2022 13th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)
1-3 February, 2022, Shahid Beheshti University, Tehran, Iran

Fast Active Balancing Circuit for Li-ion Battery Modules using a DC-DC Bipolar Converter

Mohammad Abareshi
School of Electrical and Computer Engineering
College of Engineering
University of Tehran, Iran
mohammad.abareshi.work@gmail.com

Abdolsalim Satlekhi
School of Electrical and Computer Engineering
College of Engineering
University of Tehran, Iran
satlekhi@ut.ac.ir

Mohsen Hamzeh
School of Electrical and Computer Engineering
College of Engineering
University of Tehran, Iran
mohsenhamzeh@ut.ac.ir

Shahrokh Farhangi
School of Electrical and Computer Engineering
College of Engineering
University of Tehran, Iran
farhangi@ut.ac.ir

***Abstract*—In this paper, a non-isolated DC-DC bipolar converter for fast balancing of series-connected Li-ion batteries is introduced. It is an active balancing circuit with the ability to transfer energy from an auxiliary source to the cells. Due to the importance of balancing time, in this method, energy is transferred to two adjacent cells, simultaneously. Since energy is injected into two cells simultaneously, the balancing time is reduced. To control the DC-DC converter, a PI controller is designed. To investigate the converter, its state space model has been acquired and the simulation results have been evaluated. The simulation results show the equalization time is significantly reduced.**

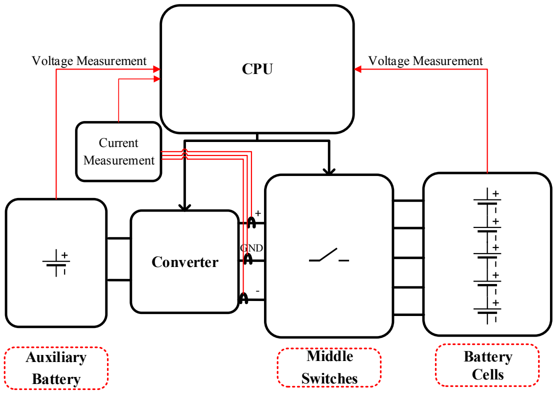
***Index Terms*—Power Electronics, Li-ion Battery, Active Cell Balancing, Balancing, DC-DC Converter.**

I. Introduction

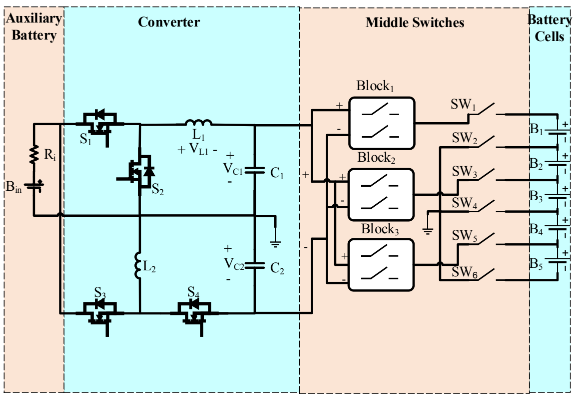
Over the past few decades, due to improved battery performance, an increase in demand has been observed in electric and hybrid vehicles, uninterruptible power supplies (UPSs), and energy storage systems (ESSs). Today, improving the performance of the battery management system (BMS) has received more attention. Due to the important features of lithium-based batteries such as high energy density, no memory effect, long life span, it has gained a special place among batteries in various applications [1]- [2]. BMS is a system managing a cell or set of rechargeable battery cells. The purpose of BMS is to prevent the battery pack from operating outside its safe operating area. Its functions include battery monitoring, evaluation, and control of important operational parameters during charging and discharging, such as monitoring voltage, current, temperature, etc., [3].

In most applications, high power is required and due to the low nominal voltage of each Li-ion cell, the cells must be series to reach the power level and high voltage. Because of inconsistent manufacturing procedures, aging, self-discharge, and working in various conditions, cells in battery modules are typically inhomogeneous [4]. Laboratory studies have shown that cell balancing is very effective in the health and increasing lifespan of cells [5]. Battery balancing is a part of BMS and it can generally be divided into passive and active categories [6]. Passive balancing, which is the most common balancing method, is a method that dissipates the unbalanced energy of battery cells as heat through resistors, [7]. The advantages of this method include low cost, high speed, and high reliability. Energy loss in form of heat is one of the disadvantages of this balancing method, which is significant at high power, [7] [8]. In active balancing circuits, unbalanced energy is returned to the system. For this purpose, inductors, capacitors, or DC-DC converters are used. In [9] and [10] the capacitor-based method is used and also in [11] and [12] the inductor and transformer-based method is used for balancing. Due to the variety of converters, different methods, algorithms, and controllers have been proposed [13]- [22]. In [22], a half-bridge converter-based active cell balancing is discussed. An isolated bidirectional DC-DC converter is developed for cell balancing in [24]. In [25], a Ćuk converter-based active cell balancing has been proposed. In [13] and [26], active cell balancing based on a flyback converter have been discussed. In [27], a multiphase interleaved active cell balancing using multiple buck-boost converters is designed. In [28], LCC resonant converter-based cell balancing has been developed. These circuits differ from each other in different aspects. Implementation cost, balancing time, number of passive elements, number of switches, modularity, reliability, control complexity, stress on components, and number of balanced cells are among the important parameters in balancing circuits.

In [13], two flyback converters have been used in the balancing circuit. One of the flyback converters works in boost mode and the other works in buck mode. The energy is either transferred from a cell with the highest voltage to the whole battery pack or from the whole battery pack to a cell with the lowest voltage. In [17], a buck-boost converter has been designed. Matrix switches are used as middle switches and have been able to balance multiple cells concurrently, which



(a) Functional block diagram.

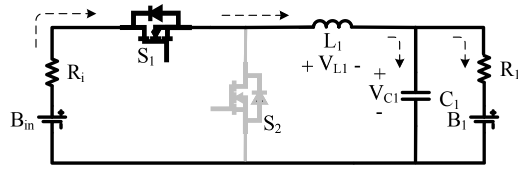


(b) Circuit schematic.

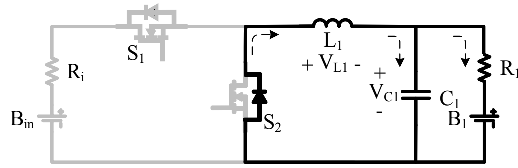
Fig. 1. Structure of proposed system which includes auxiliary battery, converter, middle switches and battery cells.

have greatly reduced the balancing time. The main disadvantage of this circuit is the considerable number of middle switches and the relatively complex balancing algorithm. Paper [23], proposed an active cell-to-cell balancing circuit using an LLC converter. The main advantage of this paper is the high speed of balancing due to the use of the LLC converter. Disadvantages include a high range of switching frequency change based on load changes, design, and control complexity.

Due to the importance of reducing balancing time and the cost of implementation and simplicity of the converter, in this paper, a low-cost converter is introduced which is able to transfer energy to two adjacent cells concurrently so that the balancing time would be reduced. In order to be able to inject energy into two adjacent cells, middle switches and blocks with special connections are used. In the following, the system will be described. The amount of balancing time reduction depends on the implemented algorithm and the initial values of the cells SOC.



(a) Mode 1



(b) Mode 2.

Fig. 2. Bidirectional buck converter operation using in the positive pole. Energy is transferred from an auxiliary source (B_{in}) to B_1 (a constant voltage source with a series resistor is used to model a battery cell).

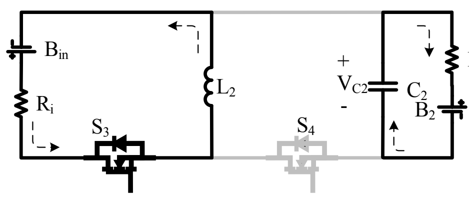
II. Power Electronics: Schematic, Operation, and Average Model

A. Overall Structure

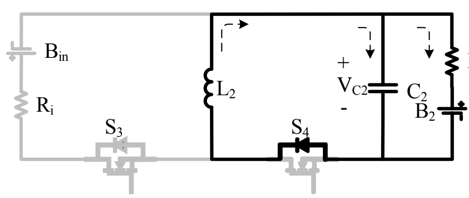
As shown in Fig. 1-(a), energy is transferred from an auxiliary source to battery cells through converters and middle switches. The auxiliary battery consists of two series li-ion cells modeled by a constant voltage source and a series resistor. The converters and middle switches are controlled by a control unit that monitors the voltages and currents of the system. In the following, the performance of the converter will be examined. In the case of the middle switches, as shown in Fig. 1-(b), switches 1 to 6 are used to select battery cells, and the other middle switches (blocks) are for connecting to the positive or negative pole. For instance, to charge cells 1 and 2, switches 1 to 3 are connected. SW_1 is connected to the positive pole through the middle block 1, and SW_3 is connected to the negative pole through the middle block 2. SW_2 is also connected directly to the ground.

To charge cells 3 and 4, switches 3 to 5 are connected. SW_3 is connected to the positive pole by the middle block 2 (in the previous case, this switch was connected to the negative pole) and SW_5 is connected to the negative pole by the middle block 3. SW_4 is also connected directly to the ground.

As shown in Fig. 1-(b) bipolar converter is used which consists of a bidirectional buck converter at the positive pole and a bidirectional buck-boost converter at the negative pole. Since these two converters have a common ground and a change in one converts duty cycle doesn't affect the output of the other, it can be said that these two converters have no coupling effect on each other, so they can be controlled separately.



(a) Mode 1



(b) Mode 2.

Fig. 3. Bidirectional buck-boost converter operation using in the negative pole. The polarity of the input and output voltages is different. Energy is transferred from an auxiliary source (B_{in}) to B_2 (a constant voltage source with a series resistor is used to model a battery cell).

B. Converter Operation

As shown in Fig. 2, in mode 1, when S_1 is connected, energy is transferred to L_1 and output. In mode 2, when S_1 is turned off, only the energy of the inductor is transferred to the output. In order to model the battery cells, a constant voltage source and a series resistor have been used. According to Fig. 3, in mode 1, by connecting S_3, the input energy is transferred to L_2, so the inductor is charged, in this case, C_2 provides the output energy and is discharged. In mode 2, when S_3 is turned off, the energy of L_2 is transferred to the output. As can be seen, the polarity of the output voltage is opposite of the input voltage which is caused by the charging and discharging of L_2 as described.

C. Modeling

By using the well-known averaging method, a small-signal state-space model of bidirectional buck converter is given by:

$$\dot{x}(t) = Ax(t) + Bu(t) + B_d d(t), \tag{1}$$

$$y(t) = Hx(t) + Ex(t) \tag{2}$$

Here, x, y, d ,and u are small-signals of $\begin{bmatrix} i_{L_1}(t) & v_{C_1}(t) \end{bmatrix}^T$, $y(t) = i_{B_1}(t)$, duty cycle, and $\begin{bmatrix} B_{in}(t) & B_1(t) & V_{D_1} & V_{D_2} \end{bmatrix}^T$, respectively, and

$$A = \begin{bmatrix} -D\frac{R_i + R_{SW1}}{L_1} & -\frac{1}{L_1} \\ \frac{1}{C_1} & -\frac{1}{R_1 C_1} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{D}{L_1} & 0 & 0 & \frac{D-1}{L_1} \\ 0 & \frac{1}{R_1 C_1} & 0 & 0 \end{bmatrix}$$

$$H = \begin{bmatrix} 1 & \frac{1}{R_1} \end{bmatrix}, E = \begin{bmatrix} 0 & \frac{-1}{R_1} & 0 & 0 \end{bmatrix}$$

Define the steady-state (capital letters) and small-signal (small letters) parameters as follows:

$$d = D + \tilde{d},\ u = U + \tilde{u},\ x = X + \tilde{x},\ y = Y + \tilde{y}. \tag{3}$$

Here, D is the duty cycle at steady state, R_{SW_1} is the internal resistance of S_1, R_i is the internal resistances of auxiliary source, and R_1 is the internal resistance of first battery cell.

The transfer functions from $\tilde{d}$ and $\tilde{u}$ to $\tilde{y}$ are obtained as follows:

$$P_{\tilde{d}\tilde{y}}(s) = H(sI - A)^{-1}B_d + E_d, \tag{4}$$

$$P_{\tilde{u}\tilde{y}}(s) = H(sI - A)^{-1}B + E, \tag{5}$$

Here, s is Laplace operator.

According to Fig. 3, to model bidirectional buck-boost converter, it acts as before and the following results are obtained. Here, x, y, d, and u are small-signals of $\begin{bmatrix} i_{L_2}(t) & v_{C_2}(t) \end{bmatrix}^T$, $y(t) = i_{B_2}(t)$, duty cycle, and $\begin{bmatrix} B_{in}(t) & B_2(t) & V_{D_3} & V_{D_4} \end{bmatrix}^T$, respectively, and

$$A = \begin{bmatrix} -D\frac{R_i + R_{SW3}}{L_2} & \frac{D-1}{L_2} \\ \frac{1-D}{C_2} & -\frac{1}{R_2 C_2} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{D}{L_2} & 0 & 0 & \frac{D-1}{L_2} \\ 0 & \frac{1}{R_2 C_2} & 0 & 0 \end{bmatrix}$$

$$H = \begin{bmatrix} 1 & \frac{1}{R_2} \end{bmatrix}, E = \begin{bmatrix} 0 & \frac{-1}{R_2} & 0 & 0 \end{bmatrix}$$

The desired circuit is designed in CCM mode and switching frequency is considered 50 kHz. Table I summarizes the values of the proposed converter components.

TABLE I
COMPONENTS VALUES

Part	Value
$L_1 = L_2$	330μH
$C_1 = C_2$	470μF
B_{in}	7.2V
R_{in}	2mΩ
$B_1 = B_2$	3.6V
$R_1 = R_2$	1mΩ

III. Control System Design

Because of decoupled nature of the converters used in the bipolar converter, a separate controller for each converter is employed as shown in Fig. 4 . In this control structure, the current of the battery, i_{B_1} is measured and compared with the reference signal $r(t)$. The purpose is to design a PI controller $G(s)$, in order to compensate and reach the reference value in the circuit of Fig. 2, D is given to the SW_1. Also, for the design of buck-boost converter controller, which supplies negative voltage, i_{B_2} is compared with the reference signal $r(t)$ and the result is given to the controller. The D value obtained from the controller is given to SW_3.

The PI controllers are designed according to the conversion functions obtained in the previous section. MATLAB software Sisotools are used to determine the control coefficients. According to these two converters, the coefficients are determined

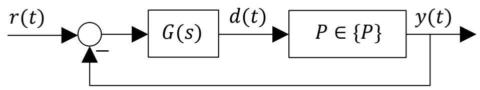
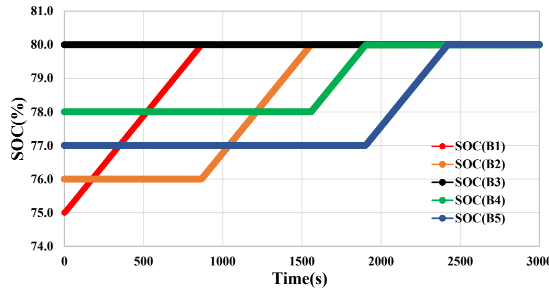
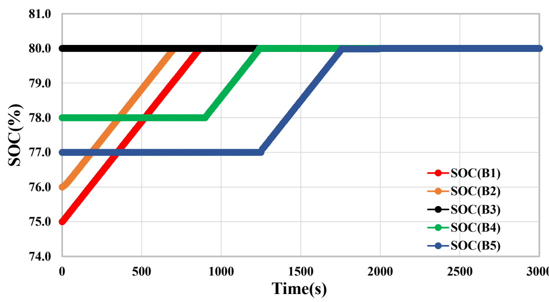


Fig. 4. The structure the control system.



(a) SOC balancing using a buck converter



(b) SOC balancing using the proposed converter

Fig. 5. Balancing five cells whose initial SOC is listed in TableII. Cell balancing begins with the transfer of energy from the cell with the lowest SOC and continues until all cells SOC reach the maximum SOC.

according to the conversion function of each converter as follows:

A. G_{Top} for buck converter.

$$G_{Top}(s) = 2 + \frac{18}{s}. \tag{6}$$

B. G_{Bottom} for buck-boost converter.

$$G_{Bottom}(s) = 0.8 + \frac{5}{s}. \tag{7}$$

IV. Simulation Results

The simulation results and the initial SOC values of the cells are shown in Fig. 5 and Table II, respectively. It demonstrates two cases. Fig. 5-(a) shows the result of balancing using a buck converter and Fig. 5-(b) shows the result of the proposed system. The balancing current in both cases is 0.5 A. Based on the test, energy is injected from the auxiliary source into the battery with the lowest SOC level until the SOC level of this battery reaches the maximum SOC. In Fig. 5-(a), a conventional buck converter is used. This converter is able to inject energy into only one cell. In Fig. 5-(b), the proposed system in this paper is used, which is able to inject energy into two adjacent cells concurrently.

In Fig. 5-(a), the converter begins to inject energy into the cell with the lowest SOC level, is bringing the SOC value of that cell to the maximum SOC value, which is the third cell here. This procedure continues until the SOC of the entire cells reaches the third cell SOC value. The first and second cells have the lowest level of SOC, as shown in Fig. 5-(b), the proposed battery balancing system starts to inject energy and charges these two cells simultaneously until they reach the highest value of SOC in the battery pack. Because two cells are charged simultaneously, balancing time is reduced significantly, and then the system charges the fourth and fifth cells separately. According to the results, the balancing time in the proposed system is reduced by about 28% compared to the buck converter. Of course, in different scenarios, this number may differ.

TABLE II
Initial SOC of cells in the simulation

Part	Value (%)
SOC_1	75
SOC_2	76
SOC_3	80
SOC_4	78
SOC_5	77

V. Conclusions

In this paper, in order to reduce balancing time, a battery balancing circuit using a bipolar converter was proposed. The bipolar converter consisted of a bidirectional buck converter and a bidirectional buck-boost converter and could simultaneously transfer energy to two cells. The proposed battery balancing circuit is simple, bidirectional, non-isolated, inexpensive, and can reduce the balancing time. To control the bipolar converter, PI controllers were designed. Simulation results showed that the proposed structure reduced battery balancing time. By comparing the proposed structure with the buck converter, it was found that the proposed structure had better performance and was more suitable for battery balancing.

References

[1] Feng, Fei and Hu, Xiaosong and Liu, Jianfei and Lin, Xianke and Liu, Bo "A review of equalization strategies for series battery packs: variables, objectives, and algorithms," Renewable and Sustainable Energy Reviews, vol. 116, 2019.

[2] Ouyang, Quan and Han, Weiji and Zou, Changfu and Xu, Guotuan and Wang, Zhisheng "Cell balancing control for lithium-ion battery packs: A hierarchical optimal approach," IEEE Transactions on Industrial Informatics, vol. 16, no. 8, pp. 5065–5075, 2019.

[3] Chatzinikolaou, Efstratios and Rogers, Daniel J "Hierarchical distributed balancing control for large-scale reconfigurable AC battery packs," IEEE Transactions on Power Electronics, vol. 33, no. 7, pp. 5592–5602, 2017.

[4] N. Ghaeminezhad, Q. Ouyang, X. Hu, G. Xu and Z. Wang, ”Active Cell Equalization Topologies Analysis for Battery Packs: A Systematic Review,” in IEEE Transactions on Power Electronics, vol. 36, no. 8, pp. 9119-9135, Aug. 2021.

[5] A. F. Moghaddam and A. Van den Bossche, A Cell Equalization Method Based on Resonant Switched Capacitor Balancing for Lithium Ion Batteries, 9th International Conference on Mechanical and Aerospace Engineering (ICMAE), Hungary, pp. 337-341, 2018.

[6] Lee, Sang-Won and Lee, Kyung-Min and Choi, Yoon-Geol and Kang, Bongkoo “Modularized design of active charge equalizer for Li-ion battery pack,” IEEE Transactions on Industrial Electronics, vol. 65, no. 11, pp. 8697–8706, 2018.

[7] M. D. Monaco, F. Porpora, G. Tomasso, M. DArpino and C. Attaianese, ”Design Methodology for Passive Balancing Circuit including Real Battery Operating Conditions,” 2020 IEEE Transportation Electrification Conference and Expo (ITEC), 2020.

[8] Friansa, Koko and Haq, Irsyad Nashirul and Leksono, Edi and Tapran, Nugraha and Kurniadi, Deddy and Yuliarto, Brian “Battery module performance improvement using active cell balancing system based on switched-capacitor boost converter (S-CBC),” 2017 4th International Conference on Electric Vehicular Technology (ICEVT), pp. 93–99, 2017.

[9] Y. Shang, N. Cui, B. Duan and C. Zhang, ”Analysis and Optimization of Star-Structured Switched-Capacitor Equalizers for Series-Connected Battery Strings,” in IEEE Transactions on Power Electronics, vol. 33, no. 11, pp. 9631-9646, Nov. 2018.

[10] Shang, Yunlong and Zhang, Qi and Cui, Naxin and Duan, Bin and Zhang, Chenghui “An optimized mesh-structured switched-capacitor equalizer for lithium-ion battery strings,” IEEE Transactions on Transportation Electrification, vol. 5, no. 1, pp. 252–261, 2018.

[11] K. Lee, S. Lee, Y. Choi and B. Kang, ”Active Balancing of Li-Ion Battery Cells Using Transformer as Energy Carrier,” in IEEE Transactions on Industrial Electronics, vol. 64, no. 2, pp. 1251-1257, Feb. 2017.

[12] Li, Siqi and Mi, Chunting Chris and Zhang, Mengyang “A high-efficiency active battery-balancing circuit using multiwinding transformer,” IEEE Transactions on Industry Applications, vol. 49, no. 1, pp. 198–207, 2012.

[13] Hannan, Mohammad Abdul and Hoque, Md Murshadul and Peng, Seow Eng and Uddin, M Nasir “Lithium-ion battery charge equalization algorithm for electric vehicle applications,” IEEE Transactions on Industry Applications, vol. 53, no. 3, pp. 2541–2549, 2017.

[14] F. Peng, H. Wang and L. Yu, ”Analysis and Design Considerations of Efficiency Enhanced Hierarchical Battery Equalizer Based on Bipolar CCM BuckBoost Units,” in IEEE Transactions on Industry Applications, vol. 55, no. 4, pp. 4053-4063, July-Aug. 2019.

[15] Lu, Junlong and Wang, Yi and Li, Xin “Isolated bidirectional DC-DC converter with quasi-resonant zero-voltage switching for battery charge equalization,” IEEE Transactions on Power Electronics, vol. 34, no. 5, pp. 4388–4406, 2018.

[16] Cao, Jianwen and Xia, Bizhong and Zhou, Jie “An Active Equalization Method for Lithium-ion Batteries Based on Flyback Transformer and Variable Step Size Generalized Predictive Control,” Energies, vol. 14, no. 1, p. 207, 2021.

[17] Raeber, Manuel and Heinzelmann, Andreas and Abdeslam, Djaffar Ould “Analysis of an Active Charge Balancing Method Based on a Single Non-isolated DC/DC Converter,” IEEE Transactions on Industrial Electronics, vol. 68, no. 3, pp. 2257–2265, 2020.

[18] M. Feizi and R. Beiranvand, ”Simulation of a High Power Self-Equalized Battery Charger Using Voltage Multiplier and Phase-Shifted Full Bridge Converter for Lithium-Ion Batteries,” 2020 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), 2020.

[19] Pham, Van-Long and Duong, Van-Tinh and Choi, Woojin “A low cost and fast cell-to-cell balancing circuit for lithium-Ion battery strings,” Electronics, vol. 9, no. 2, p. 248, 2020.

[20] Chatzinikolaou, Efstratios and Rogers, Daniel J “Cell SoC balancing using a cascaded full-bridge multilevel converter in battery energy storage systems,” IEEE Transactions on Industrial Electronics, vol. 63, no. 9, pp. 5394–5402, 2016.

[21] A. Z. Jahromi, A. Siadatan and S. E. Afjei, ”Isolated DC-DC series-resonant converter with two-step current-driven rectifier equalizing series lithium-ion battery cells,” 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC), 2018.

[22] Dam, Shimul K and John, Vinod “A Multi-Active-Half-Bridge Converter based Soft-switched Fast Voltage Equalizer for Multi-cell to Multi-cell Charge Transfer,” 2019 IEEE Transportation Electrification Conference (ITEC-India), pp. 1–6, 2019.

[23] Pham, Van-Long and Duong, Van-Tinh and Choi, Woojin “High-efficiency active cell-to-cell balancing circuit for Lithium-Ion battery modules using LLC resonant converter,” Journal of Power Electronics, vol. 20, no. 4, pp. 1037–1046, 2020.

[24] J. Lu, Y. Wang and X. Li, “Isolated Bidirectional DC-DC Converter With Quasi-Resonant Zero-Voltage Switching for Battery Charge Equalization, IEEE Transactions on Power Electronics, vol. 34, no. 5, pp. 43884406, May 2019.

[25] A. F. Moghaddam and A. Van den Bossche, “A Battery Equalization Technique Based on Ćuk Converter Balancing for Lithium Ion Batteries, 8th International Conference on Modern Circuits and Systems Technologies (MOCAST), pp. 14, Thessaloniki, Greece, 2019.

[26] L. Tian, M. Hong, Z. He and M. Gao, “Active Battery Balancing Circuit Based on Optimized Flyback Convertor for Large Lithium-ion Battery Packs, IEEE 4th International Conference on Control Science and Systems Engineering (ICCSSE), Wuhan, China, pp. 212216, 2018.

[27] F. Mestrallet, L. Kerachev, J.-C. Crebier and A. Collet, “Multiphase interleaved converter for lithium battery active balancing, IEEE Transactions on Power Electronics, vol. 29, no. 6, pp. 2874 2881, June 2014.

[28] Z. Wei, F. Peng and H. Wang, “A String-to-Cell Battery Equalizer Based on Fixed-Frequency LCC Resonant Converter, IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1450 1455, New Orleans, LA, USA, 2020.