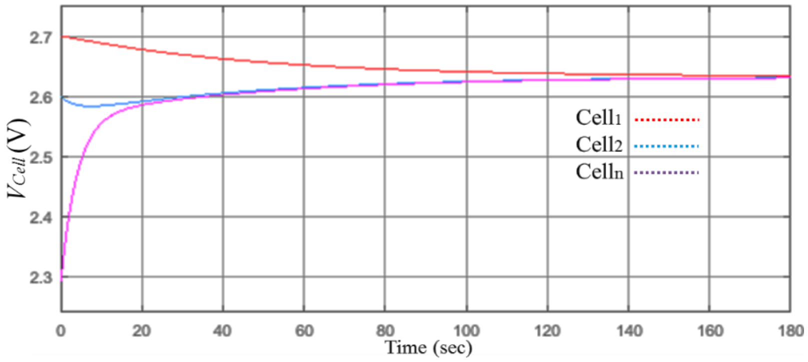
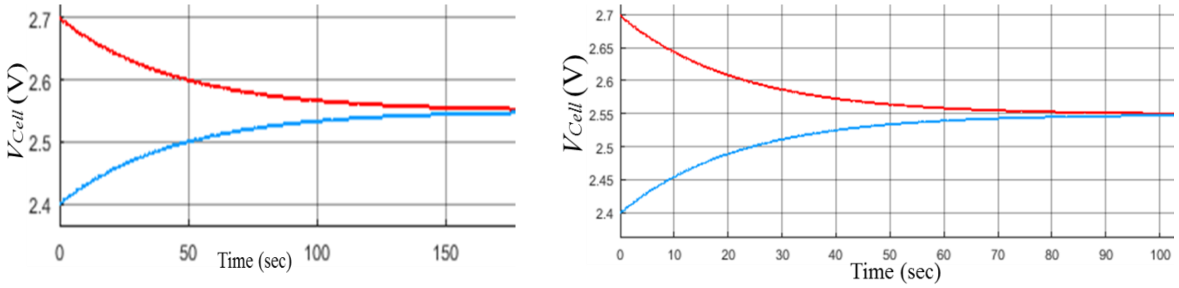


Figure 6. Simulation waveforms of the multiple cell balancing result



(a) (b)

Figure 7. Comparison of simulation result of [6] in (a) Proposed circuit, (b) For cell$_1$ & cell$_n$

5. CONCLUSION

In this paper, a single resonant circuit with parallel capacitor based voltage balancing system has been proposed. This balancing circuit not only inherits the improvement of conventional single series resonant converter based balancing system, but also transfers the energy from overcharged or higher voltage cell to undercharged or lower voltage cell and have achieved zero voltage gap between cells string. The proposed circuit takes less voltage balancing time, small in size and easy to implement in battery module for that it will be suitable for battery management system in EV. The effect of temperature is not considered in this study. In future, we will consider the analysis of balancing circuit with variation of temperature and also under overcharged and undercharged condition.

REFERENCES

[1] I. Husain, “Electric and hybrid vehicles: design fundamentals,” *CRC press*, 2011.

[2] A. A. Habib, et al., “A Single LC Tank Based Active Voltage Balancing Circuit for Battery Management System,” *IIUM Engineering Journal*, vol. 19, no. 1, pp. 158-167, 2018.

[3] N. Chowdhury, et al., “Optimization of Solar Energy System for the Electric Vehicle at University Campus in Dhaka, Bangladesh,” *Energies*, vol. 11, no. 9, pp. 2433, 2018.

[4] Y Shang, et al., “A switched-coupling-capacitor equalizer for series-connected battery strings,” *IEEE Transactions on Power Electronics*,” vol. 32, no. 10, pp. 7694-7706, 2016.

[5] X. Jin, et al., “Applicability of available Li-ion battery degradation models for system and control algorithm design,” *Control Engineering Practic*e, vol. 71, pp. 1-9, 2018.

[6] A. A. Habib, et al., “A Series Regeneration Converter Technique for Voltage Balancing of Energy Storage Devices,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 8, no. 2, pp. 475-481, 2017.

[7] Y. Shang, et al., “A cell-to-cell equalizer based on three-resonant-state switched-capacitor converters for series-connected battery strings,” *Energies*, vol. 10, no. 2, 2017.

[8] M. A. Hannan, et al., “Charge equalization controller algorithm for series-connected lithium-ion battery storage systems: Modeling and applications,” *Energies*, vol. 10, no. 9, pp. 1390, 2017.

[9] X. Wang, et al., “Dependency analysis and degradation process-dependent modeling of lithium-ion battery packs,” *Journal of Power Sources*, vol. 414, pp. 318-326, 2019.

[10] M. M. Hoque, et al., “Battery charge equalization controller in electric vehicle applications: A review*,” Renewable and Sustainable Energy Reviews*, vol. 75, pp. 1363-1385, 2017.

[11] J. Gallardo-Lozano, et al., “A novel active battery equalization control with on-line unhealthy cell detection and cell change decision,” *Journal of Power Sources*, vol. 299, pp. 356-370, 2015.

[12] Y. Ye and K. W. Cheng, “Modeling and analysis of series–parallel switched-capacitor voltage equalizer for battery/supercapacitor strings,” *IEEE journal of emerging and selected topics in power electronics*, vol. 3, no. 4, pp. 977-983, 2015.

[13] Y. Ye and K. W. Cheng, “An automatic switched-capacitor cell balancing circuit for series-connected battery strings,” *Energies*, vol. 9, no. 3, pp.138, 2016.

[14] Y. Ye, el al., “Topology, modeling, and design of switched-capacitor-based cell balancing systems and their balancing exploration,” *IEEE Transactions on Power Electronics*, vol. 32, no. 6, pp. 4444-4454, 2016.

[15] K. M. Lee, et al., “Active cell balancing of li-ion batteries using LC series resonant circuit,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 9, pp. 5491-5501, 2015.

[16] Y. Shang, et al., “A delta-structured switched-capacitor equalizer for series-connected battery strings,” *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 452-461, 2018.

[17] Y Ye, and K. W. Cheng, “Analysis and design of zero-current switching switched-capacitor cell balancing circuit for series-connected battery/supercapacitor,” *IEEE Transactions on Vehicular Technology*, vol. 62, no. 2, pp. 948-955, 2017.

[18] Z. Zhou, et al., “An any-cell (s)-to-any-cell (s) equalizer based on bidirectional inductor converters for series connected battery string,” *Industrial Electronics and Applications (ICIEA), 2016. IEEE 11th Conference*, pp. 2511-2515, 2016.

[19] F. Mestrallet, et al., “Multiphase interleaved converter for lithium battery active balancing*,” IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2874-2881, 2013.

[20] Y Fong, et al., “Multi-Port Zero-Current Switching Switched-Capacitor Converters for Battery Management Applications,” *Energies*, vol. 11, no. 8, pp. 1934, 2018.

[21] T. H. Phung, et al., “An optimized topology for next-to-next balancing of series-connected lithium-ion cells,” *IEEE transactions on power electronics*, vol. 29, no. 9, pp. 4603-4613, 2013.

[22] M. A. Hannan, et al., “Lithium-ion battery charge equalization algorithm for electric vehicle applications,” *IEEE Transactions on Industry Applications*, vol. 53, no. 3, pp. 2541-2549, 2017.

[23] Y. Chen, et al., “A multiwinding transformer cell-to-cell active equalization method for lithium-ion batteries with reduced number of driving circuits,” *IEEE Transactions on Power Electronics*, vol. 31, no. 7, pp. 4916-4929, 2015.

[24] T. Anno and H. Koizumi, “Double-input bidirectional DC/DC converter using cell-voltage equalizer with flyback transformer,” *IEEE Transaction on Power Electron*, vol. 30, no. 6, pp. 2923-2934, 2014.

[25] Y Shang, et al., “A global modular equalizer based on forward conversion for series-connected battery strings,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 3, pp. 1456-1469, 2017.

[26] H Nazi, et al., “Bidirectional active charge equaliser for series-connected cells,” *IET Power Electronics*, vol. 12, no. 5, pp. 1229-1240, 2019.

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