Cell Balancing Scheme with Series Coupling of Multiple Primary Windings for Hybrid Electric Vehicle Lithium-Ion Battery Cells

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Abstract

Charge equalization scheme for HEV lithium-ion battery system is proposed in this paper, where all the primary windings with in parallel bi-directional switches are coupled in series to provide the equalizing energy from the whole battery string to the specific under charged cells. Moreover, to realize minimized size of equalization circuit employing the proposed cell balancing scheme, the optimal power rating design rule according to equalization time and SOC distribution of imbalance is proposed. A prototype of HEV lithium-ion battery system of four cells shows the outstanding charge equalization performance while maintaining greatly reduced size of cell balancing circuit.

1. Introduction

HEV has become one of the most promising vehicles in the automotive markets due to its ability of energy saving and low emission of CO_2 [1]. This is because a HEV can recover energy from the wheels, which have been wasted in the past, and then reuse it to propel the vehicle at low speeds or boost extra power required in high acceleration. The greater part of HEVs on the streets of these days uses nickel-metal hybrid (Ni-MH) batteries [1]. Recent development of lithium-ion battery and its test result show that the lithium-ion battery has higher power and energy density, lower self-discharge rate, and higher single cell voltage than the Ni-MH battery such that it has the potential of taking the place of Ni-MH battery in the HEVs of the future [2], [3]. However, to realize this possibility, reliability and safety should be first of all ensured; in other words, the lithium-ion battery should be maintained within the ranges of the allowed voltage and current limits to prevent permanent deterioration of characteristics and, in the worst case, explosion or fire in the vehicle [1], [3]. To avoid this critical situation in advance, a charge equalization circuit for series connected lithium-ion battery string is necessary.

To avoid this critical situation in advance, a charge equalization circuit for the series connected lithium-ion battery string is necessary. A protection circuitry is, of course, important in the battery management, but it is beyond the scope of this paper. In conventional, the continual charge and discharge of the series connected battery cells can cause charge imbalance among them. The problem is if they are left in use without any action such as cell equalization, the serious circumstance is more prone to occur. This is because in the regenerative braking mode the highly charged cells are more susceptible to over voltage problem, and in the battery powered motor driving mode the deeply discharged cells are more vulnerable to under voltage problem. Due to these reasons, the highly charged cells or the deeply discharged cells can neither capture optimal amount of renewable energy nor provide the stored energy, respectively. Therefore, charge equalization for the series connected battery cells in HEV is essential to prevent these serious situations in advance, accomplish the maximum utilization of battery, and prolong the lifetime.

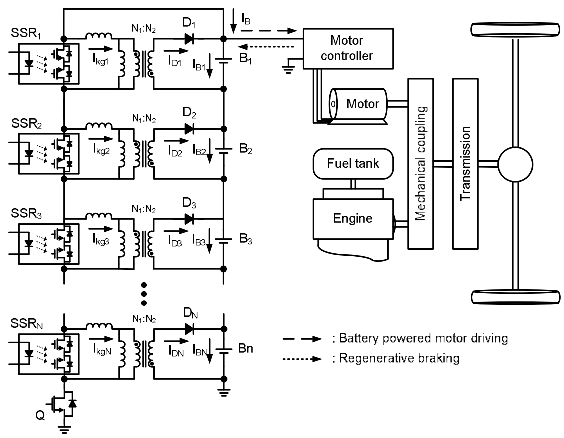

Fig. 1. HEV lithium-ion battery system with the proposed charge equalization converter.

2. Proposed Two-stage cell balancing scheme

2.1 Circuit description

Fig. 1 shows the HEV lithium-ion battery system with the proposed charge equalization converter, where a stack of lithium-ion battery cells is connected to the HEV propulsion system to capture the renewable energy form the wheels and to supply the recovered energy to the wheels reversely. In the proposed cell balancing circuit, each cell has the flyback DC/DC converter of low power, compact size, and easy implementation and all the primary windings are in series coupled. Moreover, every primary winding has the charge control switch to realize the efficient cell balancing process; that is, while driving the main MOSFET switch in pulse width modulation (PWM) mode, equalizing current does flow into the particular under charged cells of which the corresponding charge control switches are turned off. These two points are the great advantages of the proposed cell balancing circuit.

2.2 Operational principles

The operational principles of the proposed charge equalization circuit are very simple and easy. Basically, the circuit operations are so much similar to those of the conventional flyback DC/DC converter with multiple transformers in series. Shortly, the charge equalization of the proposed cell balancing circuit can be achieved by driving the main MOSFET switch of the flyback DC/DC converter. The only difference is that before driving the main MOSFET switch, the charge control switches of the under charged cells are turned off, while the other charge control switches are turned on. In addition, the charge control switch is driven by the BMS of high quality with a very low frequency such as ON/OFF

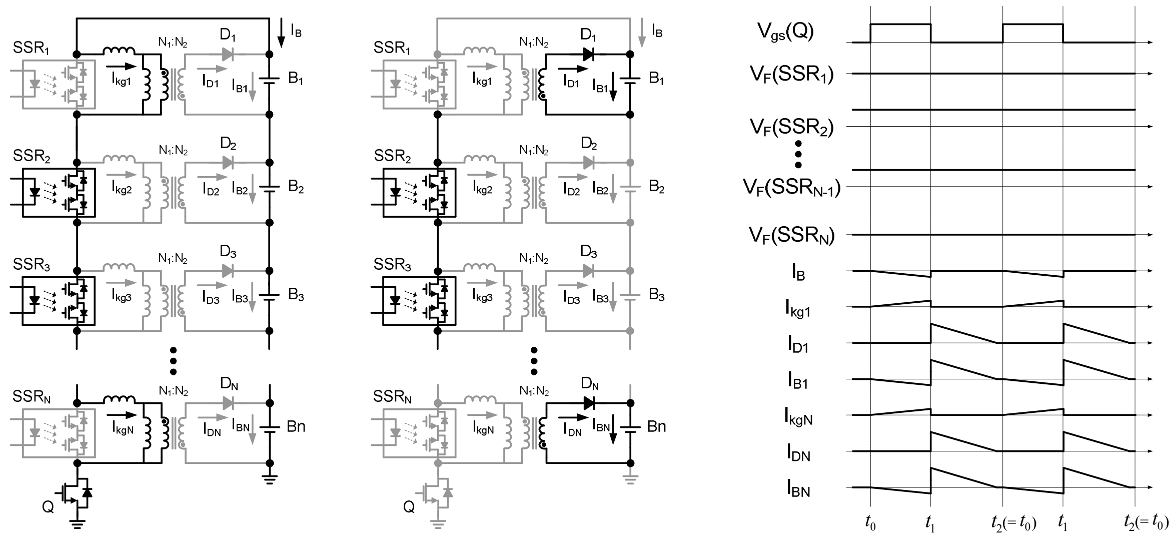

Fig. 2. Operational modes and key waveforms of the proposed charge equalization circuit. (a) Mode1. (b) Mode 2. (c) Key waveforms.

operations, not switching. The operational modes of the proposed charge equalization converter can be divided into two steps, where it is assumed that the first and the last cells are under charged and only the charge control switches of the first and last cell are turn off before driving the MOSFET switch.

- Mode 1(t_0-t_1): When Q is turned on with a fixed duty ratio by the control of a BMS, mode 1 starts. As shown in Fig. 2(a) and Fig. 2(c), magnetizing currents build up at only the first and the last cell by

$$I_{\text{kg1}} = I_{\text{kgN}} = \frac{V_{\text{stack}} \cdot DT_S}{N_{\text{OFF}} \cdot L_m},$$

where N_{OFF} is the number of charge control switches turned off and V_{stack}, L_{m}, and DT_{S} are the stack voltage of the battery cells in series, magnetizing inductance, and turn-on period of the main MOSFET switch.

- Mode 2(t_1-t_2): When Q is turned off, mode 2 begins. In this mode, equalizing current flows into the first and the last cell through the rectifier diode at each cell and reset of magnetizing current is achieved at the same time.

3. Experimental results

To verify the operational principles of the proposed cell balancing circuit with the proposed power rating design rule of optimum [4], an industrial sample is implemented and its circuit diagram is shown in Fig. 3. In this sample, the commercial 7Ah lithium-ion batteries of four cells are used in series for a HEV battery system and the flyback DC/DC converters, constructed by applying the proposed power rating design rule, are in parallel linked with the battery string. The charge control switch at each primary winding is implemented by a solid stage relay, which is a bi-directional switch driven by the centralized control of an intelligent BMS. In addition, to apply DC current to all the lithium-ion battery cells while both charging and discharging, output capacitors, C_{O1}-C_{O4}, are in parallel linked to the batteries. The parameters used for realization of the industrial sample are described in TABLE I.

In this equalization test, the initial SOC difference between the under charged cell and the others is approximately 20%, where the last cell has the lowest SOC among them. Before driving the MOSFET switch with PWM signal of a fixed duty ratio, SSR_1 through SSR_3 are turned on and SSR4 is turned off to charge the equalizing energy into only the last cell. In fact, the cell equalization is one of the functions of a BMS, but in this sample the start and the termination of cell equalization are manually controlled.

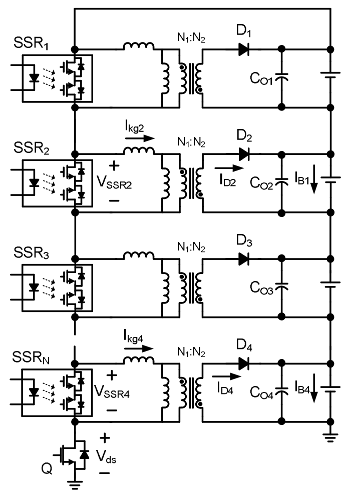

Fig. 3. Circuit diagram of the industrial sample implemented by employing the proposed cell balancing scheme.

Fig. 4 shows the experimental waveforms of the industrial

TABLE I
PARAMETERS FOR THE PROPOSED CELL BALANCING CIRCUIT

Parameters			Value
Cell balancing circuit	MOSFET switch, Q		IRF7452
	Charge control switch, SSR_1-SSR_4		PS710E-1A
	Diode, D_1-D_4		SS24
	Transformer	Core	EP41010
		N_1:N_2	23:7
		L_{m}, L_{kg}	750μH, 570nH
Lithium-ion battery	Capacity		7Ah
	SOC of B_1 at t=0		62.6%
	SOC of B_2 at t=0		62.4%
	SOC of B_3 at t=0		62.6%
	SOC of B_4 at t=0		40.5%

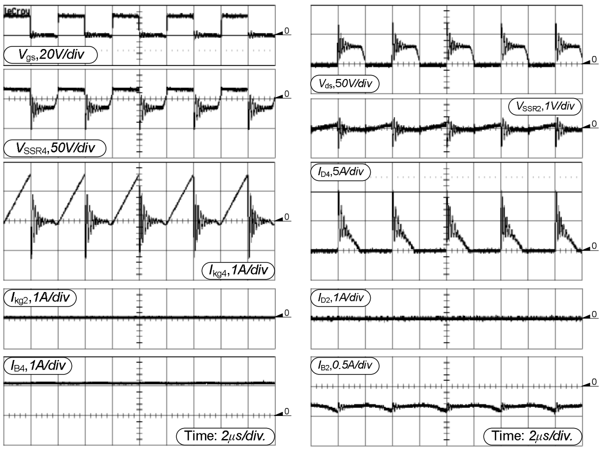

Fig. 4. Experimental waveforms of the industrial sample.

sample, in which the last cell is assumed to be the most under charged. As shown in Fig. 4, when the MOSFET switch is turned on, the overall voltage of the battery string is applied to the primary side of the last DC/DC converter and then, when the switch is turned off, the equalizing current flows into the last battery. To ensure that no energy flows into any other cell, the second cell is more carefully investigated; for example, the currents through the leakage inductor at the primary side and the rectifier diode at the secondary side. As expected, there exists no energy which flows into the second cell.

To evaluate the cell balancing performance of the proposed charge equalization circuit, real equalization test is conducted and its result is plotted in Fig. 5. In this test, to achieve charge equalization within 70 minutes under the SOC 20% difference between the under charged cell and the other cells, average output current of 0.35A is drown out from the battery stack, in which the overall efficiency of the cell balancing circuit is measured to be 75%. This equalization performance is similar to that of the computer simulator; in other words, equalization time of about 70 minutes is consumed to achieve charge equalization in the computer simulation. From the above experimental results, the proposed cell balancing circuit and the power rating design rule of optimum show the good charge equalization performance while maintaining the minimized size of cell balancing circuit as well as satisfying equalization requirements.

4. Conclusions

In this paper, the charge equalization converter with its optimal power rating design rule is proposed, where the primary sides of all the DC/DC converters are in series coupled to selectively charge only the specific under voltage cells through the centralized control of an intelligent BMS. Moreover, the proposed power rating design scheme can provide the minimized size of the cell balancing circuit to the designer while achieving cell balancing within the required equalization time. The proposed cell balancing circuit and the power rating design rule of optimum can be widely used to charge equalization of the lithium-ion battery cells in HEV or EV.

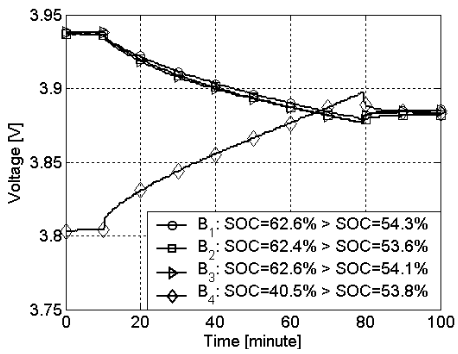

Fig. 5. Charge equalization performance of the proposed cell balancing circuit.

Acknowledgment

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