Modularized Charge Equalization Converter for Hybrid Electric Vehicle Lithium-Ion Battery Stack

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Abstract

Modularized charge equalization converter for HEV lithium-ion battery cells is proposed in this paper, in which intra-module and inter-module charge equalization can be achieved at the same time. For intra-module charge equalization, the conventional flyback DC/DC converters of low power and small size are employed, in which all of the primary sides are coupled in parallel for selective charge of the specific under charged cell within the module. For inter-module charge equalization, the flyback DC/DC converters are also added, in which all the secondary windings are electrically linked in parallel for automatic charge balancing among the modules. An engineering sample of forty cells hiring the proposed cell balancing scheme is implemented and its experimental result shows that the proposed modularized charge equalization circuit has good cell balancing performance.

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.

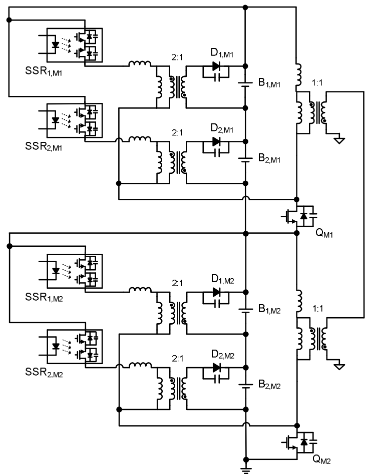

Fig. 1 Proposed modularized charge equalization converter

2. Proposed Two-stage cell balancing scheme

2.1 Circuit description

Fig. 1 shows the proposed modularized charge equalization converter, where imbalanced battery strings of 4 cells are assumed even though imbalancing circuitry is not shown. As shown in Fig. 1, there exist two modules divided and each module involves two cells. Every cell has a flyback DC/DC converter of low power of which all the primary windings with in series bi-directional switches are coupled in parallel. The two modules also have flyback DC/DC converters in parallel, respectively, and their secondary windings are electrically connected in parallel for current diverting. All the MOSFET switches are used for intra-module and inter-module charge equalizations and the bi-directional switches are selectively turned on by the centralized control of HEV BMS (battery management system).

2.2 Operational principles

The operational modes of the proposed circuit are summarized below, where it is assumed that the BMS always monitors SOC of all batteries and initiates charge equalization processes after complete turn-off of the ignition. Equalization time and equalizing current are programmed in advance. All MOSFET switches are controlled by the BMS with fixed duty ratio, and before driving all the MOSFET switches, bi-directional switches of the low voltage cells are turned on. In this mode analysis, $SSR_{1,M1}$ is turned on in advance assuming that the first module is more under charged than the second module and the first cell in the first module is more under charged than the second cell. Mode 1 (t_0~t_1) begins when Q_{M1} and Q_{M2} are turned on at the same time. The primary current,

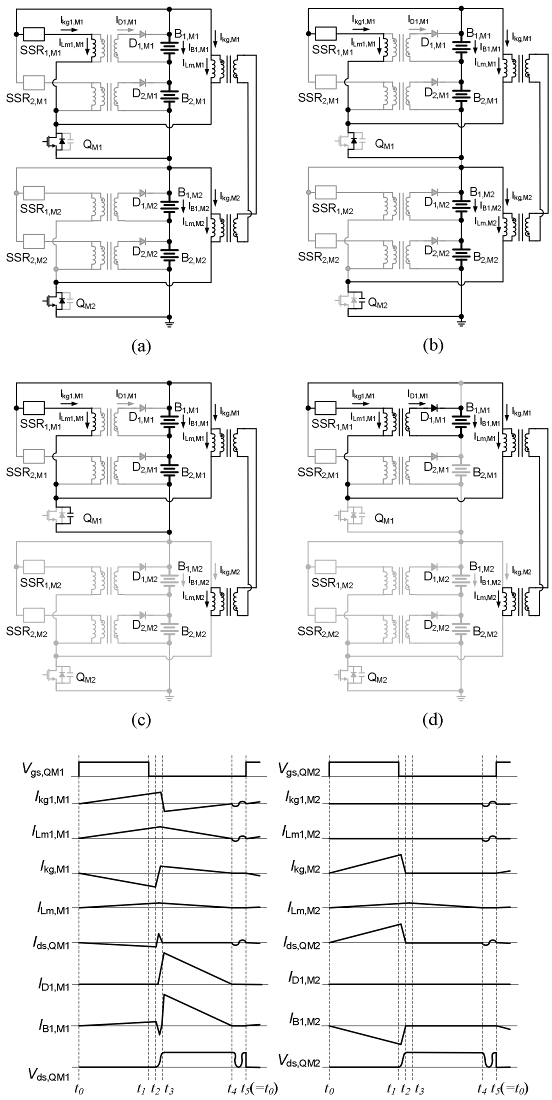

Fig. 2. Operational principles of the proposed modularized charge equalization converter. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Key waveforms.

$I_{kg1,M1}$, builds up at the magnetizing inductor through $SSR_{1,M1}$ for intra-module cell balancing while module current diverts from the second module to the first module for inter-module balancing as shown in Fig. 2(a) and Fig. 2(e). Mode 2 (t_1~t_2) starts when Q_{M1} and Q_{M2} are turned off. In this mode, the output capacitor of Q_{M2} is fully charged. Then, when the magnetizing current of the second module transfers into the first module through the magnetic coupling of the secondary windings, mode 3 (t_2~t_3) begins. In this mode, the output capacitor of Q_{M1} is fully charged too. Mode 4 (t_3~t_4) starts when $D_{1,M1}$ is turned on. In this mode all the magnetizing currents, $I_{Lm1,M1}$, $I_{Lm,M1}$, and $I_{Lm,M2}$ flow into the first cell. After reset of all the magnetizing currents finished, mode 5 (t_4~t_5) starts. In this mode, resonance caused by the parasitic components in the circuit is observed until the start of mode 1.

3. Experimental results

To verify the operational principles of the proposed cell balancing circuit, an engineering sample is implemented,where 5 modules are realized and each module has eight cells as shown in Fig. 3. In this engineering sample, the commercial 7Ah lithium-ion batteries of forty cells are used for a HEV battery system. The intra-module and inter-module flyback DC/DC converters, which are constructed by applying the power rating design rule [4], are coupled to the battery stack. The charge control switch linked in series with primary winding is implemented by using a solid stage relay, which is a bi-directional switch driven by the centralized control of an intelligent BMS. The parameters used for realization of the prototype are described in TABLE I.

Fig. 3 Implemented engineering sample for 40 cells

To evaluate the cell balancing performance of the proposed charge equalization circuit, real equalization test is conducted and its result is plotted in Fig. 4. In this equalization test, forty cells are used for a HEV lithium-ion battery system and only two battery cells are temporarily under charged among the forty cells. The more specific environment of the batteries of forty cells is as follows; the average SOC of the overall cells is approximately 40 % and the SOC gap between the lowest cell and the highest cell is about 22%. In addition, an intelligent BMS is employed in this equalization test to control the proposed modularized charge equalization converter. The employed BMS find the cell which has the lowest cell voltage and then, charge it to the average voltage of the batteries. Once BMS have the lowest cell to get to the average SOC level, then find the next lowest cell again to charge the cell to the average SOC level again. From the equalization test with the control scheme of this sort, it is observed that the proposed modularized cell balancing circuit shows good equalization performance; in other words, the initial SOC gap of 21.9% decreases to SOC gap of 5.4%.

TABLE I
PARAMETERS FOR THE MODULARIZED CHARGE EQUALIZATION CIRCUIT

Parameters			Value
Intra-module converter	Bi-directional switch $SSR_{1,M1}$ ~ $SSR_{8,M2}$		PS710EL-A
	MOSFET switch		IRF7495
	Diode		STPS2L30A
	Transformer	Core	CM102200
		N_1:N_2	39:5
		L_m, L_{kg}	127μH, 2.8μH
Inter-module converter	Transformer	Core	RN41812
		N_1:N_2	14:14
		L_m, L_{kg}	500μH, 200nH
Lithium-ion battery	Capacity		7Ah
	SOC_{B1} at t=0		28.0%
	SOC_{M1} at t=0		28.9%
	SOC_{M2} at t=0		49.4%

4. Conclusions

In this paper, modularized charge equalization converter is proposed for HEV lithium-ion battery cells. In the proposed circuit,

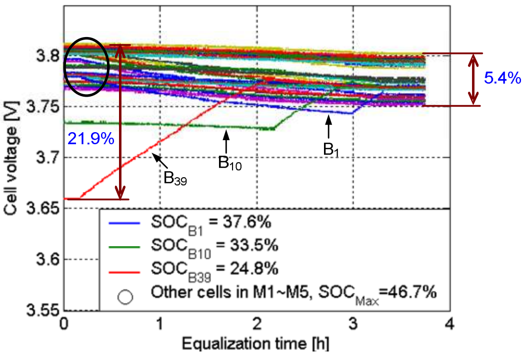

Fig. 4 Charge equalization performance of the proposed modularized charge equalization circuit.

the intra-module equalization part for cell balancing within the module and the inter-module cell equalization part for module balancing among the modules are implemented. In the intra-module charge equalization, each cell employs the conventional flyback DC/DC converter with series coupling of the bi-directional switch. The proposed intra-module equalization converter is current-fed type so that it can shows good equalization performance even for the lithium-ion battery. On the other hand, in the inter-module charge equalization, voltage-fed type cell balancing scheme is realized. This voltage-fed type equalization scheme can achieve automatic charge equalization without the careful control by BMS. In addition, the proposed modularized charge equalization scheme enables all the electronic devices to have low voltage stresses. Therefore, the proposed modularized equalization circuit will be widely used for the lithium-ion battery systems such as HEV or EV.

Acknowledgment

This work was supported through research fund by SK Corporation, Republic of Korea.

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