A modularized BMS with an Active Cell Balancing Circuit for Lithium-ion Batteries in V2G System

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***Abstract*- In the lithium-ion batteries for an electric-drive vehicle, the cell balancing is required to enhance life time of batteries and to guarantee safety. In the vehicle-to-grid (V2G) system, batteries of electric-drive vehicle are more frequently charged or discharged, which increases probability of cell imbalance. Therefore, battery management system (BMS) with efficient cell balancing operation is necessary. To achieve efficient management of lithium-ion batteries with high capacity for the V2G system, this paper proposes a modularized BMS structure with an active cell balancing circuit. The proposed BMS shares a multifunctional switching block for cell voltage monitoring and cell balancing. By sharing monitoring and balancing operation, a cost-effective BMS with small size can be achieved. In this paper, the structure and operational principles of the proposed BMS are presented. To confirm the validity of the proposed scheme, a prototype of 20 lithium-ion batteries with 25Ah is designed and implemented. Cell balancing performance is also verified by an experiment.**

I. INTRODUCTION

Nowadays, lithium-ion batteries are considered as one of the viable energy storage device for electric-drive vehicles (EDVs), such as hybrid electric vehicle (HEV) or electric vehicle (EV), due to its high energy density and low self-discharge rate [1]-[11]. However, since the cell voltage of lithium-ion battery is as low as 4V, the series connected battery string is required for driving a high voltage electric motor in EDVs [12]. Nevertheless, when the battery string is repeatedly charged or discharged, the charge imbalance of the batteries occurs owing to mismatching of internal impedance and ambient effects [1]-[11]. Fig. 1 shows an available range according to state of charge (SOC) when batteries are charged or discharged. Lithium-ion batteries should be protected from overvoltage because overcharging of the batteries may incur explosion and fire, and undervoltage protection is also required since deep discharge degrades characteristics of batteries [13]. Therefore, batteries should be charged or discharged within the safe operating range [13]. However, when SOC is unbalanced as shown in Fig.1 (a), the charging/ discharging operation is limited by the strongest or the weakest cell, which reduces the available range of batteries [14]. Hence, this phenomenon decreases the effective storage

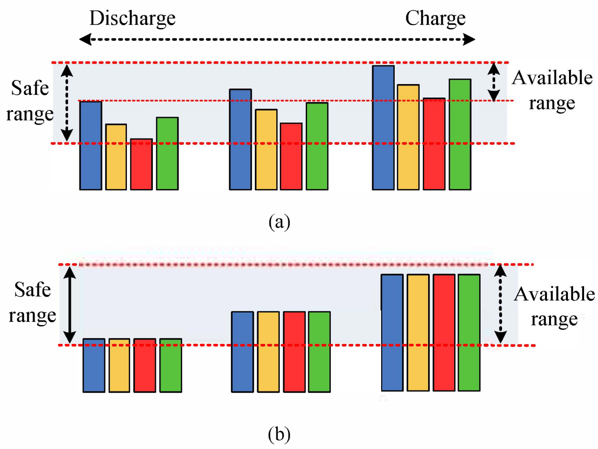

Fig. 1. Available range according to state of charge (SOC), (a) Unbalanced cells, (b) Well-balanced cells

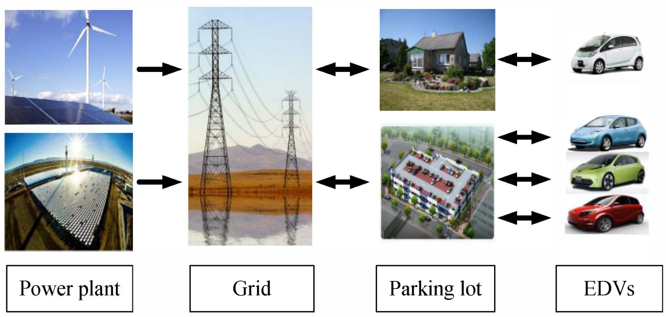

Fig. 2. Vehicle-to-grid (V2G) system

capacity and worsens characteristics of the batteries because of more frequent charging/discharging cycle [15]. Therefore, as shown in Fig.1 (b), cell balancing should be realized to widen the available charging/discharging range and to extend the life cycle of the batteries [1]-[22].

Fig. 2 shows a V2G system [23]. In the V2G system, bi-directional power transfer exists between a grid and a vehicle. A Battery can be charged during low demand times and discharged when power is needed in the grid [23]. Hence, batteries of EDVs in the V2G system are more frequently charged or discharged, compared to general EDVs. It increases probability of cell imbalance. Therefore, a BMS with efficient cell balancing operation is more necessary in the V2G system.

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In order to achieve efficient and feasible management of lithium-ion batteries with high capacity in the V2G system, this paper proposes a modularized BMS structure with an active cell balancing circuit. The proposed BMS shares a multifunctional switching block for cell voltage monitoring and cell balancing. By sharing monitoring and balancing operation, a cost-effective BMS with small size can be achieved.

In this paper, the structure and operational principles of proposed BMS are presented. To confirm the validity of the proposed scheme, a prototype of 20 lithium-ion batteries with 25Ah is designed and implemented. The experiment results show outstanding cell balancing performance of the proposed BMS with an active cell balancing circuit.

II. PROPOSED MODULARIZED BMS STRUCTURE

A. *Structure description*

To increase the reliability and productivity of battery, the modularized batteries are usually used in the EDVs [24]. Because a large battery pack is required in the EDVs, the centralized BMS is not suitable for EDVs due to the complexity of the wiring harness between the cells and the BMS as shown in Fig.3 (a). Therefore the BMS should also be modularized as shown in Fig.3 (b). Slave BMS of modularized batteries is independently operated regardless of other slave BMS and communicates with master BMS. Each slave BMS contains a microcontroller to perform the following basic battery management functions:

- Communication with master BMS
- Battery voltage and temperature sensing
- Over voltage and current protection
- Cell balancing

Fig.4 shows the mechanical structure of proposed BMS. Whole Batteries and BMS are divided into N-modules. Connection board is mechanically connected to each battery module by soldering. Slave BMS can be easily connected to slot on the connection board without the bulky wiring harness. Fig.5 presents the block diagram of the proposed BMS structure. Modularized microcontroller monitors cell voltage of battery module by using a multifunctional switching block, and communicates with a master BMS to transfer sensing data. Module DC-DC converter is also connected to the switching block to achieve active cell balancing. The Charge of the battery module can be distributed to the undercharged cell through DC-DC converter and switching block.

B. *Time-shared operation of switching block*

Time-shared operation of the switching block is determined as following conditions:

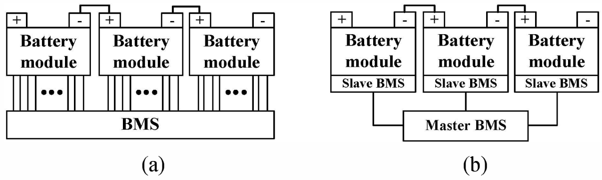


Fig. 3. Modularized batteries, (a) centralized BMS, (b) modularized BMS

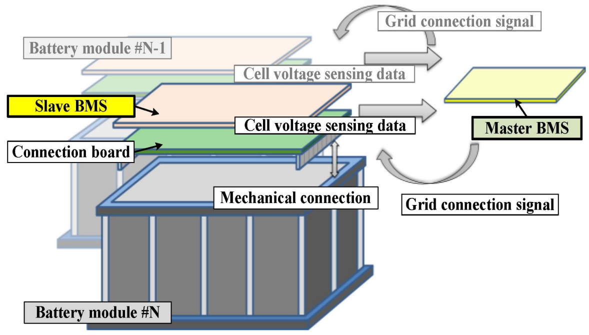


Fig. 4. Mechanical structure of proposed BMS

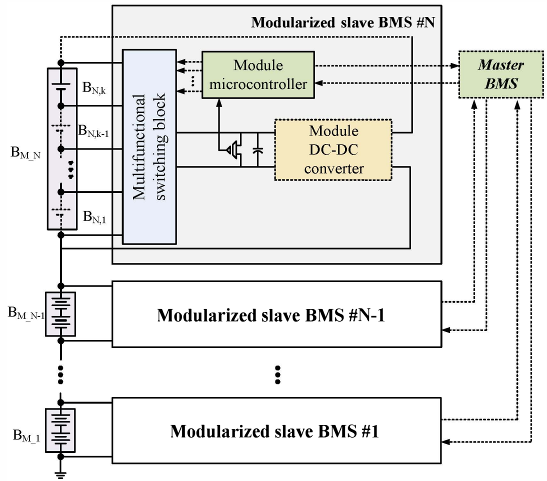


Fig. 5. Block diagram of the proposed BMS

- When EDVs are operated in normal driving, states of batteries are varied according to driving conditions of EDVs, such as acceleration and regenerative braking. Hence, accurate and fast sensing operation is required to predict exact voltage and state of the batteries. Therefore, slave BMS uses switching block as sensing path only when battery string is not connected to grid. As shown in Fig. 6 (a), microcontroller obtains the cell voltage through the cell selection switches (S_k) and ADC switch (Q_A). Because the series connected cells are at different voltage reference levels, cell voltage can be obtained by flying capacitor. The operation process is as follows. First, S_k makes connection between one of the cells and flying capacitor, then the cell voltage is transferred to the flying capacitor. Second, the connection status is changed from S_k to Q_A and the microcontroller reads the voltage of the flying capacitor. These switches are sequentially turned on from first cell to last one. At the same time, microcontroller stores the voltage

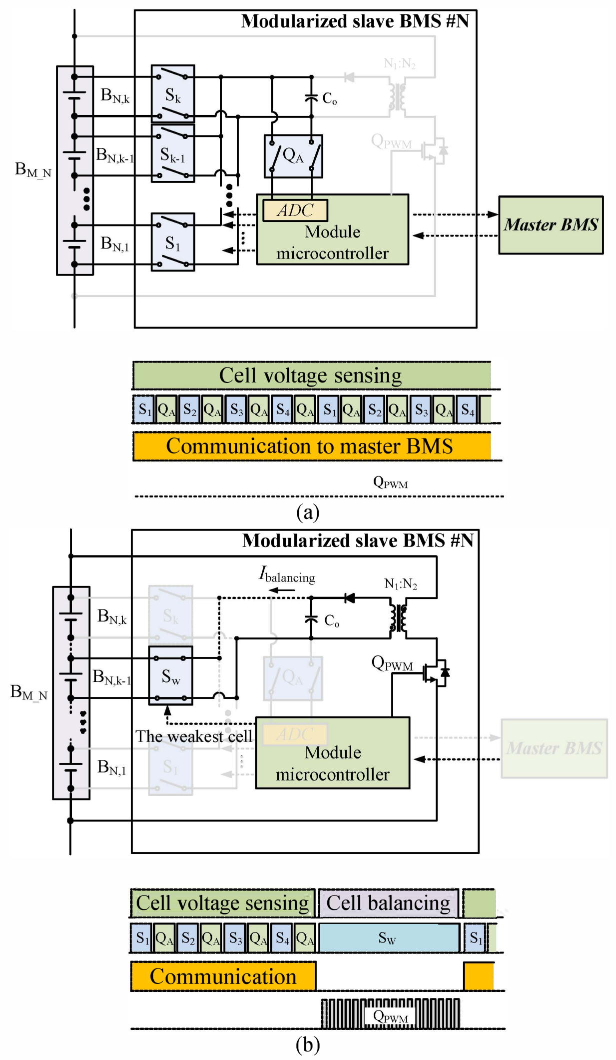


Fig. 6. Operational principle and switching signal,
(a) w/o grid connection, (b) with grid connection

information of each cell, and sends sensing data to the master BMS. In this state, PWM switch (Q_{PWM}) for DC/DC converter is not operated.

- When batteries are connected to grid, the charging and discharging current is predictable by constant charging/ discharging current of on-board charger (OBC). Therefore, slower sensing cycle is permitted. Switching block is used as powering path as well as sensing path. Fig. 6 (b) shows operational principle and switching signal when batteries are connected to grid. Sensing method is the same with Fig.6 (a). But time-shared switching block provides powering path for cell balancing. After all of the cell voltages are obtained, microcontroller makes the priority list of cell balancing and turns on the switch of the weakest cell (S_w). The weakest cell is connected to output of DC-DC converter through cell selection switches. Microcontroller also turns on Q_{PWM} to operate DC-DC converter. By using DC-DC converter, the charge of battery module can be redistributed to the weakest cell.

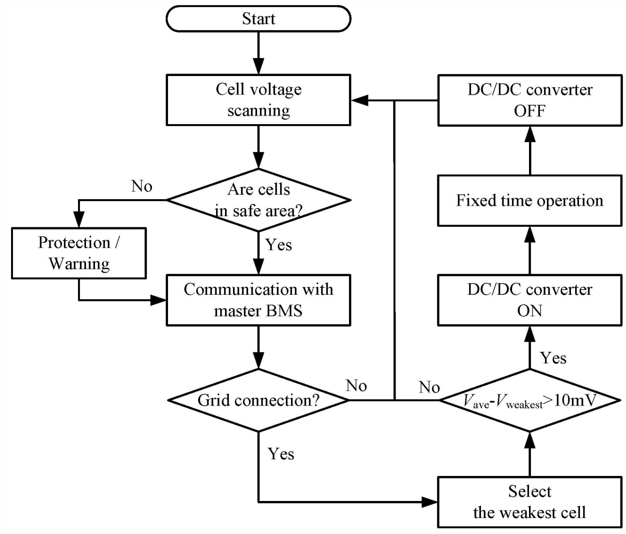


Fig. 7. Flow chart of proposed BMS with an active charge equalization

Fig.7 shows flow chart of the proposed BMS with an active cell balancing. Master BMS wakes the slave BMS up when EDVs are working or connected to grid. The Slave BMS scans the cell voltage and judges the cell status. If one of batteries is even deviated from safe area, the protection circuit operates and slave BMS gives signal to warn. When every cell is located in safe area, slave BMS starts to communicate with master BMS. Master BMS gives the information of grid connection state. If EDVs are not connected to grid, the slave BMS continues scanning cell voltage. In case EDVs are connected to grid, the active cell balancing is started. Module-microcontroller finds the weakest cell and compares the voltage of the weakest cell and the average voltage of battery module. When the voltage difference is larger than the specified voltage gap, e.g., 10mV, microcontroller operates the DC-DC converter and the active cell balancing is started. After active cell balancing during fixed time, the cell voltage sensing is restarted. The operating time of DC-DC converter is designed by minimal sensing period because sensing is not permitted during balancing operation.

C. Sub-modules of switching block

The voltage stress of switching block is the same with the whole voltage of the modularized battery. The proposed structure requires many switches for multifunctional switching block. Therefore, high voltage stress of switches increases the production cost and decreases the efficiency due to worse characteristics, such as high on-resistance of switch. To reduce the voltage stress of switches, the switching block is composed of two sub-modules as shown in Fig. 8. However, to obtain the two sub-modules of switching block, multi-output converter is needed. Moreover, additional noise filter and ADC relay switch are required. Therefore, sub-modules should be properly divided considering the voltage stress of switches and additional components.

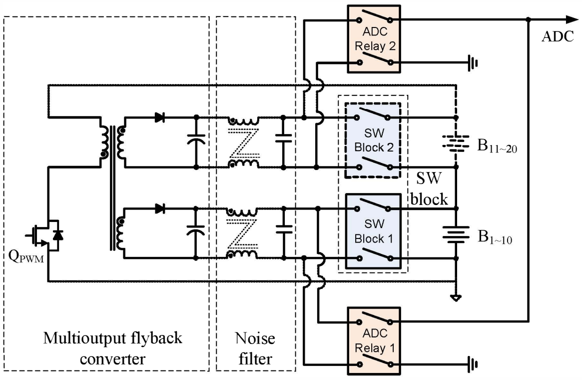
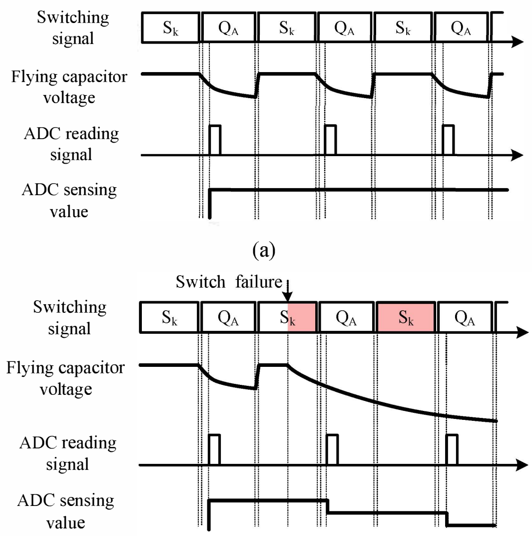


Fig. 8. Sub-modules of switching block for low voltage stress



(a)

(b)

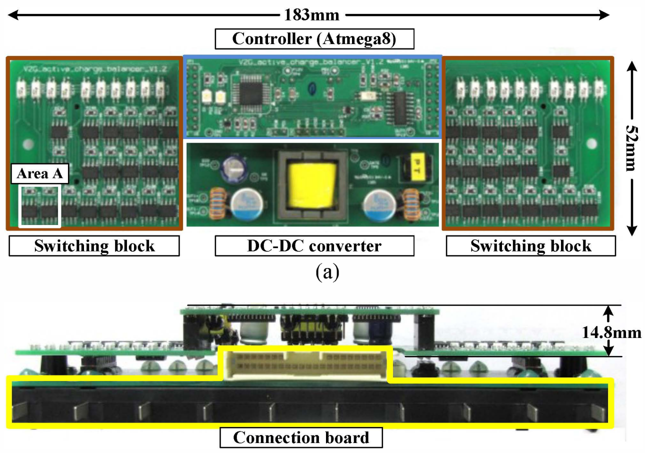
Fig. 9. Fault check of multifunctional switching block (a) normal state, (b) Malfunction state

D. *Fault check of switching block*

If any switch in the switching block broke down, the slave BMS cannot operate properly because multifunctional switching block is used as sensing path as well as balancing path. Therefore, the fault check of switching block is important. Fig.9 shows a simple fault checking method of switching block. The voltage of flying capacitor is exponentially self-discharged when it is not connected to battery cell. Therefore, multiple sensing per each cell can detect the fault of switching block as shown in Fig.9. However, multiple sensing per each cell will increase total sensing period of overall system, thus it should be limited by circuit designer.

III. EXPERIMENTAL RESULTS

In order to verify the operation of the proposed BMS, a prototype of 20 lithium-ion cells is designed and implemented. Fig. 10 shows a photograph of the prototype. The cell selection switches per each cell are located in the Area A of the Fig. 10, and the multifunctional switching block is composed of cell selection switches. A small size of



(a)

(b)

Fig. 10. The photograph of an implemented prototype, (a) top, (b) side

BMS can be achieved by adopting a multifunctional switching block. In this experiment, the commercial 25Ah lithium-ion batteries of twenty cells are used in series. The batteries consist of two sub-modules (B_1~B_{10}, B_{11}~B_{20}), and multi-output flyback converter of 10W for an active cell balancing is implemented as shown in Fig 10.

To verify the active cell balancing performance, cell balancing test is conducted. The voltage of the most overcharged cell (B_3) is 3.877V, the voltage of the most undercharged cell (B_{14}) is 3.798V and the average voltage is about 3.872V. Voltage gap is 0.079V and 11.2% SOC gap is made approximately. Table I summarizes the parameter of the proposed BMS prototype and the status of lithium-ion battery. Fig. 11 and Fig. 12 show experimental waveform of flyback converter and balancing current flowing into the weakest cell respectively. As shown in Fig. 12, balancing current periodically flows to the weakest cell according to sensing data.

TABLE I
PARAMETER FOR THE PROPOSED BMS PROTOTYPE

<table>
<tr><th colspan="4">Parameters</th><th>Value</th></tr>
<tr><td rowspan="8">Cell balancing circuit</td><td rowspan="6">DC-DC converter</td><td colspan="2">Primary switch Q_{PWM}</td><td>FQD10N20</td></tr>
<tr><td colspan="2">Secondary diode</td><td>SSC54</td></tr>
<tr><td colspan="2">PWM generator</td><td>TL494
(f_s=90kHz)</td></tr>
<tr><td rowspan="3">Transformer</td><td>Core</td><td>EPD2020</td></tr>
<tr><td>N_1:N_2:N_3</td><td>30:4:4</td></tr>
<tr><td>L_m
L_{kg}</td><td>190uH
3.17uH</td></tr>
<tr><td rowspan="2">Switching block</td><td colspan="2">Microcontroller</td><td>Atemega8</td></tr>
<tr><td colspan="2">Cell selection switch</td><td>AO4828</td></tr>
<tr><td colspan="2" rowspan="4">Lithium-ion battery</td><td colspan="2">Capacity</td><td>25Ah</td></tr>
<tr><td colspan="2">Average voltage</td><td>3.872 V</td></tr>
<tr><td colspan="2">Maximum voltage (B_3)</td><td>3.877 V</td></tr>
<tr><td colspan="2">Minimum voltage (B_{14})</td><td>3.798V</td></tr>
</table>

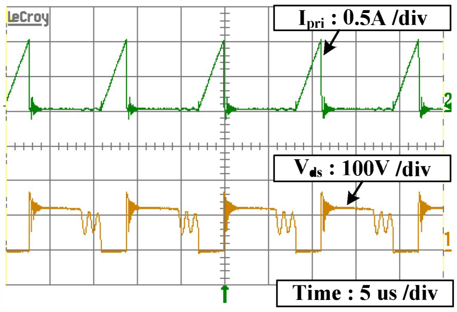


Fig. 11. Waveform of flyback converter

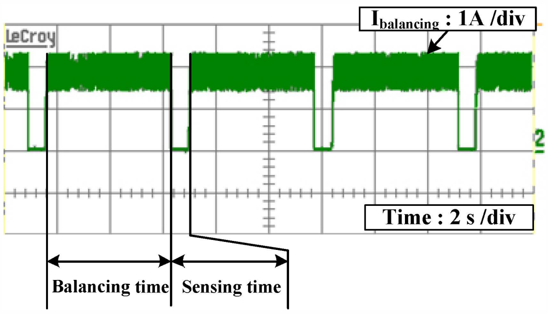


Fig. 12. Waveform of cell balancing current

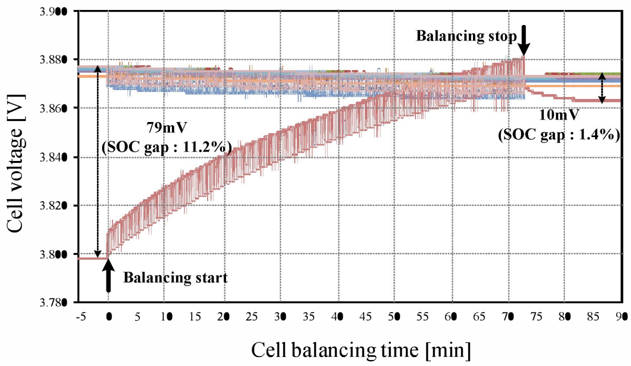


Fig. 13. The result of cell balancing test for 20 lithium-ion batteries

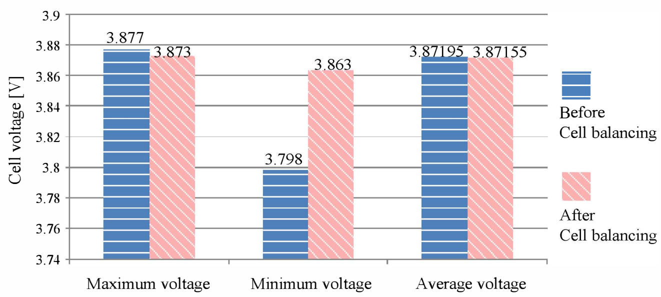


Fig. 14. Battery state before and after active cell balancing

Fig. 13 shows the cell balancing performance of the proposed BMS. After cell balancing for 72 minutes, the gap of SOC is diminished from 11.2% to 1.4% by periodic balancing current as shown in Fig. 13. Battery states before and after cell balancing are shown in Fig. 14. After active cell balancing, the minimum voltage (V_{B3}) is increased as about 65mV, but 4mV voltage reduction of the maximum voltage (V_{B14}) is only shown. The average voltage is nearly the same with that before cell balancing when the active cell balancing of 72 minutes is completed. This experimental result shows high efficiency of active cell balancing.

IV. CONCLUSION

In this paper, a modularized BMS structure with an active cell balancing circuit for the V2G system is proposed, and a prototype was implemented. The proposed BMS shares a multifunctional switching block for cell voltage sensing and cell balancing. By sharing monitoring and balancing operation, a cost-effective BMS with small size can be achieved. Moreover, high performance of active cell balancing is also shown in the experimental results. Therefore, the proposed BMS structure is expected to be suitable for the series connected lithium-ion batteries with high capacity for the V2G system.

ACKNOWLEDGMENT

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REFERENCES

[1] C. -H. Kim, M. -Y. Kim, J. -H. Kim and G. -W. Moon, “Modularized charge equalizer with intelligent switch block for lithium-ion batteries in an HEV”, Telecommunications Energy Conference, 2009. INTELEC 2009. 31st International, pp. 1 - 6

[2] B. T. Kuhn,, G. E. Pitel, and P. T. Krein, “Electrical properties and equalization of lithium-ion cells in automotive applications” in Proc. 2005 IEEE Vehicle power and Propulsion Conf., Chicago, USA, Sep. 2005, pp. 55-59

[3] H. -S. Park, C. -E. Kim, C. -H. Kim, G. -W. Moon, and J. -H. Lee, “A modularized charge equalizer for an HEV lithium-ion battery string,” IEEE Trans. Ind. Electron., vol. 56, pp. 1464-1476, May 2009.

[4] B. T. Kuhn,, G. E. Pitel, and P. T. Krein, “Electrical properties and equalization of lithium-ion cells in automotive applications” in Proc. 2005 IEEE Vehicle power and Propulsion Conf., Chicago, USA, Sep. 2005, pp. 55-59

[5] Y. -S. Lee and M. -W. Cheng, “Intelligent Control battery equalization for series connected lithium-ion battery strings,” IEEE Trans. Ind. Electron., vol. 52, pp. 1297-1307, oct. 2005

[6] C. –H Kim, Y. –D Kim, G. –W Moon, and H. –S Park, “Individual cell voltage equalizer using selective two current paths for series connected Li-Ion battery strings, “in Proc. Energy Conversion Congress and Exposition (ECCE), 2009, pp. 1812–1817

[7] S. W. Moore and P. J. Schneider, “A review of cell equalization methods for lithium-ion and lithium polymer battery systems,” in Proc. SAE 2001 World Congress, Detroit, USA, Mar. 2001, Doc. number:2001-01-0959.

[8] H. -S. Park, C. -E. Kim, G. -W. Moon, J. -H. Lee, and J. K. Oh, “Two-stage cell balancing scheme for hybrid electric vehicle Lithium-ion battery strings,” in Proc. 38th Power Electron. Specialists Conf., Orlando, USA, June 2007, pp. 273-279.

[9] C. -H. Kim, H. -S. Park, C. –E. Kim, G. –W. Moon, and J. –H. Lee, “Individual charge equalization converter with parallel primary winding of transformer for series connected lithium-ion battery strings in an HEV,” Journal of power electronics., vol. 9, No. 3, pp. 472-480, May 2009.

[10] H. -S. Park, C. –E. Kim, C. -H. Kim, G. –W. Moon, and J. –H. Lee, “A modularized charge equalizer for an HEV lithium-ion battery string,” IEEE Trans. Ind. Electron., vol. 56, pp. 1464-1476, May 2009.

[11] M-Y Kim; J-W Kim; C-H Kim; S-Y Cho; G-W Moon, “Automatic charge equalization circuit based on regulated voltage source for series connected lithium-ion batteries” Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on, pp. 2248 - 2255

[12] A. Emadi, Y. J. Lee, and K. Rajashekara, “power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles,” IEEE Trans. Ind. Electron, vol. 55. pp. 2237- 2245, June 2008.

[13] J. Chatzakis, K. Kalaitzakis, N. C. Voulgaris, and N. Manias, "Designing a new generalized battery management system," IEEE Trans. Ind. Electron., Vol. 50, No.5, pp. 990-999, October 2003.

[14] Elias, M.F.M., Nor. K.M. and Arof. A.K. “Design of Smart Charger for Series Lithium-Ion Batteries” Power Electronics and Dirves Systems, 2005. PEDS 2005. International Conference on, pp. 1485-1490

[15] N. H. Kutkut, H. L. N. Wiegman, D. M. Divan, and D. W. Novotny, “Design considerations for charge equalization of an electric vehicle battery system,” IEEE Trans. Ind. Appl., vol. 35, pp. 28-35, Feb. 1999

[16] Ming Tang, Stuart, T. “Selective buck-boost equalizer for series battery packs” Aerospace and Electronic Systems, IEEE Transactions on, vol. 36, pp. 201-211, Jan 2000

[17] Moo, C.S. ; Hsieh, Y.C. ; Tsai, I.S. “Charge equalization for series-connected batteries”, Aerospace and Electronic Systems, IEEE Transactions on. Vol. 39, pp. 704 – 710, April 2003

[18] N. H. Kutkut, H. L. N. Wiegman, D. M. Divan, and D. W. Novotny, “Design considerations for charge equalization of an electric vehicle battery system,” IEEE Trans. Ind. Appl., vol. 35, pp. 28-35, Feb. 1999

[19] A. Baughman and M. Ferdowsi, “Battery charge equalization-state of the art and future trends,” in Proc. Future Transportation Technology Conf., Chicago, USA, Sept. 2005, Doc. number:2005-01-3474.

[20] B. Lindemark, “Individual cell voltage equalizers (ICE) for reliable battery performance,” in Proc. 13th Annu. Int. Telecommunications Energy Conf., Kyoto, Japan, Nov. 1991, pp. 196-201.

[21] N. H. Kutkut and D. M. Divan, “Dynamic equalization techniques for series battery stacks,” in Proc. 18th Annu. Int. Telecommunications Energy Conf., Boston, USA, Oct. 1996, pp. 514-521.

[22] Hsieh. Y.C., Moo. C.S. and Ou-Yang. W.Y.; “A Bi-directional Charge Equalization Circuit for Series-connected Batteries” Power Electronics and Drives Systems, 2005. PEDS 2005. International Conference on , pp. 1578 – 1583

[23] W. Kempton W. and J. Tomic, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue” Journal of Power Sources, vol. 144, issue 1, 1 June 2005, pp. 268–279

[24] Thomas A. Stuart1, Wei Zhu, “Modularized battery management for large lithium ion cells”, Journal of Power Sources, vol. 196, issue 1, pp. 458-464, January 2011