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A New Modularized Balancing Circuit for Series Connected Battery cells

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Abstract: The series connected battery cells are mainly used in high voltage battery pack application. However parameter inequality of each battery cell makes battery voltage imbalance problem. In this paper, a new balancing circuit utilizing converter scheme for the series connected battery cells is proposed. Proposed circuit offers easy control and fast equalization time. Moreover the circuit can be used in a practical application because it has high modularity and can operate during the charging/discharging cycle. To show its superiorness and effectiveness, the principle of proposed circuit is explained with computer simulation and experiment is carried out using lithium-ion battery.

Key Words : BMS, Battery balancing, Li-ion, Series connected battery, Renewable source

1. Introduction

In recent years, fossil fuel depletion leads a human to have interested in renewable energies sources. Electric energies can be good example for renewable energy. Electric energy can be stored in battery. Lithium batteries are used in high effective energy storage systems because it has attractive performances such as high energy density, light weight and long life cycle compared to traditional energy storage systems[1-2].

Especially lithium batteries are playing important role as one of the viable energy storage system in electric-drive vehicles (EDVs), such as hybrid electric vehicle (HEV) or electric vehicle (EV). Since the cell voltage of lithium battery is as low as 4V, the series connected battery string is required for driving a high voltage electric motor in EDVs [3),7)].

However, voltage imbalance will come out when the string is charged or discharged as a whole for many cycles because of the parameter inequality problem in battery cells, even though the battery manufacturer has performed strictly matching and grouping of battery cells. In electric vehicles, batteries work in deep charge and discharge recycle condition. In this case, the imbalance is more critical, which results in damage to battery cell and reduction of battery life span [4)].

According to the consumption of energy in balance process, the current balance control methods for series connected Lithium battery can be divided into 2 classes: energy dissipation type and energy no-dissipation type.

Energy dissipation type is that the excessive energies are consumed in the form of heat. This

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method has advantages on cost, structure, modularity. However it has low efficiency and low balancing speed. Energy nondissipation type is that the excessive energies are transferred or converted into other batteries. Conversion efficiencies commonly reach 85%-95%. This type is mainly studied recently because it has a high efficiency and quick balancing speed even though it has disadvantages on cost and complexity [5].

Nondissipative method can be divided by capacitor, indictor/transformer, converter based methods. The capacitive shuttling balancing control strategy is simple because it has only two states. In addition, it does not need intelligent control and it can work in both recharging and discharging operation. The disadvantage of the switched capacitor topology is relatively long equalization time. The inductor based method offers a smaller balancing executing time but it takes a long time for transferring the energy from the first cell to the last one especially for long string battery pack. Transformer based method has advantages on high efficiency and fast equalization time but it has disadvantages like relatively complex structure, high cost, difficulty in modularity and the saturation problem for multi-winding transformer. Energy converters used for cell balancing fall in several categories such as; Cuk, Buck or/and Boost, Flyback, Full-bridge and Quasi-Resonant converters. They are featured by full control of balancing process. Unfortunately, the system is also facing its relatively high cost and complexity [6].

In this paper, a new balancing circuit for series connected battery which uses converter circuits is proposed. Proposed circuit offers easy control and fast equalization time. Moreover the circuit can be used for practical applications because the circuit has high modularity and can operate during charging and discharging cycle.

2. Proposed balancing circuit

The proposed series connected battery cell balancing circuit is shown in Fig. 1. Three balancing module M1, M2, M3 are used to explain its basic operation. Each modules are consisted of 2 switches and 4 diodes and 1 inductor except balancing module M1 which is connected to the ground. The balancing mechanism is that the energy stored in higher battery voltage transfer to the battery stack. Proposed circuit can operate simultaneously not only single cell balancing but also multi-cell balancing to meet fast balancing condition. The balancing operations are explained in below.

- Operation for single cell balancing

Fig.2 and Fig.3 show single cell battery balancing operation. It is assumed that the battery B2 has higher voltage than other battery cells so the energy of battery B2 is needed to be transferred to the battery B1 and B3.

Mode 1 $(t_0 - t_1)$: This period stores energy of battery B2 to inductor L2. The S21 and S22 are turned off and no current flows at L2 and D21 is assumed off before time t_0. The S21 and S22 turn on at time t_0, the battery voltage applies to inductor and the inductor current increase linearly depending on battery voltage. This mode ends when the switches S21 and S22 are turned off. The equation 1 shows the current of inductor L2 during time $t_0 - t_1$.

$$i_{L_2}(t) = \frac{1}{L_2}\int_{t_0}^{t} v_{B_2}\, dt \qquad (1)$$

Mode 2 $(t_1 - t_2)$: In this period, the stored energy in inductor L2 transfers to battery stack through diode D21 after the two switches S21 and S22 are turned off at time t_1. In this period the inductor current i_{L_2} decrease linearly depending on battery stack voltage $V_{B_{STK}}$ condition. The mode 2 ends when the current of inductor L2 decreases to 0. The equation 2 shows the current of inductor L2 during time $t_1 - t_2$.

$$i_{L_2}(t) = \frac{1}{L_2}\int_{t_1}^{t} - v_{stk}\, dt \tag{2}$$

Fig. 4 shows simulation waveforms of single cell balancing operation.

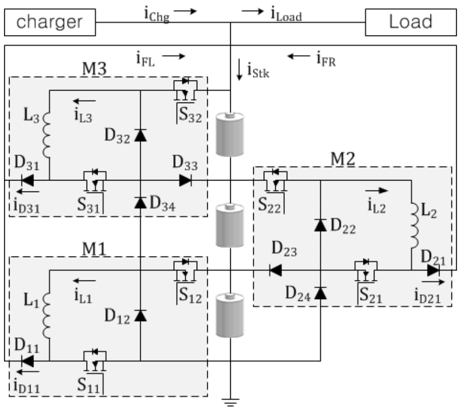

Fig. 1 Proposed circuit employing three balancing modules

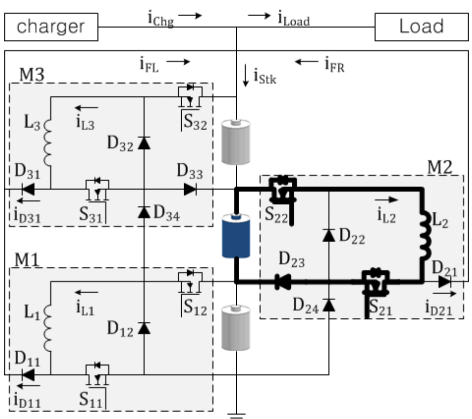

Fig. 2 Mode 1 of single cell balancing

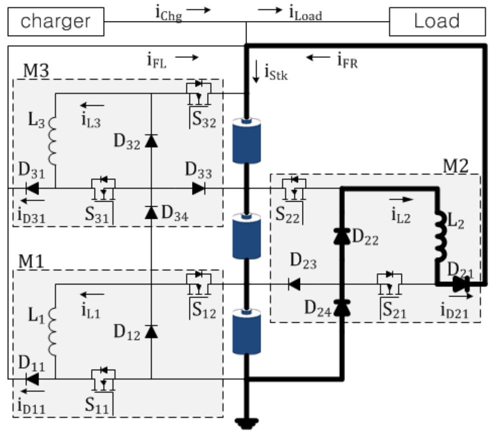

Fig. 3 Mode 2 of single cell balancing

- Operation for multi cell Balancing

Fig.5 and Fig.6 show multi cell battery balancing operation. The multi cell battery balancing operation is similar to single cell battery balancing operation except current path and current stress across each components. It is assumed that the battery B2 and B3 has higher voltage than battery B1 so that the energies of battery B2 and B3 are needed to be transferred to the battery B1.

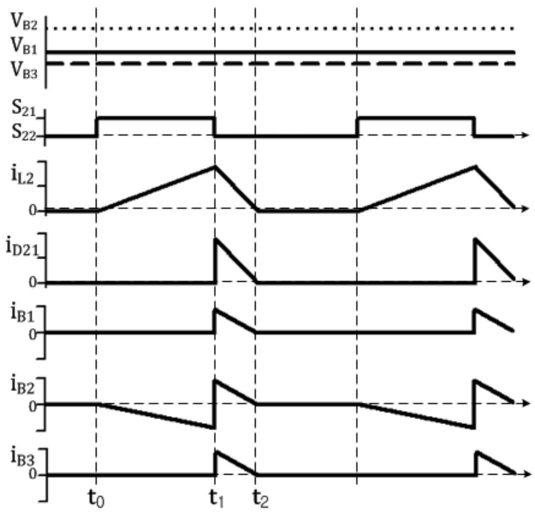

Fig. 4 Simulation waveforms of single cell balancing

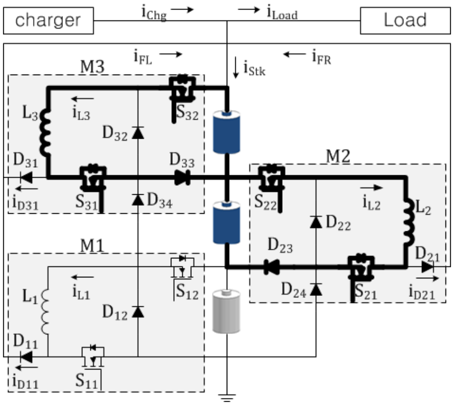

Fig. 5 Mode 1 of multi cell balancing

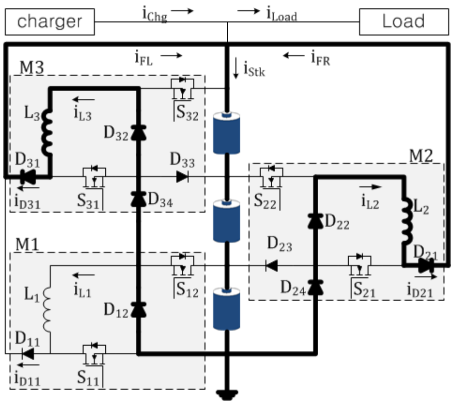

Fig. 6 Mode 2 of multi cell balancing

Mode 1 $(t_0 - t_1)$: During this period, the energy of the battery B2 and B3 is stored in their module's inductor L2 and L3. The switches S21 and S22 of module M2 and S31 and S32 of module M3 are turned on at time t_0. The mode 1 ends with switches S21, S22, S31, and S32 turned off. The increase rate of inductor currents in L_2 and L_3 depends on their own battery voltage conditions.

Mode 2 $(t_1 - t_2)$: In this period, the stored energy in each inductor L2, L3 transfers to battery stack through diode D21 and D31 after the switches S21, S22, S31, and S32 are turned off at time t_1. The current of inductor L2 and L3 decrease linearly depending on battery stack voltage $V_{B_{STK}}$ condition. The mode 2 ends when all of the magnetized inductor currents in L2 and L3 decrease to 0 like as single cell balancing operation. Fig. 7 shows simulation waveforms of multi cell balancing operation.

- Duty ratio consideration

Since series connected battery pack can be used in tough condition, the proposed circuit suggests to operate in discontinuous current mode to meet safety condition. And the proposed circuit uses a fixed switching frequency and just one control signal to achieve simple control. In other words all switches of the module which need to transfer its energy of battery to stack are turned on and off at the same time. So duty ratio determination is important to have fast balancing time and safety. As charge and discharge time goes by, the deviation of voltages of each battery can be increase because of their parameter inequality. So the battery voltage condition is important parameter to decide the duty ratio. The way to decide duty ratio is described in below.

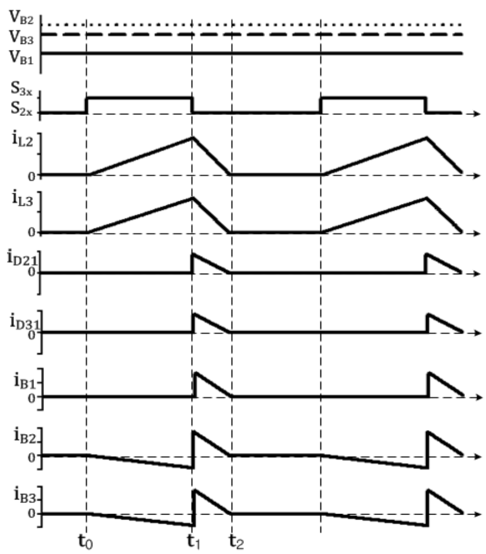

Fig. 7 Simulation waveforms of multi cell balancing

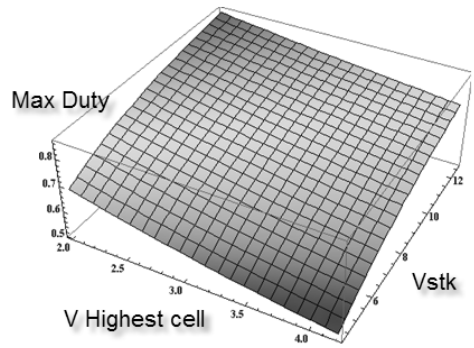

Fig. 8 Maximum duty ratio consideration

It is needed to calculate the inductor current of each mode to decide duty ratio. The proposed circuit has just 2 modes. In mode 1, increase rate of all current of each inductor depends on their own module battery voltage V_{B_N}. In this mode(DT) the voltage across L_n is given as in equation 3. (where n = 1, 2, 3)

$$V_{L_n}(t) = V_{B_n}(t) \quad (3)$$

In mode 2, decrease rate of all current of each inductor is the same if the diode forward voltage drop is ignored. In this mode(D'T) the voltage across L_n is given as in equation 4.

$$V_{L_n}(t) = V_{B_{STK}}(t) - 0 \quad (4)$$

The worst case will be occurred when the voltage deviation of battery cells are high. In this situation, the time of mode 2 becomes shortest for lowest voltage battery cell and becomes longest for highest voltage battery cell. To avoid inductor saturation, therefore, the currents of all inductor must be decreased to 0 in mode 2. So the duty calculation must be based on the module which has highest battery voltage. Equations 5 and 6 show how to decide a duty.

$$V_{B(highest\,volt)} \cdot D \cdot T \le V_{B_{STK}} \cdot (1-D) \cdot T \quad (5)$$

$$D \le \frac{V_{B_{STK}}}{V_{B(highest\,volt)} \cdot V_{B_{STK}}} \quad (6)$$

Fig. 8 shows the maximum duty ratio calculated from (6).

3. Experimental results and discussion

The experimental conditions and components are described in below. The duty of 0.45 is used in the experiment for safe operation.

- Experimental conditions
  - Switching frequency f_s : 20 $[KHz]$
  - Duty ratio D : 0.45
  - Upper switch S_{n1} : IRLML6401
  - Lower switch S_{n2} : IRLML2502
  - Diode D_{nn} : SS54CF
  - Max inductor current i_{Lmax} : 3 $[A]$
  - Ripple inductor current Δi_L : 3 $[A]$
  - Inductor L_n : 28 $[\mu H]$
  - Battery B_n : Li-ion1200$[mAH]$

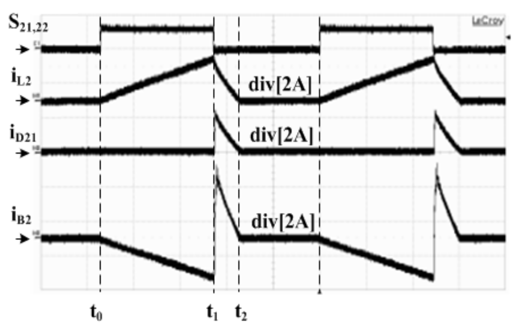

Fig. 9 Experimental waveforms of $S_{21,22}$ i_{L2}, i_{D21}, i_{B2} for single cell balancing($10\mu s$/div)

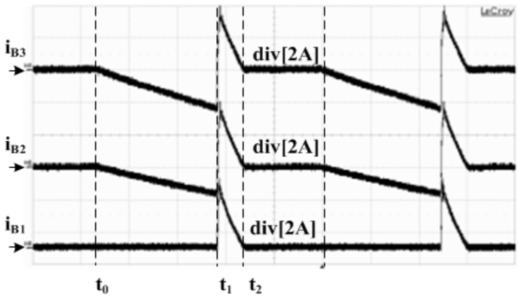

Fig. 10 Experimental waveforms of $i_{B1,} i_{B2,} i_{B3}$ for multi cell balancing($10\mu s$/div)

Fig. 9 shows experimental waveforms of $S_{21,22}$ i_{L2}, i_{D21}, i_{B2} of module M2 for single cell balancing. The initial battery voltages of B2, B3 and B1 are 3.7V, 3.5V and 3.3V respectively. The current of the battery i_{B2} start to flow into the inductor L2 at time t_0 when switches S21, S22 are turned on. And then the current of inductor i_{L2} commutate its current path to D21 after switches S21, S22 are turned off at time t_1. The current of inductor L2 decrease to 0 at time t_2. The decrease rate of current inductor L2 depends on battery stack voltage. Battery stack voltage is about 10.5V for this experiment. Fig.10 shows experimental waveforms of i_{B1}, i_{B2}, i_{B3} for multi cell balancing. The initial battery voltages of B3, B2 and B1 are 3.8V, 3.7V and 3.5V respectively.

Average voltage control method is to transfer the energy stored in battery cell whose voltage is greater than average voltage of cells to stack. Meanwhile, lowest cell based control method is to transfer the energy stored in battery cells whose voltages are greater than lowest cell voltage to stack. Fig. 10 is for the lowest cell based control method. The battery currents i_{B2} and i_{B3} start to flow into the inductor L2 and L3 at time t_0. And then the stored energy in inductor L2 and L3 start to transfer to the battery stack at time t_1. The current of inductor L2 and L3 decrease to 0 at time t_2. Fig.11 shows balancing effect based on lowest voltage cell based control method for Li-ion batteries. Battery B1 is the lowest voltage cell in this case so the energy stored in B2 and B3 is transferred to battery B1. As time goes on, VB3 reaches VB2. After this time, the energy of battery B2 is transferred to battery B1 and B3. All the battery voltages are almost the same at the last time. The balancing effect for average voltage control method for Li-ion batteries is shown in Fig.12.

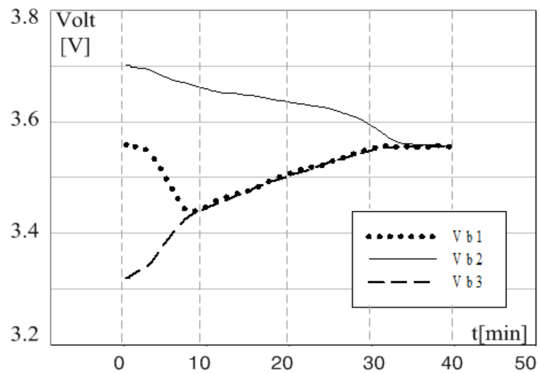

Fig. 11 Balancing effect based on lowest voltage cell based control for Li-ion batteries

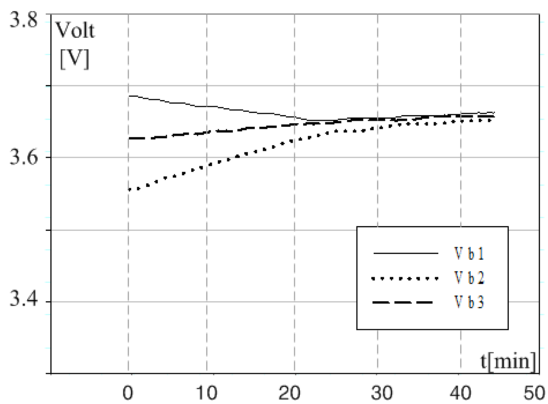

Fig. 12 Balancing effect based on average voltage control for Li-ion batteries

4. Conclusions

The series connected battery cells are mainly used in high voltage storage application. However parameter inequality of each battery cell makes some critical problems. In this paper, a new battery cell balancing circuit is proposed. Proposed circuit offers easy control and fast equalization time. Moreover the circuit can be used in practical applications because the circuit has high modularity and can operate during charging/discharging cycle. The principle of proposed circuit is explained using computer simulation. And by the experiment, the usefulness of the proposed circuit is verified.

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References

1. L. R. Chen, C. M. Young, N. Y. Chu, C. C. Li, Y. C. Hsiao, 2012, “A battery balancing seven level inverter”, IEEE ICSET 2012, Nepal, pp. 211-216.
2. D. B. W. Abeywardana, M. A. M. Manaz, M. G. C. P. Mediwaththe, K. M. Liyanage, 2012, “Improved Shared Transformer Cell balancing of Li-ion Batteries”, Industrial and Information Systems (ICIIS), pp. 1-6.
3. M. Y. Kim, C. H. Kim, J. H. Kim, G. W. Moon, 2012, “A modularized BMS with an Active Cell Balancing Circuit for Lithium-ion Batteries in V2G System”, Vehicle Power and Propulsion Conference (VPPC), pp. 401-406.
4. Z. G. Kong, C. B. Zhu, R. G. Lu, S. K. Cheng, 2006, “Comparison and Evaluation of Charge Equalization Technique for Series Connected Batteries”, Power Electronics Specialists Conference, 2006. PESC '06, pp. 1-6.
5. X. Zhang, P. Liu, D. Wang, 2011, “The Design and Implementation of Smart Battery Management System Balance Technology”, Journal of Convergence Information Technology, Vol. 6, pp. 108-116.
6. L. Simon, P. Volker, J. Holden, W. Li, X. He, 2010, “Overview of Super capacitor Voltage Equalisation Circuits for an Electric Vehicle Charging Application”, Vehicle Power and Propulsion Conference (VPPC), pp. 1-7.
7. T. K. Jeong and S. K. Jeong, 2011, "Comparison Analysis on Efficiency and Operating Characteristic between Induction and BLDC Motor according to the Load Variation Based on Battery Power Source for Electric Propulsion System of Small Ships", Journal of KSPSE, pp. 78-83.