Individual Charge Equalization Converter Using Selective Two Current Paths for Series Connected Li-ion Battery Strings

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Abstract

This paper proposes an individual charge equalization converter using selective two current paths for series connected lithium-ion battery strings. In the proposed equalizer, a central equalization converter acting as a controllable current source is sequentially connected in parallel with individual batteries through an array of cell selection switches. A flyback converter with a modified rectifier realizes a controllable current source. A central equalization converter is shared by every battery cells through the cell selection switch, instead of a dedicated charge equalizer for each cell. With this configuration, although the proposed equalizer has one dc-dc converter, individual charge equalization can be effectively achieved for the each cell in the strings. Furthermore, since the proposed equalizer would not allocate the separated dc-dc converter to each cell, such that the implementation of great size reduction and low cost can be allowed. In this paper, an optimal power rating design guide is also employed to obtain a minimal balancing size while satisfying equalization requirements. A prototype for eight lithium-ion battery cells is optimally designed and implemented. Experimental results verify that the proposed equalization method has good cell balancing performance showing small size, and low cost.

1. Introduction

Series connected battery strings find use in many practical applications such as electric vehicles (EVs), hybrid electric vehicle (HEV), uninterruptable power supplies (UPS), and space applications [1]. In these applications, battery lifetime is one of the major factors, and the battery having long life time is economically beneficial in the market. However, repetitive battery charging and discharging can cause a voltage imbalance among the battery cells because the batteries have the different characteristics; cell residual capacities, internal resistance, degradation, and the ambient temperature gradient during charging or discharging. The voltage imbalance decreases the total storage capacity and whole life cycle of the batteries [2],[3]. Hence, a series connected battery string is necessary to maintain the cell voltage for extending the battery lifetime, and the battery equalization control should be realized to balance the voltage in battery strings.

When the lithium-ion battery is applied in the practical application as the series connected battery strings, a necessary of the cell voltage balance is more important in the battery strings. Although the lithium-ion battery shows good characteristics; higher energy density, lower self-discharge rate and higher single cell voltage, the lithium-ion battery has some of serious defects. Lithium-ion battery chemistry cannot withstand overcharge. An overcharge has a high a risk for explosion. Moreover, an overdicharge of the battery cell will dissolve the copper in the electrolyte and form copper dendrite, which harms the battery and shortens the battery cell's lifecycle [4]-[6]. Hence, a lithium-ion battery should be maintained within the ranges of allowed voltage and current limits to prevent permanent deterioration of characteristics and, in the worst case, explosion or fire. Series connected lithium-ion batteries hide a more complex problem. Even though the pack voltage may appear to be within the acceptable limits, one cell in the series strings may encounter damaging voltage due to cell-to-cell imbalances. Therefore, careful control and monitoring must be provided to prevent any single cell from experiencing over or under-voltage from excessive charging or discharging. An individual cell equalizer (ICE) must be employed to prevent, diagnose, and correct any cell voltage imbalance in lithium-ion battery strings [7].

Cell control based an individual cell equalizers are discussed in [6]-[9]. These methods allocate the separated dc-dc converter to each cell, such that the implementation and individual control of equalization current are easily achieved. However, these schemes have problems of large size and high cost for a large number of lithium-ion batteries.

This paper proposes the individual charge equalizer using two current paths. The current source is realized by the flyback converter with modified rectifier, which can supply two output currents of the dc-dc converter by controlling current paths. Each battery in the strings is parallel connected by the array of cell selection switches. Through the cell selection switches, individual battery cells can have a shared dc-dc converter acting a dedicated charge equalizer for each cell. With this configuration, although the proposed equalizer has one dc-dc converter, individual charge equalization can be effectively achieved for the each cell in the strings. Moreover, since the proposed equalizer would not allocate the separated dc-dc converter to each cell, such that the implementation of great size reduction and low cost can be allowed. In this paper, a prototype of 8 lithium-ion battery cell is implemented and its experimental results are presented.

2. Proposed Charge Equalization Converter

2.1 Circuit Description

Fig. 1 shows the block diagram of the proposed charge equalization converter applied to N battery cells. The proposed equalizer consists of two parts; the dc-dc converter, and selection switches. The dc-dc converter does make the charging current from overall batteries. The selection switches consist of the bi-directional switches to make a current path between dc-dc converter and selected battery cell.

Fig. 2 presents the configuration of the cell selection switches and the dc-dc converter using selective two current paths. The cell selection switches is constructed in each battery. The current source can be controllable with two current paths as shown in Fig. 2(a), (b). Fig. 2(a) and Fig. 2(b) show the clockwise current path for charging B_1 and the counterclockwise current path for charging B_2 respectively. In the proposed circuit, the flyback dc-dc converter with modified rectifier is employed to make two charging current; clockwise and counterclockwise path.

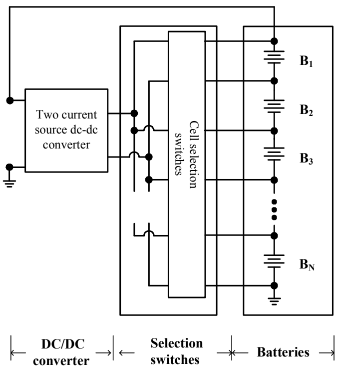

Fig. 1. Block diagram of the proposed two-stage charge equalizer.

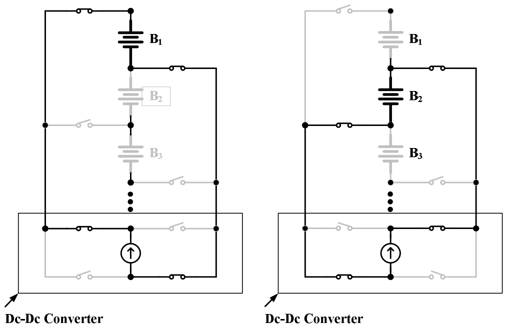

Fig. 2. Proposed charge equalizer using two current paths.
(a) Clockwise current path for charging B_1. (b) Counterclockwise current path for charging B_2.

2.2 Operational Principles

In the proposed charge equalizer, charge balance is archived by transferring the equalization current, which is extracted from the overall battery string, to the undercharged cells. To make this process, the proposed equalizer employs a battery management controller (BMC) with voltage sensing circuitry. The battery management controller collects the sensing data from the sensing circuit and determines the operating of the charge equalization in the battery strings. Then, it drives the charge equalizer with three consecutive steps. Before describing these three steps, it is assumed that the third battery, B_3, is undercharged.

- Step 1: When the battery management controller turns on the bi-directional switches, S_3 and S_4, the first step starts. In this step, the current path for B_3 is constructed. As shown in Fig. 3 (a), the charge current can flow into B_3 through this current path.
- Step 2: After complete turn-on of the bi-directional switches, the relay switch, Q_a, is driven by the BMC. As a result, the relay switches is connected with B_3 as shown in Fig. 3(b). In this mode, although the relay switch connects, the equalization current does not flow into selected cell. This is because the dc-dc converter is not turned on, such that the charge current does not flow yet.
- Step 3: In this mode, the main switch, Q_m, of the dc-dc converter is turned on by the BMC. This stage transfers the equalization current from the battery stack to selected battery cell. In this mode, the dc-dc converter can provide the equalization current to B_3 as shown in Fig. 3(c).

The proposed circuit needs another operation process for charging the fourth battery, B_4. Fig. 3(d), Fig. 3(e), and Fig 3(f) show three consecutive steps respectively to balance the fourth battery as like above mentioned steps in Fig. 3(a), Fig. 3(b), and Fig. 3(c). In these steps, the battery management controller turns on the bi-directional switches, S_4 and S_5 to make a charging path for B_4. Moreover, the relay switch, Q_b, is driven by the BMC. From these operation for charging the third battery and fourth battery, B_3 and B_4, we can find two changeable current paths in the

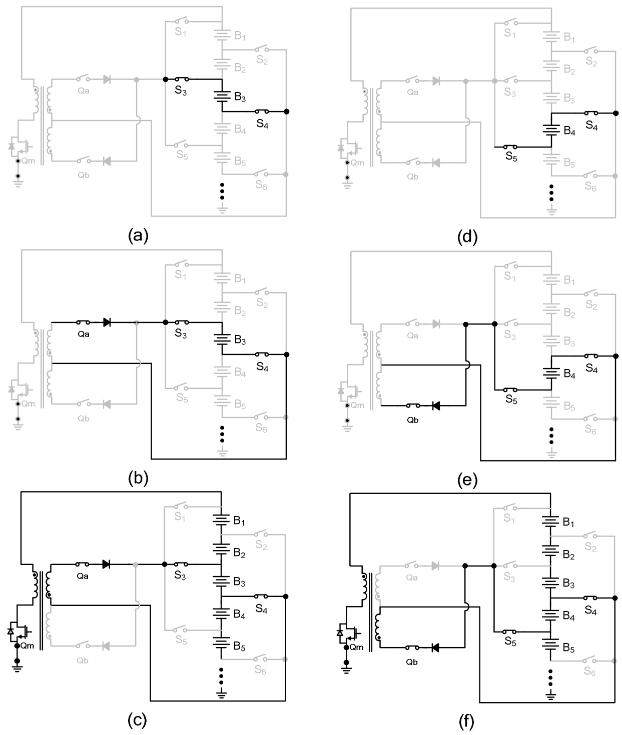

Fig. 3. Operational principles of the proposed circuit.
(a), (d) Step 1. (b), (e) Step 2. (c), (f) Step 3.

proposed equalizer.

Fig. 4 shows the turn-on process of selection switches. All of the bi-directional selection switches is employed with the opto-couplers to obtain a gate signal of the MOSFET switch according to the on or off commend from BMC. There are two kinds of techniques to turn on the bi-directional switches. As shown in Fig. 4, an N-channel MOSFET switch can be turned on by using the upper layer batteries, B_1, B_2, and B_3. On the other hand, a P-channel MOSFET switch can be turned on by using the lower layer batteries, B_2, B_3, and B_4. The opto-couplers, Q_1 and Q_2, give a gate signal to the MOSFET switch. This P-channel MOSFET switches are used only for three cells, B_1, B_2 and B_3.

3. The Power Rating Design Scheme

This section presents the optimal power rating design guide for a charge equalization converter. The power rating of an equalization circuit has a close relation with the equalization time; that is, the higher the power rating, the shorter the equalization time. The power rating is also related to the size of the circuit. Hence, we employ a way of determining the power rating while achieving cell balance within the desired equalization time [8],[9].

The proposed charge equalizer is applied to a lithium-ion battery string of 8 cells, where only one cell is assumed to be undercharged. To expect the equalization time, the equalization current of the flyback dc-dc converter should be calculated. This equalization current indicates the output current of the flyback dc-dc converter. The relation between the equalizing current and the equalization time can be found by the following two simultaneous equations:

$$\frac{1}{(2*4)-1}\sum_{n=2}^{n=8} Q_k(t) = Q_1(t) \tag{1}$$

$$P_{out,avg} = \eta \cdot P_{in,avg}, \tag{2}$$

where the left side of (1) is the average charge quantity of the overall batteries except the undercharged cell at equalization time t, and the right side is the charge quantity of the undercharged

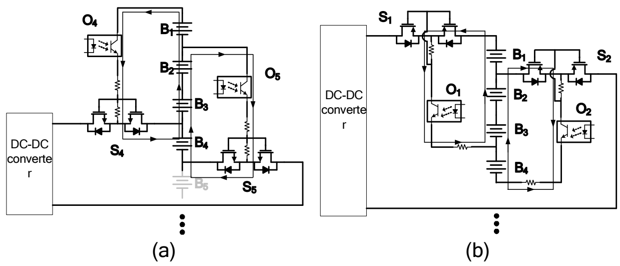

Fig. 4. Turn-on process of selection switches. (a) In case of N-channel MOSFET. (b) In case of P-channel MOSFET.

battery cell at equalization time *t*.

Equation (2) indicates the relation between the input power and the output power of the proposed equalizer with efficiency of η.

Fig. 5 shows the simulation results of the equalization current versus equalization time. By using this simulation results, the power rating of the flyback dc-dc converter can be obtained at 10% SOC gap, where the voltage of over-charged cells is 3.86V at 50% SOC and the voltage of single under-charged cell is 3.80V at 40% SOC. Moreover, the efficiency of the proposed equalizer is temporarily assumed to be 60%, 70%, and 80%. The equalization time is plotted in relation to the equalization current of the equalizer into the undercharged cell. From the simulation results, we know that the shorter equalization time will be taken for the higher equalization current of equalizer. In addition, the higher efficiency of equalizer takes the higher equalization current. As one design example, to obtain charge balance within 70 minutes, the equalization current of about 0.45 A is required at an efficiency of 60%.

3. Experimental Results

In order to verify the operational principles and show the performance of the proposed charge equalization converter, a prototype of eight lithium-ion cells is designed and implemented. The prototype consists of a flyback dc-dc converter, 9 cell selection switches, $S_1 \sim S_9$, are established in the prototype circuit.

To verify the cell balancing performance of the proposed charge equalizer, we conducted an equalization test. The battery SOC distribution is as follows. The SOC of the most undercharged cell, $B_{1,1}$ is 40.5%, and the SOC of the remained cells is 50.5%; thus, approximately 10% SOC gap is made.

The control strategy of the BMC is two steps. The first step is to find the most undercharged cell and then, drives the proposed equalizer based on the simulation results as shown in Fig. 5.

Fig. 6 shows the equalizer performance of the proposed equalizer. In this test, average current of 0.47A is designed to flow into the under-charged cell, and about 70 minutes was taken to achieve cell balancing as expected by the simulation result as shown in Fig. 5.

4. Conclusions

In this paper, individual charge equalization converter using selective two current paths for lithium-ion battery cells was proposed, and a prototype was implemented. In proposed circuit, by applying the concept of two current paths and the cell selection switches, individual charge equalization can be effectively achieved for the each cell in the strings. Moreover, by sharing the dc-dc converter among the battery strings, the proposed equalizer solves a size and cost problem effectively. Therefore, the proposed charge equalizer can be used widely for a high stack of lithium-ion battery cells.

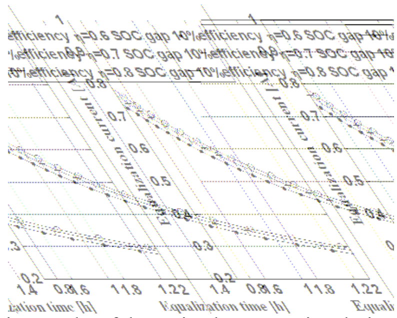

Fig. 5. Simulation results of the optimal power rating design under the SOC gap of 10%.

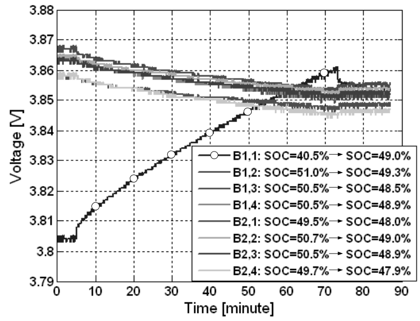

Fig. 6. The result of cell equalization test for 8 lithium-ion battery cells.

Acknowledgment

This work was supported by the STSAT-3 program of the Korea Aerospace Research Institute (KARI) grant funded by the Korea Ministry of Education, Science and Technology (MEST).

Reference

[1] M. J. Isaacson, M. E. Daman and R. P. Hollandsworth, "Li-ion batteries for space applications," in Proc. Of the 32nd intersociety, Vol. 1, pp. 31-34, Aug. 1997.

[2] N. Takeda, S. Imai, Y. Horii, and H. Yoshida, "Development of high-performance lithium-ion Batteries for hybrid electric vehicles," *Mitsubishi Motors Technical Review*, pp. 68-72, Jan. 2003.

[3] 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.

[4] W. F. Bently, "Cell balancing considerations for lithium-ion battery systems," in *Proc. 12th Annu. Battery Conf. Appl. Adv.*, Jun. 12-17, 1997, pp.223-226.

[5] S. W. Moore and P. J. Schneider, "A review of cell equalization methods for lithium ion and lithium polymer battery systems," in *Proc. SAE '01 World Congress,* Detroit, USA, Mar. 2001, Doc. No 2001-01-0959.

[6] 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.

[7] Y. -S. Lee and G. -T. Cheng, "Quasi-resonant zero-current-switching bidirectional converter for battery equalization applications," *IEEE Trans. Power Electron.*, vol. 21, pp. 1213-1224, Sept. 2006.

[8] H. –S. Park, C. –E. Kim, G. –W. Moon, J. –H. Lee, and J. K. Oh, "Charge Equalization with Series Coupling of Multiple Primary Windings for Hybrid Electric Vehicle Li-ion Battery System," in *Proc. IEEE PESC '07*, Orlando, USA, June 2007, PP. 266-271.

[9] 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. IEEE PESC '07*, Orlando, USA, June 2007, PP. 273-279.