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Individual Charge Equalization Converter with Parallel Primary Winding of Transformer for Series Connected Lithium-Ion Battery Strings in an HEV

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ABSTRACT

In this paper, a charge equalization converter with parallel-connected primary windings of transformers is proposed. The proposed work effectively balances the voltage among Lithium-Ion battery cells despite each battery cell has low voltage gap compared with its state of charge (SOC). The principle of the proposed work is that the equalizing energy from all battery strings moves to the lowest voltage battery through the isolated dc/dc converter controlled by the corresponding solid state relay switch. For this research a prototype of four Lithium-Ion battery cells is optimally designed and implemented, and experimental results show that the proposed method has excellent cell balancing performance.

Keywords: Hybrid electric vehicle (HEV), Charge equalization, Lithium-ion battery

1. Introduction

Recently, hybrid electric vehicles (HEV) have become popular vehicles for energy conservation and eco-friendly demands, since the HEV has employed the battery as an alternative power source [1]. In HEV, the energy from the wheel, which has been wasted in the past, converts the electrical energy into the battery energy and then it is reused from the battery to propel the vehicle at low speeds or boost extra power required in high acceleration. In addition, there is no emission of CO_2 during utilizing the battery as a power source. Therefore, in HEV, employing the battery power source is one of the major advantages and the battery having long life time is economically beneficial in the automotive market.

Currently, various batteries have been discussed to employ the battery as an alternate power source in HEV. Among them, nickel-metal hybrid (Ni-MH) batteries are most numerous in HEVs today[1]. Recent developments in lithium-ion batteries and test results show that the lithium-ion battery has higher power, higher energy density, lower self-discharge rate, and higher single cell voltage than the Ni-MH battery that has the potential of taking the place of the Ni-MH battery in the HEVs of the future[2]. However, to realize this possibility, reliability and safety is first of all ensured; in other words, the 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 cases,

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explosion or fire in the vehicle [1], [2].

In the HEV, the series-connected battery string is normally used to achieve a high voltage for driving electric motors. However, repetitive battery charging and discharging can cause a charge imbalance among the battery cells. The problem associated with this phenomenon is that this charge imbalance will decrease the total storage capacity and whole life cycle of the battery [3].

Therefore, to avoid the possible risks and enhance the battery life cycle, the charge equalization method for Lithium-Ion battery strings is a significant necessity in HEV.

Charge equalization methods for series-connected battery strings have been presented in [3]-[18]. One of them is an energy dissipative method such as a resistive current shunt [4], [5]. The resistive current shunt, which consists of a resistor and an active switch, is in parallel connected across each battery cell as shown in Fig. 1. This dissipative method is attractive to balance the charge among battery cells because of its simple and easy implementation. However, energy dissipation and long equalization time are critical drawbacks of this circuit compared with the other cell balancing circuits. For this reason, such a cell balancing scheme is not strongly recommended for charge equalization of a high power system such as an HEV.

To obtain more effective charge balancing, non-dissipative methods, such as the lossless charge equalization method, are presented in [6]-[17]. In general, non-dissipative charge equalization schemes are divided into three categories: charge-type, discharge-type, and charge- and discharge-type. Charge-type equalization scheme is intended for the environment of a few of under-

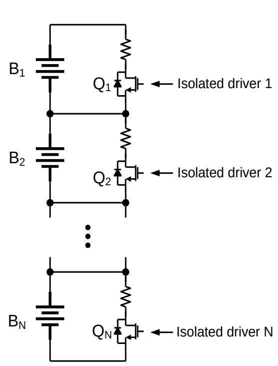
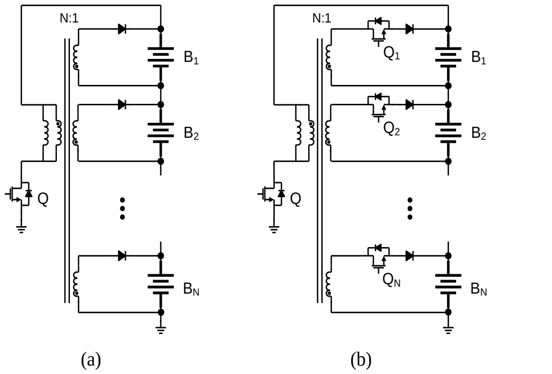


Fig. 1. Resistive current shunt.

charged cells among all batteries [6]-[9] and discharge-type is for a few of over charged cells [10]-[12]. Bi-directional charge equalization scheme has both characteristics; charge- and discharge-type [13]-[15]. Among these equalization schemes, in case under-charged cells occur in battery strings frequently, the charge-type scheme is attractive in HEV.

A Charge-type cell equalization converter can be classified into two styles as shown in Fig. 2, where the control scheme for the cell balancing circuit is mainly taken into account. In the centralized control based equalization shown in Fig. 2(a) [6], [7], every cell in the string is in parallel coupled with the corresponding secondary winding and all the secondary windings are realized at the single common core as well as the primary winding. In this centralized control based equalization scheme, only the single power switch at the primary side is controlled in pulse width modulation (PWM) mode to achieve charge equalization automatically. This centralized control based cell balancing circuit has the merit of the simple structure of a controller, but it cannot show good equalization performance for a large number of cells since the unbalancing parasitic components appear at the secondary sides of the single common transformer. In detail, equalization performance is limited due to the parasitic leakage inductance among the mismatched transformers. Moreover, from the implementation point of view, it is not easy to establish a large number of secondary windings, equal to the number of cells, in a single common core.

To improve cell balancing performance of the centralized control based equalization scheme, the cell control based equalization scheme is discussed as shown in Fig. 2(b) [8]-[9]. Compared with the centralized control based scheme, the cell control based scheme employs the external switches in all the secondary sides of the transformer to efficiently control the equalizing current; that is, these external switches can govern the cell balancing current to selectively charge the specific under-charged cells. The prime advantage of this control scheme is to obtain high quality cell balancing performance especially for the lithium-ion battery. However, like the centralized control based scheme, it has still an implementation problem with a large number of cells due



(a) Centralized control based (b) Cell control based

Fig. 2. Charge-type cell equalization converter.

to a single common core. In addition, since the switch current rating in the secondary side of the transformer is higher than the switch in the primary side, the external switches in the secondary sides of the transformer are limited in their employ.

To directly apply to Lithium-Ion battery equalization of HEV, unlike the previous balancing scheme, the charge equalization method has requirements as excellent cell balancing, simple controlling and easy implementation. To meet these requirements, this paper proposes a charge equalization converter with parallel-connected primary windings of transformers. The principle of the proposed work is that the equalizing energy from all battery strings moves to the lowest voltage battery through the isolated DC/DC converter controlled by the corresponding bi-directional switch.

In the proposed circuit, by using the solid state relay switch, an ability of charge equalization is enhanced even at the low voltage gap between the over-charged and the under-charged cells in Lithium-Ion battery strings and total equalization time is reduced. Furthermore, the proposed circuit can be easily implemented with each magnetic core individually.

In this paper, a prototype of four Lithium-Ion battery cells employing the proposed method is optimally designed and implemented, and experimental results show that the proposed method has excellent cell balancing performance.

2. Proposed Charge Equalization Converter

2.1 Circuit descriptions

Fig. 3 shows the proposed charge equalization circuit with parallel primary windings of transformers. In this circuit, each cell has its own flyback DC/DC converter. The flyback DC/DC converter is is parallel connected to each battery in the output stage and input stage is coupled together to connect across the voltage of strings. The solid state relays, S_1~ S_{N-1}, are placed in series with the primary side of the transformer as shown in Fig.3.

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 system (BMS) with voltage sensing circuitry. The battery management system (BMS) always monitors the state of charge (SOC) of every battery in the strings.

The circuit operations are similar to conventional flyback DC/DC converters, where flyback DC/DC converters operate individually at the selected battery cell by the solid state relay switch, S_N. In detail, the flyback DC/DC converter is driven with a fixed duty ratio by the centralized control of BMS. The relay switch control signal is also taken by BMS, which checks the lowest voltage cell and selects the corresponding relay switch.

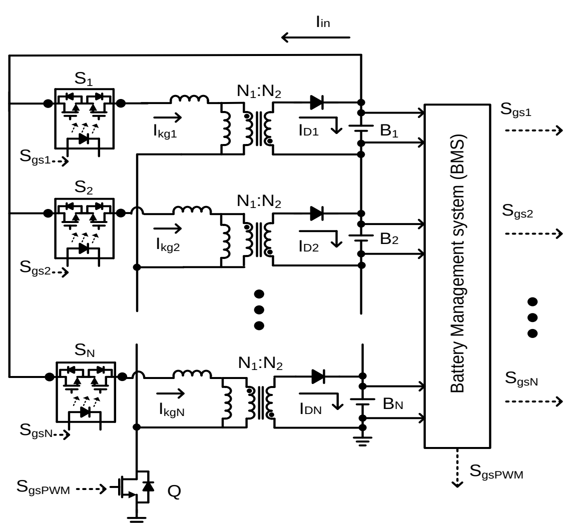


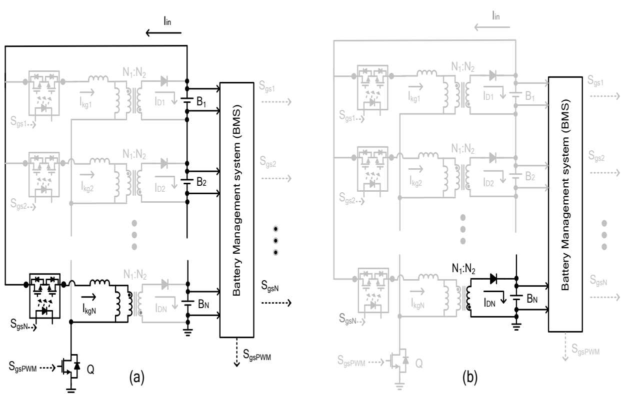
Fig. 3. Proposed charge equalization converter.

2.3 Modal analysis

The proposed equalization circuit operates in two modes according to the switching states of the primary single MOSFET and the secondary diodes. The operational modes and the key waveforms are presented in Fig. 4 and Fig. 5, respectively. Before starting mode 1, it is assumed that only the last cell, B_N, is under-charged.

- Mode 1(t_0-t_1): mode 1 begins when Q is turned on, where S_1~ S_{N-1} are turned off and S_N is turned on. In this mode, the primary current of the Nth cell, I_{kgN}, builds up, as shown in Fig. 4(a).
- Mode 2(t_1-t_2): mode 2 starts when Q is turned off, as shown in Fig. 4 (b). In mode 2, the corresponding rectifier diode, D_N, is turned on so that the magnetizing current flows into the B_N.

It is similar to a conventional flyback converter operation. With this process, equalizing currents from the overall cells can be transferred to the lowest voltage cell effectively.



(a) mode 1 (b) mode 2

Fig. 4. Operational modes of the proposed circuit.

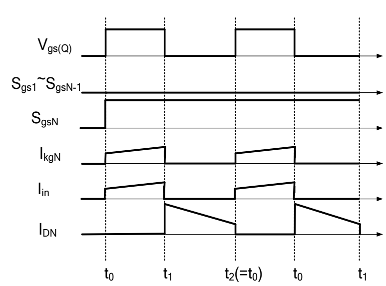


Fig. 5. Key waveforms of the proposed circuit.

3. The Optimal Power Rating Design Scheme

This section presents the optimal power rating design rule for the charge equalization converter considering equalization time for a given SOC distribution of imbalance [16], [17].

Before presenting the power rating design scheme, we should find the relationship between the estimation of SOC and the cell voltage in the lithium-ion battery. Through SOC estimation of the battery, BMS is considered as the charging and discharging level of the battery cell. However, the estimation of SOC can be obtained by using many variables in a very complex algorithm [18]. In this paper, SOC is represented with only open circuit voltage of the battery cell for simplicity.

In Fig. 6, the dot symbol represents the experimental results and the solid line is the linear approximation of those findings. In this figure single cell voltage is plotted according to SOC of a commercial 7Ah battery. From 30% to 70% of SOC is the recommended operational range of safety and this paper shows the experimental result in the safety range.

- $Q_n(t)$: charge quantity of the nth cell at time t,
- $V_n(t)$: voltage of the nth cell at time t,
- I_{in}: constant input current from the overall cells to the converter,
- I_{out}: constant output current from the converter to the overall cells,
- $P_{in}(t)$, $P_{out}(t)$: input power, output power of an equalization circuit at time t, respectively,
- $P_{in,avg}$, $P_{out,avg}$: average input power, average output power of an equalization circuit, respectively, and
- η: overall efficiency of an equalization circuit.

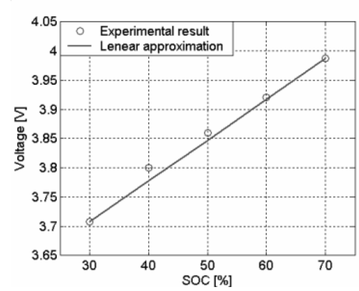


Fig. 6. Cell voltage according to SOC of a commercial lithium-ion 7Ah battery from 30% to 70%.

To obtain the optimal power rating of the cell balancing circuit, the following simultaneous equations should be satisfied:

$$\frac{1}{N-1}\sum_{n=2}^{n=N} Q_n(t) = Q_N(t) \tag{1}$$

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

Where it is noted that by (1) and (2), the left side of equation (1) is the average charge quantity of the overall battery at equalization time t and the right side is the charge quantity of the selected battery cell due to the lowest battery voltage or SOC in the battery string. In equation (2), it shows that the average power flow to the selected battery cell is equal to the average power of the overall battery cell's converted power by the cell balancing circuit; efficiency of the cell balancing circuit is η. Through the block diagram of the proposed scheme as shown in Fig. 7, this equation can be explained more easily. This block diagram indicates the charge transferring from all battery cells to the selected battery cell. This charge transference occurs by the output current of the charge-type DC/DC converter and the input current comes from all battery cells. The output power of the DC/DC converter flows into the selected cell for charging the battery cell and that is the equalizing current for balancing the lowest voltage or SOC cell.

Furthermore, the amount of average charge remained in the under-charged cell, $Q_N(t)$ and average output power of the DC/DC converter that also indicates the input power from the output power of the DC/DC converter to the under-charged cell, $P_{out,avg}$ is given by, respectively,

$$Q_N(t) = Q_N(0) + (I_{out} - I_{in}) \cdot t \tag{3}$$

$$\begin{aligned} P_{out,avg} &= \frac{1}{t}\int_0^t P_{out}(\tau)d\tau = \frac{1}{t}\int_0^t V_N(\tau)(I_{out} - I_{in})d\tau \\ &= \frac{1}{t}\int_0^t \left(V_N(0) + \frac{(I_{out} - I_{in})\cdot\tau}{C}\right)(I_{out} - I_{in})d\tau \\ &= \left(V_N(0) + \frac{1}{2C}(I_{out} - I_{in})\cdot t\right)(I_{out} - I_{in}) \end{aligned} \tag{4}$$

where C is capacitance of the 7Ah lithium-ion battery used in this paper and the negative sign means that the current flows from the cell to the DC/DC converter. Therefore, the output current of the DC/DC converter, I_{out}, is the charging current for the under-charged cell and the difference between input and output current of the DC/DC converter, $I_{out} - I_{in}$, is the equalization current that is actually utilized for balancing the cell voltage at the under-charged cell. In the power rating design of a cell balancing circuit, average power is taken into account since the cell voltages, even a little, can change during the equalization process.

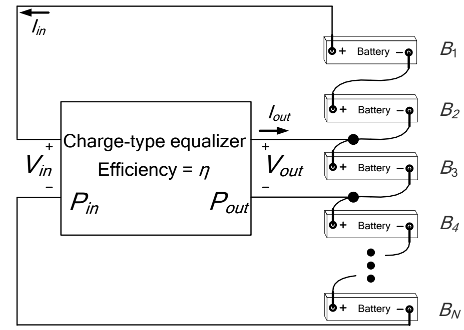


Fig. 7. Simple block diagram of proposed scheme.

Fig. 8 shows the simulation result of the equalizing current versus equalization time. This result comes from solving the above equations. As expected, the shorter equalization time will be taken for the higher equalizing current and also higher power rating of balancing circuit. To obtain the optimal power rating of the cell the balancing circuit, the equalization time must be decided. By the result in Fig. 8, the equalizing current can be obtained. Hence, the power rating of the DC/DC converter can be calculated by equalizing current and voltage of the battery cell. For instance, if the equalization time is

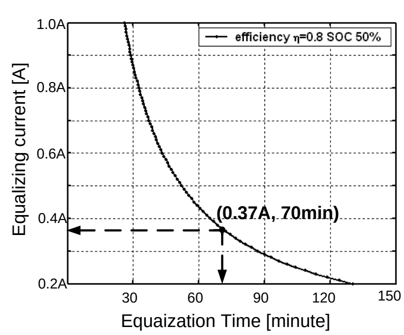


Fig. 8. The equalizing current according to the equalization time of the DC/DC converter.

70min, at that time the equalization current is about 0.37A. When the input current from the overall battery to the DC/DC converter, I_{in} is 0.13A, the output current, I_{out}, is about 0.5A. Since the voltage of the battery cell is about 4V and the efficiency is assumed to be about 80% as shown in Fig. 7, the power rating of the DC/DC converter can be estimated to be about 2.5W.

4. Experimental Results

To verify the operational principles of the proposed cell balancing circuit and the usefulness of the proposed power rating design rule, a prototype is implemented and its circuit diagram is shown in Fig. 9. In this prototype, the commercial 7Ah lithium-ion batteries of four cells are used for an HEV battery system and the flyback DC/DC converters, constructed by utilizing the proposed power rating design rule.

In detail, for this prototype system a 2.5W flyback converter is utilized at unbalanced SOC gap 10%, where the voltage of over-charged cells is 3.86V at SOC 50% and the voltage of a single under-charged cell is 3.80V at SOC 40%.

The parameters used for realization of the prototype are described in Table 1.

In this experiment, the initial SOC difference between the under charged cell and the others is approximately 10%, where the fourth cell has the lowest SOC among them. In this circuit, instead of using BMS signal to select the lowest voltage battery cell, VCC 5V of power supply is used as the selection signal of the mechanical relay switch; this signal can operate the corresponding solid state relay switch at the lowest voltage battery cell. If Solid state relay is connected by the mechanical relay switch at the lowest voltage battery cell, the corresponding flyback DC/DC converter is driven in PWM mode with fixed duty ratio.

Fig. 10 and Fig. 11 show the experimental waveforms of the implemented prototype. In this prototype work, it is assumed that the fourth cell of the battery string is under-charged and the only selection switch, S4, is turned on. At this time, when the MOSFET switch is operated with on time duty, the input current, I_{in}, builds up at the fourth battery cell. After the MOSFET switch is turned off,

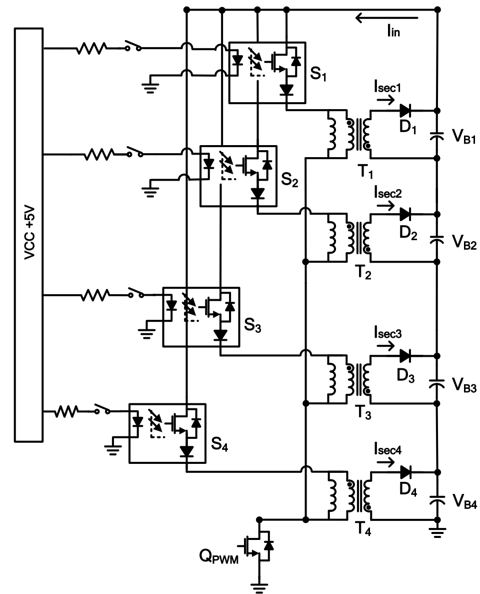


Fig. 9. Proposed charge equalization converter with parallel primary winding.

the input current is transferred to the secondary side of the transformer as the output current, I_{out} or the secondary current, $I_{\sec 4}$, at the fourth battery cell as shown in Fig. 10.

Fig.11 shows the differing results of two current waveforms at the secondary diode, $I_{\sec 1}$ and $I_{\sec 4}$. At the first battery cell, there is no current in the secondary diode. This is because the selection switch, S1, is not operated at the first battery cell.

Table 1 Parameters used for the implemented prototype

Parameters			Value
Balancing circuit	*Solid state relay, S_1-S_4*		PS710B-1A
	MOSFET switch		IRF7452
	Diode, D_1-D_4		SS24
	Transformer	*Core*	EP41313
		N_1:N_2	22:7
		L_m *L_{kg}*	130μH, 750nH
Lithium-ion battery	*Capacity*		7Ah
	SOC of B_1 at t=0		50%
	SOC of B_2 at t=0		50%
	SOC of B_3 at t=0		50%
	SOC of B_4 at t=0		40%

To show the cell balancing performance of the proposed charge equalization circuit, the equalization test cooperated with the lithium-ion battery cells is conducted and its result is plotted in Fig. 12. In this test, to achieve charge equalization within 70 minutes under the SOC difference of 10% between the under- charged cell and the other cells, the average input current, I_{in}, of 0.15A is designed to flow into the DC/DC converter of the fourth cell. With this charged current, I_{out} of 0.6A, equalizing current of 0.45A which is the measured value in this experimental environment is recovered into the overall battery pack. In addition, the measured efficiency of the DC/DC converter is 81%. As shown in Fig. 12, the prototype shows the equalization performance to be similar to that of the simulator as an expected result in Fig. 8. Furthermore, the voltage of the under-charged cell linearly increases during the operation of charge equalization. This is because the charging current has uniform value and this characteristic can achieve the effective balancing of the battery string at a low voltage gap between the over-charged cells and the under-charged cells.

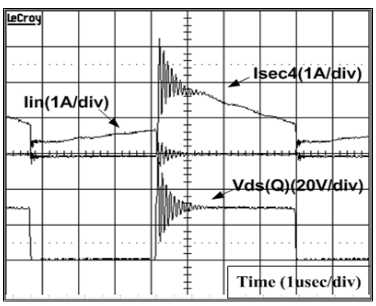


Fig. 10. Experimental waveform of the prototype at the fourth cell.

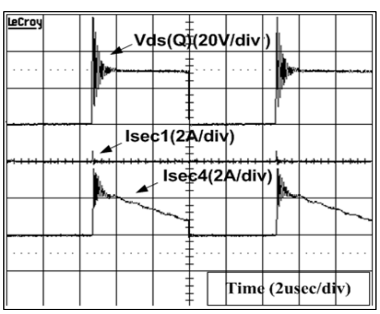


Fig. 11. Comparative experimental waveforms of the prototype between the first cell and fourth cell.

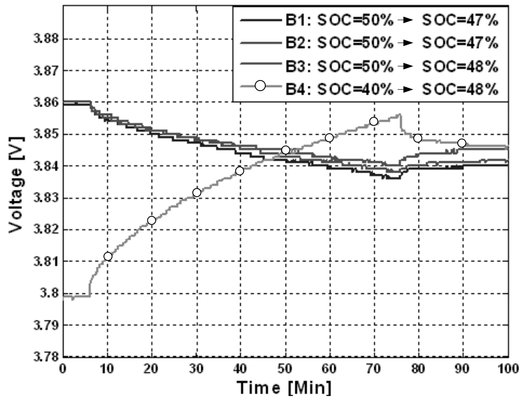


Fig. 12. Charge equalization performance of the proposed cell balancing circuit.

From the above experimental results, the proposed charge equalization circuit and the optimal power rating design scheme proposed in this paper show the outstanding cell balancing performance with simple operation and control.

5. Conclusions

In this paper, a charge equalization converter with parallel primary winding for HEV lithium-ion battery cells is proposed with the optimal power rating design and implementation of the prototype.

This proposed work can achieve excellent charge balancing for an under-charged cell, in which much more current can flow to the under-charged batteries by controlling the solid state relay switch. Moreover, it can be directly applied to Lithium-Ion battery equalization of HEV, since it is simple to control the equalizing current at the low voltage gap between the over-charged and the under-charged cells. The implementation of one common core with the multiple secondary winding is easy for a large number of battery cells.

In this paper, a prototype employing the optimal power rating design method is implemented for verifying the usefulness of the proposed power rating design rule of optimum and excellent performance of the proposed cell balancing circuit.

The proposed cell balancing circuit is expected to be widely applicable to a series connecting the lithium-ion battery string of HEV or EV.

Acknowledgment

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