Development of Highly Effective Control Circuit Using Converter Method for Multiple Series Battery Systems

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Abstract

In multiple series lithium secondary batteries, the cell with the smallest capacity determines the rechargeable and dischargeable capacities when individual cell capacities and SOC (state of charge) vary, since the current flow remains the same. As a result, the capacity as an assembled battery becomes lower than that of the sum of all the individual batteries, reducing use efficiency. To solve this problem, it is necessary to reduce the loss as much as possible and control the balance using a regenerative, cell-balance-correcting circuit. There are two kinds of regenerative, cell-balance-correcting circuits: those that use a transformer and those that use a converter. Circuits with a converter, which surpass those with a transformer in terms of power conversion efficiency and accuracy of voltage, are anticipated for practical application. In the simple converter method, however, another problem arises where the circuit continues to consume power after balance control has been achieved. In this study, we will report the development of a new converter method control logic that automatically turns off the circuit once balance control has been accomplished.

Keywords: "cell balance", "state of charge", "battery system", "hybrid electric vehicles", "EV"

1 Introduction

As seen in Fig. 1, the lithium battery power system for HEVs has the characteristic of using lithium secondary batteries in dozens of series [1][2]. In this system, the batteries cannot be used as assembled batteries if the capacity of

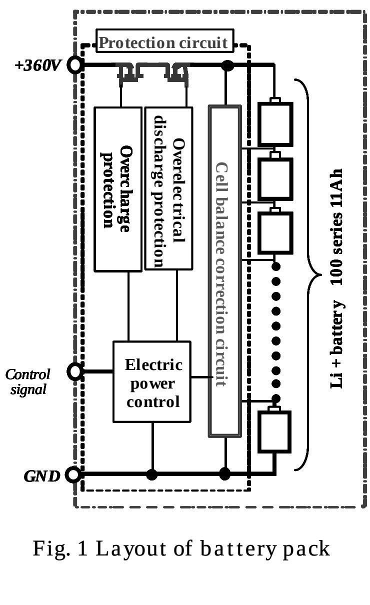
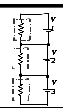
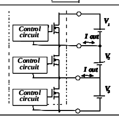
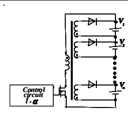
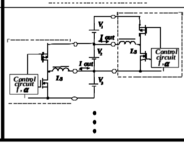


Fig. 1 Layout of battery pack

Table 1 Type of the cell balance circuit

Type	Circuit composition	Principle	Loss	Accuracy	Balance
Bleeder resistor		・Partial pressure by resistance	×× Excessive	△	×× slow.
Shunt Regulator		・High voltage cell is selectively discharged.	× Regenerative efficiency 0%	○	× slow.
Transformer		・The correction power is output through the transformer.	△ Regenerative efficiency 70%	×	◎ early.
Converter		・Magnetize and the resurrection are repeated between cells of adjacent.	○ Regenerative efficiency 90%	◎	○ early.

individual cells and SOC vary. This necessitates the control of cell balance. Table 1 shows the type and characteristics of balance correcting circuits. Cell balance control using a converter[3], which surpass other methods in terms of power loss and accuracy of voltage, are anticipated for practical application in the future.

2 Current Issues

Fig. 2 shows a balance correcting circuit using a converter, where the high side switch Q_1 and the low side switch Q_2 are turned on alternately for the same duration. The inductor current i_L flows

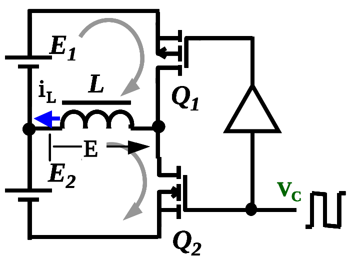


Fig. 2 SOC equalization circuit (converter method)

from cells with high voltage to those with lower voltage, correcting the voltage balance. (1) indicates the relational

$$i_L = \frac{1}{L}\int E dt \qquad (1)$$

expression between the voltage E applied to the inductor and the current i_L. The balance accuracy of E_1 and E_2 are determined by the duty accuracy of switching. Since there is no need to measure the voltage, a reference voltage is not necessary, thereby low cost and high accuracy can be expected. However, this behavior is not enough to stop the switching behavior after a balance has been achieved, and power loss from both high-frequency currents and from the drive currents of Q_1 and Q_2 occurs.

3 Technology Developed

We have developed a control system where the ON times of Q_1 and Q_2 automatically get shorter once a balance has been

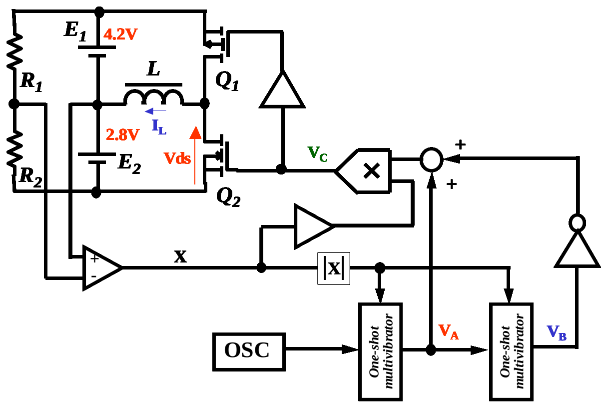


Fig. 3 Developed control circuit

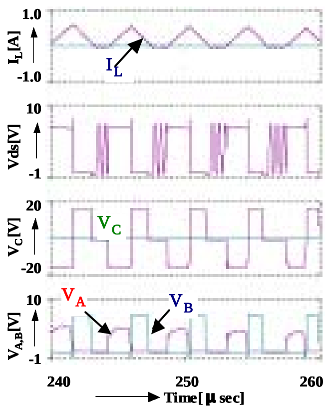


Fig. 4 Operation waveform

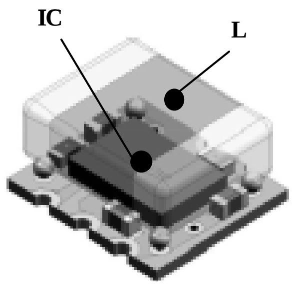


Fig. 5 Structure of composing converter

achieved, and the circuit is turned off. Fig. 3 shows the circuit we have developed, while Fig. 4 indicates the behavior waveform. With the cycle fixed, first turn on the switch element on the cell with the higher voltage for the amount of time that corresponds to the voltage differential to an upper limit of duty 50%. Then turn on the opposite side switch element for the same duration. After that, switch off both elements for the remainder of the time. Since E_1 is almost equal to E_2 in the discontinued mode, where the inductor current passes intermittently, synchronous rectification always occurs by driving Q_1 and Q_2 at the same and continuous pulse width. This circuit configuration can be varied by connecting two one-shot multivibrators in series, and basing the pulse width on the absolute value of the results of the cell voltage comparison. Which of Q_1 or Q_2 should be turned on first is determined based on the results of the cell voltage comparison. This way, the control signal is produced easily and reliably.

4 Efforts for Practical Use

The balance correcting circuit with a converter is capable of combining voltages of two adjacent cells. To support multiple series battery systems, converter circuits numbering as many as the total of all series minus 1 are necessary. Therefore, the converter circuits will have to be extremely small for practical use. Main components are an IC (integrated circuit) with Q_1 and Q_2, and an L (inductor), the only component affecting the size being the inductor. Fig. 5 shows a structure of a converter module. The inductance value needed for the converter is inversely proportional to the conversion frequency. Our experiments revealed that an extremely small inductor of about 150W/cc could be created when a multi-layer power inductor operated at a high conversion frequency of 3 to 5 MHz.

As the frequency goes higher, some modification must be made to the inductor to be used. Fig. 6 through 8 show the winding structure of the improved multi-layer inductor. In Fig. 6, the magnetic field that occurs perpendicular to the normal magnetic path is weakened. A magnetic gap has been created so that magnetic flux does not go around on the inside of the laminated magnetic layers. In Fig. 7, the magnetic path has been shut off, so that the magnetic field appearing in the drawer part of the winding does not cause unnecessary magnetic flux. In Fig. 8, the magnetic field appearing at the rising edge of the winding layer has been shut off. Each example shows a countermeasure to the fact that usually trivial factors become predominant ones when the number of coils decreases due to higher frequencies. With this method, an inductor with a small number of coils can perform well with multiple-series systems.

Additionally, with the converter method comes the issue of reduced efficiency when the control process utilizes many converters if balance control becomes necessary between separate cells. In such cases, balance out several series cells with the converter method to configure the battery module, and combine two or more of these modules to configure a battery pack. Control of balance between battery modules can be achieved efficiently in a short period of time by performing it using the transformer method shown in Table 1.

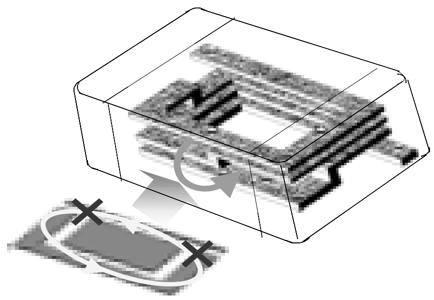


Fig. 6 Decrease in vertical magnetic field to magnetic pass

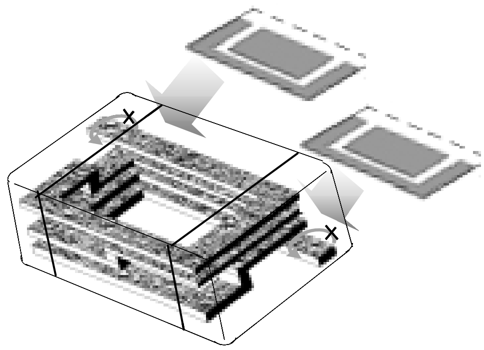


Fig. 7 Reduction in lead magnetic field

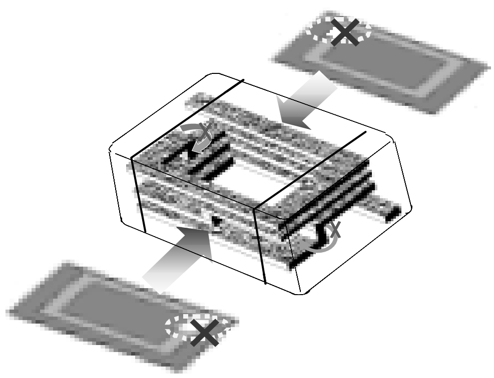


Fig. 8 Magnetic field reduction in volume line layer conversion part

5 Results and Discussions

Fig. 9 shows a simulated result of our experiment using the converter method, cell-balancing circuit we have developed. The application used for simulation was SPICE (simulation program with integrated circuit emphasis). In this experiment, a 100 μF capacitor was substituted for batteries in order to shorten analysis time, with the conversion frequency set at 250kHz. The results showed that a voltage differential as small as 38mV was achieved in 300 μsec by having the 4.2V and 2.8V cells balanced at 1A regeneration. If we translate this to a 10Ah correction of batteries, the balancing action would complete in about 20 hours because half the inductor current would be used for correction.

Condition: The capacitor of 100μF was substituted for the battery.

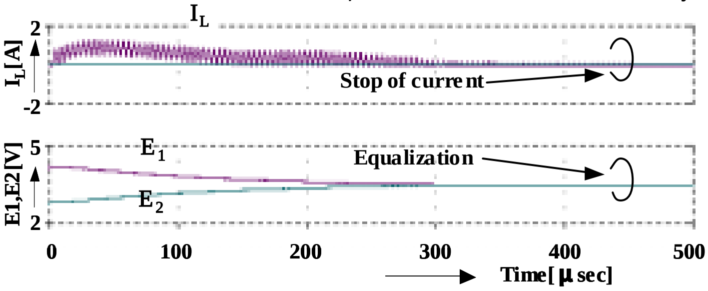


Fig. 9 Operation waveform

Acknowledgments

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References

[1] H. Suzuki and T. Shinpo, Development of Battery Management System for Electric Vehicle, EVS-14 (2001).

[2] Hong San Park, Charge Equalization with Series Coupling of Multiple Primary Windings for Hybrid Electric Vehicle Li-ion Battery System, PESC (2007).

[3] K. Nishijima, H. Sakamoto, and K. Harada, Electric Voltage Balancing Circuit of Battery with Series Connection, VOL. J84-B No.9 (2001).

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