VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

RESONANT-BOOST LC CONVERTER BASE CHARGE BALANCING SYSTEM FOR ELECTRIC VEHICLE

Mizanur Rahman[1], M. M. Rashid[1], A. Rahman[2] and Sheroz Khan[3]
[1]Department of Mechatronics Engineering
[2]Department of Mechanical Engineering
[3]Department of Electrical and Computer Engineering

ABSTRACT

Cell voltage equalization is essential in a battery pack to guarantee high performance, safety and extend the lifetime by eliminating the charge unbalancing problem. Many conventional charge balancing systems have been designed and developed to solve this problem. Besides this, there are some problems still exist: switching power loss and longer charge balancing time that lead to a less efficient charge balancing system. In this paper, resonant-boost LC converter base charge balancing system has been proposed. The switching power loss in the switching components is reduced by achieving zero current switching and the speed of balancing is substantially accelerated using a resonant boost converter. In the simulation, the result of charge balancing with current and voltage characteristics of a series connected cells has been shown. The result shows that the balancing process is substantially improved.

Keywords: resonant boost converter, LC network, BMS, and charge equalization.

INTRODUCTION

Battery as a portable electronics component plays an important role providing electrical energy in the various applications such as mobile, laptop, robot, electric vehicle (EV) and hybrid electric vehicle (HEV). Based on power and energy requirements, the size of battery or battery pack is varied since a single battery cell has a limited range of voltage and capacity which may not fulfill [1-4]. However, especially in EV, Series and/or parallel connected Li-ion batteries are used to provide high voltage and/or current. Nowadays, Li-ion battery has been focused for EV due to high energy density, power capacity, and low self-discharge rate. However, Li-ion battery cannot tolerate overcharging and under-discharging limit (4.2V-2.7V) [5-7]. Charging-discharging is the common fact for EV. Indeed, a chemical reaction occurs during charging and discharging operation. Frequently charging and discharging causes ambient temperature and unbalancing charge issue in the battery pack. This unbalancing charge cannot provide the required power demand during EV in traction and can even cause fire or explosion. However, the battery pack needs to be provided safety and protect from any hazardous circumstances. Therefore, a charge balancing system in the battery management system (BMS) is needed to keep the battery pack in prolonging high performance [9].

Previously a lot of research on the development and design of the charge balancing system for battery cells in battery pack have been proposed and very well summarized [10-14]. The balancing systems are mainly categorized into passive and active balancing. It is very common for a passive balancing method that resistor components are used to make a same state of charge (SOC) between higher capacity and lower capacity cells. The resistor components can be used in either fixed mode or switch mode. The advantage of the passive balancing method is simple to control and easy to implement. However, in such a way balancing charge is just a large amount of wasting energy in a battery pack.

Another charge balancing method rather than wasting energy called active balancing method which transfers energy from higher voltage cell to the lower voltage cell. Based on the performance and efficiency, this active balancing method can also be grouped into various types of converter base balancing technique such as DC-DC converter, Buck-Boost converter, flyback converter, switch capacitor converter, resonant and quasi-resonant switch capacitor converter. In the converter base charge balancing technique, capacitor, inductor or/and transformer diode and MOSFET switch are basically used [15, 16, 17].

VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

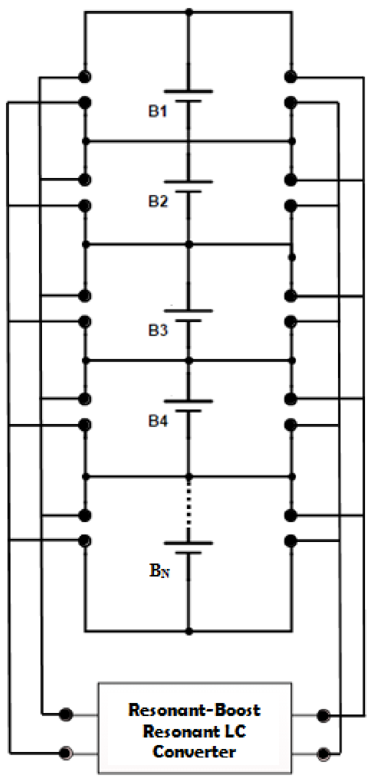

Figure-1. Block diagram of proposed balancing system.

Nowadays, resonant based efficient charge equalization systems are more being focused due to achieving zero current switching (ZCS) and zero voltage switching (ZVS) to reduce the loss of switching, conduction and electromagnetic interference [17]. A resonant switch capacitor converter (RSCC) with phase shift control has been proposed to balance the series connected capacitor voltage during the charging and discharging [18]. Moreover, based on RSCC, an automatic charge equalization system has been designed and developed. In the above work, the authors discussed LC resonant tank, ZCS, and zero voltage gap (ZVG) to reduce switching loss and finite voltage difference [19]. However, this technique is perfect only for the two cell charge balancing not for multiple cells because of the increasing the battery cells, the number of LC resonant tank is increased. To balance the charge among the multiple series connected cells to cells, a concept of a bridge network as well as LC resonant tank is introduced [20]. Another charge balancing system based on the combination of boost DC to DC converter and LC resonant converter is presented for the sake of boosting zero voltage gap between the cells [21-24]. However, this balancing system has still switching power loss problem. Overall, a high- efficiency charge equalization system by reducing power loss and improving balancing time is needed.

Therefore, a new method based on resonant-boost LC network is presented in this work. This method offers an efficient and faster balancing system that reduces the balancing time along with achieving ZCS and ZVG and reducing circuit power loss and finite voltage difference.

THE PROPOSED BALANCING METHOD

The concept of the proposed balancing method is come up with the combination of resonant boost and resonant LC network (RBRLC) to increase the overall system performance. Figure-1 shows the schematic diagram of the charge balancing system for N series-connected battery cells. The resonant boost converter has been designed by adding a capacitor C_r which is shown in Figure-2. Resonant current flows through into an inductor Lr and a capacitor Cr which leads to reduce switching power loss of the higher battery cell. The circuit configuration of the proposed balancing system is shown in Figure-3. The main purposes of using RBRLC are as follows:

1. Stepping up the voltage from battery B1.
2. Storing the step up voltage and provide to battery B2.
3. Achieving ZCS on the both sides (source cell and destination cell) switches.
4. Improving the charge balancing time.

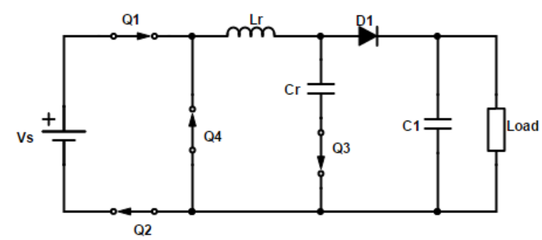

Figure-2. Resonant boost converter [23].

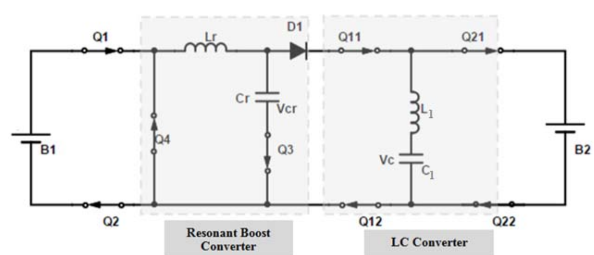

Figure-3. The configuration of the proposed charge equalization system based on RBRLC for two cells.

OPERATION PRINCIPLE

There are two resonant tanks L_rC_r and L_1C_1 from resonant boost and LC resonant respectively. All switches are MOSFET used in the proposed system and controlled by the PWM pulse with the switching frequency and 50% duty cycle. The switching frequency employed in the system which is related to the resonant frequency from the

VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

equation-1. Particularly, in the resonant boost converter portion, 25% duty cycle is used to control an auxiliary switch Q3. The equalization process for two cells is accomplished in four states.

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} = \frac{1}{\sqrt{L_1 C_1}} \tag{1}$$

State1 (0, t_1):

The switches Q1 and Q3 are turned ON and the battery, B1 is applied to the L_rC_r resonant tank. The current from B1 starts to flow through the LC resonant at the resonant frequency and causes sinusoidal current $I(L_r)$ and voltage $V(C_r)$ into an inductor and across a capacitor.

$$V_{Cr}(t_1) = V_{B1}[1-\cos(\omega_r t_1)] \tag{2}$$

$$i_{Lr}(t_1) = \frac{V_{B1}\ \sin(\omega_r t_1)}{Z_r} \tag{3}$$

$$\text{where } Z_r = \sqrt{\frac{L_r}{C_r}}$$

State2 (t_1, t_2):

When resonant capacitor Cr is charged, the diode becomes forward biased. The capacitor Cr is clamped with the LC network. The switch Q3 is turned off and stops conducting current. The stored magnetizing current in the resonant inductor is then delivered to the L_1C_1 network.

$$i_{L1}(t_2) = \frac{V_{B1} - V_{C_1}}{L_1} t_2 + i_{Lr}(t_1) \tag{4}$$

$$V_{C1}(t_2) = \frac{V_{B1} - V_{C1}}{L_1} t_2 + \frac{C_r}{C_1} V_{B1}[1-\cos(\omega_r t_1)] \tag{5}$$

State 3 (t_2, t_3):

As the sinusoidal current, the stored energy in the resonant inductor discharges to zero. On the other hand, the stored energy in LC network is delivered to battery B2. At this moment, the switches Q1, Q2, Q3, Q11, and Q12 are OFF and Q4, Q21 and Q22 are ON. The resonant current flows in the opposite direction. The stored charged in capacitor C1 also flows into battery B2.

$$i_{Lr}(t_3) = -\frac{V_{B1} - V_{Cr}\sin(\omega_r t)}{Z_r} \tag{6}$$

$$V_{C1}(t_3) = V_{B2} - \frac{V_{B1} - V_{C1}(t_2)}{L_1}\cos(\omega_r t) \tag{7}$$

$$i_{L1}(t_3) = -i(B_2) \tag{8}$$

State 4 (t_3, t_4):

In this state, the switch Q2 is still turning ON but no current flow through the resonant tank. As the negative half cycle of the gate pulse, the other switches Q1 and Q3 are turned OFF.

$$i_{Lr}(t_4) = -\frac{V_{B1} - V_{Cr}\sin(\omega_r t_3)}{Z_r} \Rightarrow \qquad t_3 = \frac{\pi}{\omega_r} \tag{9}$$

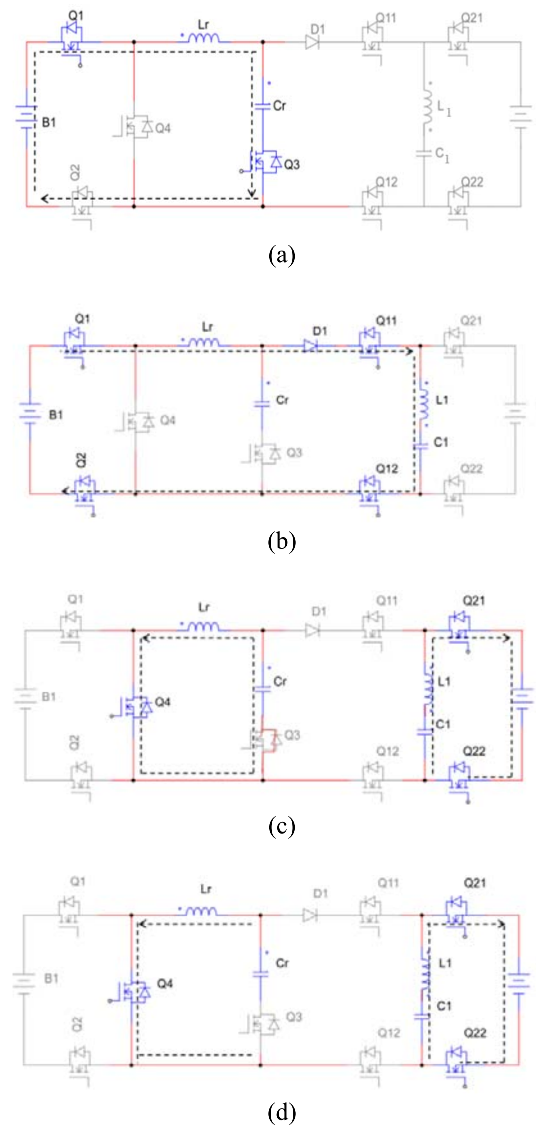

Figure-4. The states of energy transferring process for proposed RBRLC (a) state 1 (b) state 2 (c) state 3 and (d) state 4.

CIRCUIT ANALYSIS

In the resonant boost converter portion at the charging state, while current flows through the inductor Lr and capacitor Cr, the voltage across the magnetizing

VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

inductor Lr and the amplitude of resonant boost current Im are equal to

$$L_r \frac{di_{Lr}}{dt} = V_{B1} - V_{Cr} \tag{10}$$

$$I_m(L_{r1}) = \frac{V_{B1} - V_{Cr}}{\omega_r L_r \cos(\omega_r t)} \tag{11}$$

At discharging state

$$I_m(L_{r2}) = -\frac{V_{B1} - V_0}{\omega_r L_r \cos(\omega_r t_2)} \tag{12}$$

Where $V_0 = L_1 \frac{di_{L1}}{dt} + V_{C1}$

Charging in the LC network,

$$L_r \frac{di_{Lr}}{dt} = -(V_{B1} + L_1 \frac{di_{L1}}{dt} + V_{C1}) \tag{13}$$

$$I_m(L_1) = \frac{V_{B1} - V_{C1} + L_r \frac{di_{Lr}}{dt}}{\omega_1 L_1 \cos(\omega_1 t_{3})} \tag{14}$$

RESULTS AND DISCUSSIONS

According to verify the system operation analysis and to show charge balancing results, the simulation results have been performed using PSIM 9.2 simulator. The proposed equalization system is built for two cells. A battery cell is modeled capacitor and resistor. Two electrolytic capacitors of 20F with the initial voltage 3.6V and 3.2V respectively and 40mΩ have been chosen. MOSFET switches are used as the switching components and controlled by complementary PWM signals. The values of two resonant tanks LrCr of 5uH, 10uF and L_1C_1 of 5uH, 10uF are assumed. The switching frequency of 22 KHz is employed, which is closer to the resonant frequency.

Figure-5 shows the resonant current and voltage through inductor Lr and across capacitor Cr in terms of gate signal of switches. It can be seen from the figure resonant current starts to increase from 0 to maximum 10Amp while switch Q3 is ON and again starts to decrease to 0 while switch Q3 is OFF. The diode D1 is conducting fully when resonant current starts to decrease.

The current and voltage of inductor and capacitor are flowing while diode is conducting shown in Figure-6. It is noticed that current and voltage waveform is in quasi-sinusoidal form.

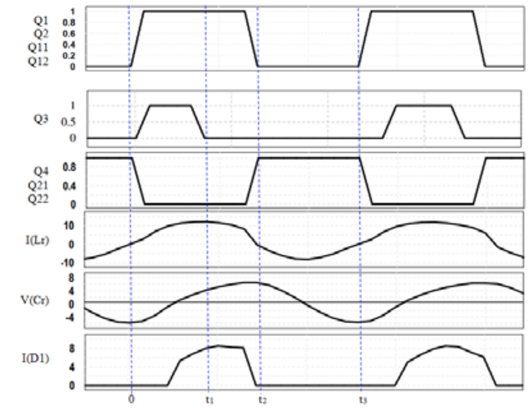

Figure-5. Resonant current and voltage waveform in the resonant boost converter part.

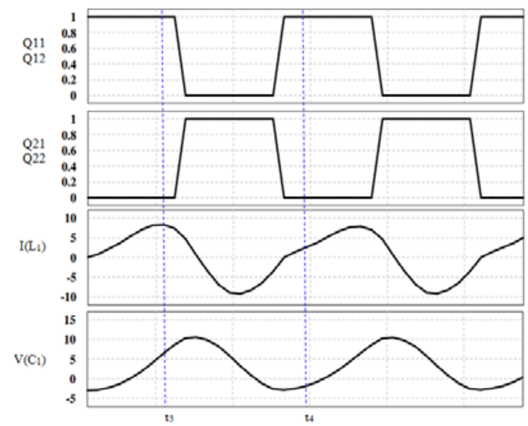

Figure-6. Resonant current and voltage waveform in the resonant LC converter part.

The technique of achieving ZCS has a great impact on improving system efficiency. Therefore, for analyzing ZCS, Figure-7 shows the current flows through the switching components (Q1, Q3 and Q21 as for example). It can be seen that the switches are turned ON when gate voltages are at zero. Figure-8 and 9 show the results of equalization with different state of charge.

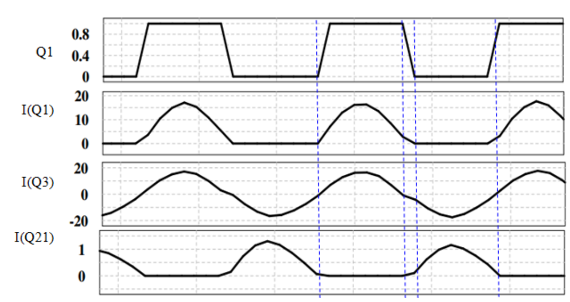

Figure-7. Realization of ZCS of proposed RBRLC charge balancing system.

VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

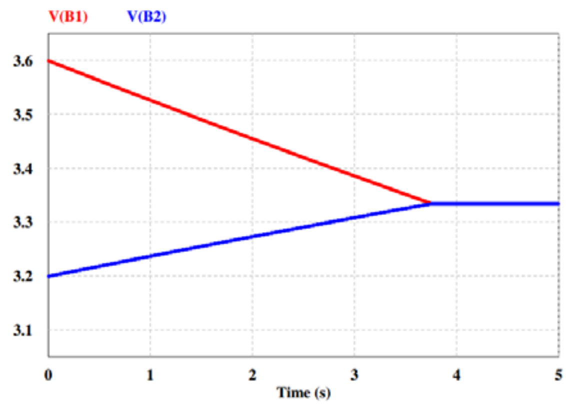

Figure-8. The balancing result for two cells.

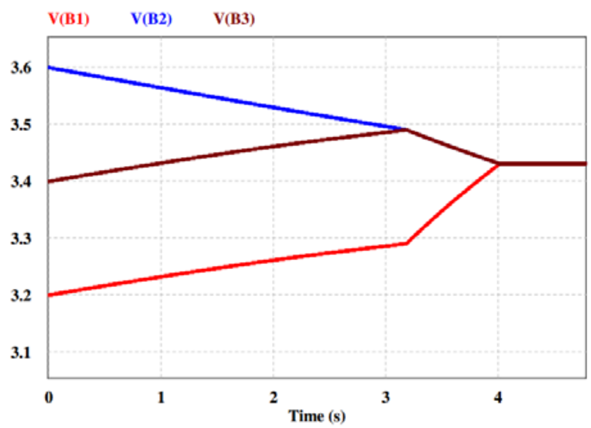

Figure-9. The balancing result for three cells.

CONCLUSIONS

A charge balancing system is a crucial part of battery management system. This system helps to protect the battery pack in EV from any awkward situation: ambient temperature, unbalancing and fire explosion and to improve the system efficiency. Therefore, in this paper, resonant boost- LC network (RBRLC) has been presented. The key term of the proposed system is a resonant boost converter that not only boosts energy from higher cell to lower cell, but also achieves ZCS in the switching component of the higher cell voltage. The resonant LC network also helps to transfer energy to lower cells with the zero voltage gap. In the future work, the proposed system will be improved for series and parallel combination with modularization cells.

REFERENCES

[1] S. T. Tung, D. C. Hopkins, and C. R. Mosling, “Extension of battery life via charge equalization,” IEEE Trans. Ind. Electron., vol. 40, no. 1, pp. 96–104, February 1993.

[2] Lu, Shuai, Keith Corzine, and Mehdi Ferdowsi. 2007. "A new battery/ultracapacitor energy storage system design and its motor drive integration for hybrid electric vehicles." Vehicular Technology, IEEE Transactions on 56, no. 4: 1516-1523.

[3] Li, Siqi, Chris Mi, and Mengyang Zhang. 2013. "A High Efficiency Active Battery Balancing Circuit Using Multi-Winding Transformer." Industry Applications, IEEE Transactions on 49.1: 198-207.

[4] Y.-S. Lee and M.-W. Cheng. 2005. “Intelligent Control battery equalization for series connected lithium-ion battery strings,” IEEE Trans. Ind. Electron., vol. 52, no. 5, pp. 1297–1307.

[5] M. Tang and T. Stuart. 2000. “Selective buck-boost equalizer for series battery packs,” IEEE Trans. Aerosp. Electron. Syst., vol. 36, no. 1, pp. 201–211.

[6] H.-S. Park, C.-H. Kim, K.-B. Park, G.-W. Moon and J.-H. Lee. 2009. “Design of a charge equalizer based on battery modularization,” IEEE Trans. Veh.Technol., vol. 58, no. 7, pp. 3216–3663.

[7] N.H.Kutkut, H.L.N.Wiegman, D.M.Divan, and D. W.Novotny. 2007. “Design considerations for charge equalization of an electric vehicle battery system,” IEEE Trans. Ind. Electron., vol. 35, no. 1, pp. 28–35.

[8] N. H. Kutkut. 1997. “Non-dissipative current diverter using a centralized multi-winding transformer,”inProc. 28th Annu. IEEE Power Electron.Spec. Conf. (PESC’97), vol. 1, pp. 648–654.

[9] C. Bonfiglio and W. Roessler. 2009. “A cost optimized battery management system with active cell balancing for lithium ion battery stacks,” in Proc. IEEE VPPC, pp. 304-309Dfsafds

[10] S.W. Moore and P. J. Schneider. 2001. “A review of cell equalization methods for lithium ion and lithium polymer battery systems,” in 2001 SAE Technical Paper Series, pp. 1-5.

[11] M. Daowd, N. Omar, P. Van Den Bossche, and J. Van Mierlo. 2011. “Passive and active battery balancing comparision based on MATLAB simulation,” in IEEE 2011 Vehicle Power and Propulsion Conference. pp. 1-7.

[12] C. -H. Kim, M. -Y. Kim, and G. -W. Moon. 2013. “A modularized charge equalizer using a battery monitoring IC for series-connected li-ion battery

ARPN Journal of Engineering and Applied Sciences

string in electric vehicles," IEEE Trans. Power Electron., vol. 28, no. 8, pp. 3779–3787.

[13] A. M. Imtiaz and F. H. Khan. 2013. "Time shared flyback converter" based regenerative cell balancing technique for series connected li-ion battery strings," IEEE Trans. Power Electron., vol. 28, no. 12, pp. 5960–5975.

[14] Guo, Xiangwei, Longyun Kang, Zhizhen Huang, Yuan Yao, and Huizhou Yang. 2015. "Research on a Novel Power Inductor-Based Bidirectional Lossless Equalization Circuit for Series-Connected Battery Packs." Energies 8, no. 6: 5555-5576.

[15] Y. -S. Lee and G. -T. Cheng. 2006. "Quasi-resonant zero current switching bidirectional converter for battery equalization applications," IEEE Trans. Power Electron., vol. 21, no. 5, pp. 1213–1224.

[16] C. Pascual and P. T. Krein. 1997. "Switched capacitor system for automatic series battery equalization," in Proc. 12th Annual Applied Power Electronics Conference and Exposition, vol. 2, Atlanta, USA, pp. 848–854.

[17] A. C. Baughman and M. Ferdowsi. 2007. "Double-tiered switched-capacitor bat-tery charge equalization technique," IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2277–2285.

[18] K. Sano and H. Fujita. 2009. "A resonant switched-capacitor converter for voltage balancing of series-connected capacitors," inProc. Int. Conf. Power Electron. Drive Syst., pp. 683–688.

[19] Sano, Kenichiro, and Hideaki Fujita. 2009. "A resonant switched-capacitor converter for voltage balancing of several capacitors connected in series." IEEJ Transactions on Industry Applications 129: 628-635.

[20] Y. Yuanmao, K. W. E. Cheng, and Y. P. B. Yeung. 2012. "Zero-current switching switched-capacitor zero-voltage-gap automatic equalization system for series battery string," IEEE Trans. Power Electron., vol. 27, no. 7, pp. 3234–3242.

[21] Lee, Kyung-min, Yoo-chae Chung, Chang-Hyeon Sung, and Bongkoo Kang. 2015. "Active Cell Balancing of Li-Ion Batteries using LC Series Resonant Circuit." Industrial Electronics, IEEE Transactions on. vol. pp. no.99, pp. 1, 1 doi: 10.1109/TIE. 2408573.

[22] Mizanur, R.; Khan, S.; Rahman, A.; Hrairi, M.; Ferdaus, M.; Shahid, Z. 2014. "A Battery Charge Balancing system with reducing inrush high spike current for electric vehicle," Smart Instrumentation, Measurement and Applications (ICSIMA), 2014 IEEE International Conference on , vol., no., pp.1,6, 25-25.

[23] Shang, Yunlong, Chenghui Zhang, Naxin Cui, and Josep M. Guerrero. 2015. "A cell-to-cell battery equalizer with zero-current switching and zero-voltage gap based on quasi-resonant LC converter and boost converter." Power Electronics, IEEE Transactions on 30, no. 7, pp. 3731-3747.

[24] Simeonov, Gregor. 2010. "Resonant Boost Converter for Distributed Maximum Power Point Tracking in Grid-Connected Photovoltaic Systems." PhD diss., University of Toronto.