A High Efficiency DC/AC Inverter for Energy Balancing of Battery Modules

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***Abstract*—Battery energy balancing is crucial in large scale battery energy storage applications. By power electronic circuits, energy transfers from one battery to another with little loss. This paper introduces a DC/AC inverter for battery modules balancing. The DC port is connected to positive and negative electrodes of a battery module and the AC port is connected to that of another inverter. Therefore, more than two inverters can be joined together to the AC bus for battery balancing at the same time. Among all of the inverters, one is a master and the others are slaves, for that is convenient to keep all the inverters work at the same frequency and phase. Energy transfers from the batteries with high voltages to those with low voltages. The currents are auto-adjusted according to the voltage differences. The experiment results showed that the balance current is up to 10A and the power efficiency of the DC/AC inverter achieved higher than 96%.**

Keywords—energy balancing; battery module; DC/AC inverter; AC bus.

I. INTRODUCTION

In a battery energy storage system (BESS), a battery pack consists of serial-connected battery modules, and one of which contains dozens of cells to achieve high voltage and large capacity. The limit of technical level in battery manufacture causes cell capacity variance and internal impedance difference. When battery is charging or discharging, not all cells perform identically, such as self-discharge rate, aging rate [1], [2]. Generally, it is impossible to keep all the cells the same in characteristics, including capacity, state-of-charge (SOC), voltage and internal resistance [3]. In serial-connected battery applications, the capacity of battery modules or battery packs is limited to the minimum capacity of all the cells. If cells differ in SOC, charging is limited by the highest cell SOC and discharging is the limited by the lowest one. For safety reasons, cell voltage must keep within a fixed voltage range. When difference exists in cell voltages, the battery modules or battery packs are limited in a smaller voltage ranges than those with cells in a same voltage. Internal resistance difference is a source that enlarges voltage disparity as the charge/discharge current increases.

Battery imbalance makes the battery packs charge quickly to full-charge state when actually only a few cells rise to the upper-limited voltage and discharge quickly to empty-discharge state when actually only a few cells decline to the lower-limited voltage. It looks like that the battery capacity decreases sharply. The application of multi-cells energy storage has demanded the need for battery balancing methods. In a BESS, battery balance falls into three categories, cell balance, module balance and pack balance. Most balance methods are developed for cell balance while little attention is paid to module balance. The pack balance is implemented by the power converter connected to the battery back. Most of cell balance methods, especially those for lithium-ion battery, are active [4]-[11]. They use external circuits to transport charge among cells or dissipate energy. In cell balance circuits, the cell voltage is so low that a large proportion of energy consumes in switches. Meanwhile, the cost to improve the balance efficiency is high because the number of cells is large in a BESS. For module balance, the voltage is higher and low efficient balance circuits may lead to large energy dissipation. Compared to the cost, the efficiency of module balance method is more important.

Based on the major components in balance circuits, there are three major classifications of active balancing method. They are resistor method, inductor/capacitor method [4]-[8] and transformer method [9]-[11]. The resistor method wastes the whole charge by resistors so that it is not suitable for module balance. The inductor/capacitor method transfers the charge from one cell to another by inductors or capacitors. This method is low-cost, but hard to reach a large balance current and a high efficiency. The transformer method takes a multiple transformer or several single transformers to connect cells. The topology is similar to forward converter or flyback converter. This method is convenient for cells extension and easy to control. It is expensive and inefficient for cell balance, but not for module balance. Paper [12] presents a review and comparisons between different balancing topologies for battery string based on MATLAB/Simulink simulation.

This paper introduces a DC/AC inverter for battery module balance. The module consists of $LiFePO_4$ cells with large capacity and the module voltage is up to 48V. Firstly, comparison of different balance methods for battery module balance is made. Secondly, the topology of the balance circuit is discussed, so is the implement of multi-module balance. At last, experiment results showed how the balance devices worked on the $LiFePO_4$ battery modules.

II. BATTERY BALANCE METHODS

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Two categories of battery module balance methods are discussed in this section. One is inductor/capacitor method and the other is transformer method.

A. Inductor method

Because energy can be temporarily stored in an inductor, the inductor is used as media for charge transfer from one cell to another. Generally, the two cells in balance are neighbor. One example is the Buck-Boost circuit [4], [5], as shown in Fig.1. By controlling the pair of MOSFETs connected to two adjacent batteries, energy transfers from one cell to the next one. By adjusting the duty cycle of the PWM for controlling the switches, the current direction changes, and so does the current value.

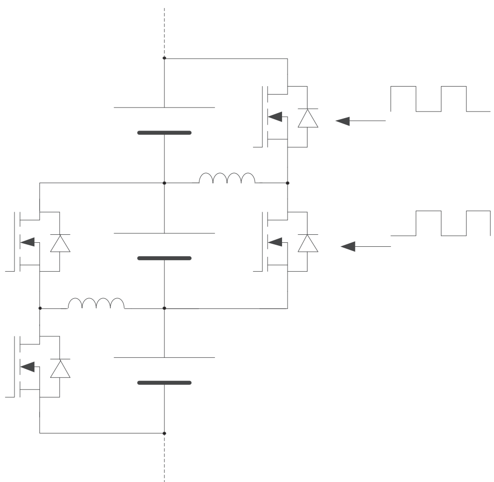

Fig. 1. Buck-Boost circuit for battery balance

If the energy transfer efficiency of one buck-boost circuit is η, which means two neighboring batteries balance efficiency is η, the balance efficiency between the top battery and the bottom one is as followed:

$$\tilde{\eta}(1,n) = \eta^{n-1} \tag{1}$$

As the battery number increases, the balance efficiency decreases. This method is not applicable in numerous battery modules situation.

B. Capacitor method

The capacitor is another energy storage device. Capacitor is usually connected to batteries by switches to transfer charge. It is the so-called switched capacitor [6]. One topology is similar to the inductor balance example, which can only transfer energy from one battery to the next, just as shown in Fig.2 (a). In this circuit, all switches connect to the upper points and alter to the under points at a synchronous frequency to make all the battery balance in voltage. The control is simple but the efficiency is low. If there are *n* cells in module, *n*-1 capacitors are demanded. Another circuit only takes one capacitor no matter how many cells are in modules, as shown in Fig.2 (b). The capacitor takes turns connecting the cell with highest voltage and the one with lowest voltage. The disadvantage of this circuit is that it cannot balance three or more batteries at the same time.

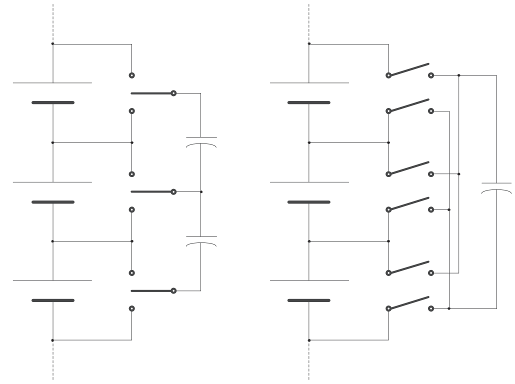

Fig. 2. Switched capacitors for battery balance, (a) multi capacitors, (b) single capacitor

Some balance circuits contain both inductors and capacitors, such as the Cuk circuit [7], [8]. The balancing principle is just as that of inductor method or capacitor method.

C. Transformer method

One kind of transformer methods is cell-to-pack or pack-to-cell topology [9-11], by which the energy transfers between cells and the pack/module, as shown in Fig.3.

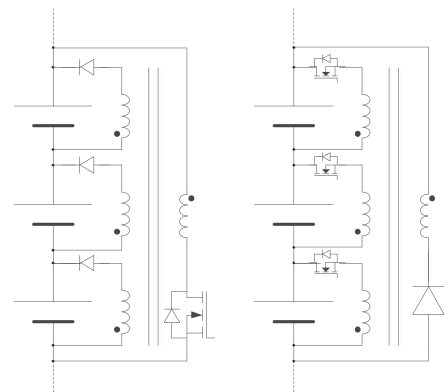

Fig. 3. Transformer methods for battery balance, (a) pack-to-cell topology, (b) cell-to-pack topology

In both of the circuits, a multi-winding transformer is needed. In some research, several single transformers are used in place of the multi-winding transformer. Based on the single transformers for isolations, a two-port energy converter is a good choice for battery balance. With a DC/DC converter, one port connects to a cell and the other port connects to another cell or the pack so that energy can shuttle between two cells or cell-to-pack [13]-[15]. For three or more batteries balancing simultaneously, more converters are required and the connection must change. Only one port of the converter connects to a battery and the other port connects to a common bus, as shown in Fig.4. Charge directly flows out from the higher voltage battery to the lower voltage battery. What's more, this method is suitable for modular design. If one more battery is added, one more DC/DC converter connects to the DC bus to join in balance with other batteries. The DC/DC converter is one of the best balance methods.

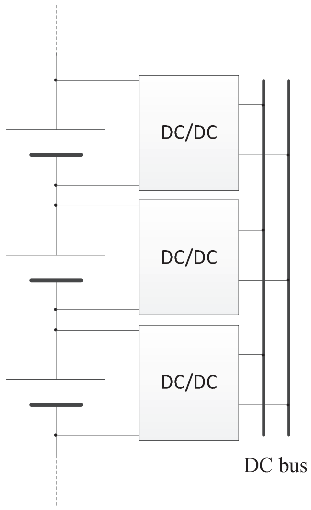

Fig. 4. DC/DC converter for battery balance

III. PROPOSED DC/AC BALANCER

A. Circuit Topology

One disadvantage of the DC/DC converter is low energy transduction efficiency, which is a limited factor for battery module balance. Usually, a DC/DC converter contains a few parts, as shown in Fig.5. There are two bi-directional DC/AC inverters and an isolation transformer. Long chain makes low efficiency so that simplifying the DC/DC converter is necessary.

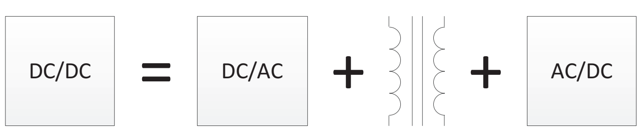

Fig. 5. Structure of the DC/DC converter

According to the structure of the DC/DC converter, an isolated DC/AC circuit for battery module balance has been proposed. The converter consists of a bi-directional DC/AC inverter and an isolation transformer. A battery module connects to the DC port of the DC/AC inverter and all the devices connect to a common AC bus, as shown in Fig.6.

The balancer is distributed, that is one balancer for one battery module. The main circuit is an isolated push-pull DC/AC inverter and energy transfers among all battery modules through the AC bus.

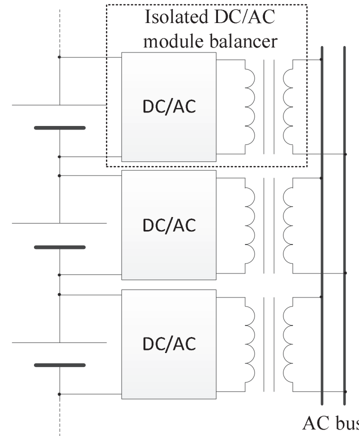

Fig. 6. Topology of the DC/AC balancer

B. Operating Principle

The schematic diagram of DC/AC balancer is shown in Fig.7. The two MOSFETs are alternately switched on and off to reverse the current into the transformer. The charge is drawn from the battery during both halves of the switching cycle. The push-pull converter has steady input current, with little noise on the battery and high efficiency in high power application.

The transformer is designed for high-frequency operation to reduce energy loss.

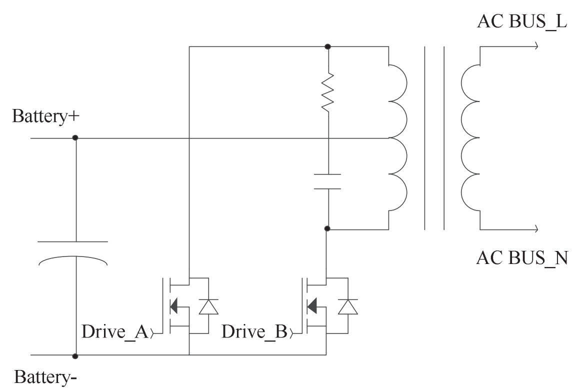

Fig. 7. Schematic diagram of DC/AC balancer

When two or more balancers connecting together to the AC bus, the AC voltage outputs of all balancers must keep synchronously in frequency and phase. To meet the synchronization requirement, communication among the balancers is needed. The amplitude difference of the voltages leads to circulating current, which is the balance current.

C. Current Calculation

Fig.8 shows the equivalent circuit for three battery modules balancing. The impedance Z consists of battery internal resistance, switch impedance, transformer inductance and other components in the balancer. u is square wave voltage source and its amplitude equals the battery voltage.

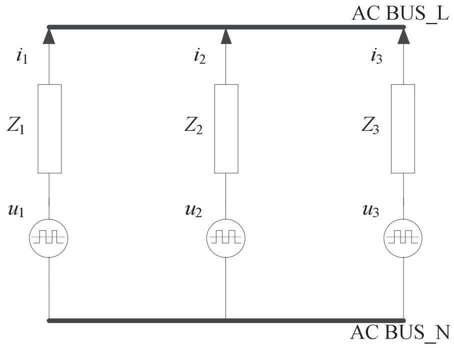

Fig. 8. Equivalent circuit for three modules balance

Based on Kirchhoff's current law, the input current at the AC BUS_L is equal to the output current, that is:

$$i_1 + i_2 + i_3 = 0 \tag{2}$$

According to the superposition theorem, output current of each balance module is:

$$\begin{cases} i_1 = \dfrac{u_1}{Z_1 + Z_2 // Z_3} - \dfrac{u_2 \cdot \dfrac{Z_3}{Z_2 + Z_3} + u_3 \cdot \dfrac{Z_2}{Z_2 + Z_3}}{Z_1 + Z_2 // Z_3} \\ i_2 = \dfrac{u_2}{Z_2 + Z_3 // Z_1} - \dfrac{u_3 \cdot \dfrac{Z_1}{Z_3 + Z_1} + u_1 \cdot \dfrac{Z_3}{Z_3 + Z_1}}{Z_2 + Z_3 // Z_1} \\ i_3 = \dfrac{u_3}{Z_3 + Z_1 // Z_2} - \dfrac{u_1 \cdot \dfrac{Z_2}{Z_1 + Z_2} + u_2 \cdot \dfrac{Z_1}{Z_1 + Z_2}}{Z_3 + Z_1 // Z_2} \end{cases} \tag{3}$$

Assume that there are n balancers and all the balancers keep the same impedance ($Z = Z_1 = Z_2 = \ldots = Z_n$), then the output current of balancer k to the AC bus is:

$$\begin{aligned} i_k &= \frac{u_k}{Z + \dfrac{Z}{n-1}} - \frac{\sum_{j=1, j\neq k}^{n} u_j \cdot \dfrac{1}{n-1}}{Z + \dfrac{Z}{n-1}} \\ &= \frac{(n-1)\cdot u_k - \sum_{j=1, j\neq k}^{n} u_j}{Z} = \frac{u_k - \dfrac{1}{n}\cdot \sum_{j=1}^{n} u_j}{Z} \end{aligned} \tag{4}$$

The formula shows that if the module voltage is higher than the average value of all modules, the battery module outputs balancing current and if not, the battery module inputs balance current. Furthermore, larger difference to the average module voltage and/or lower impedance makes larger balancing current. To improve the balance efficiency, the balancing current should be large and the impedance Z should be low.

IV. Experiment Results

To validate the proposed battery module balance method, several isolated AC/DC balance devices have been produced and experiments on $LiFePO_4$ battery modules have been conducted. The nominal voltage of the battery module is 48V and the capacity is 180Ah. Table I lists the main parameters of the AC/DC balancer.

TABLE I. The Main Parameters of The Proposed Balancer

Parameter	Value
Nominal Voltage/V	48
Voltage Range/V	37~60
Nominal Current/A	5
Maximum Current/A	10
AC Frequency/kHz	40
Balancer Efficiency/%	>96
Battery Module Number	Unlimited

The test bench is shown as follows:

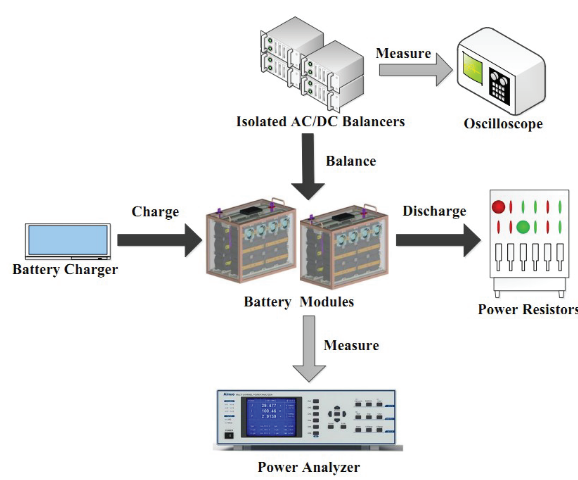

Fig. 9. Test bench for battery module balance

A. Two Modules Balance

Two battery modules have been taken into balance experiment. One charged to a relatively high voltage and the other discharged to a low voltage so that voltage difference is distinct. An oscilloscope was used to measure the voltages on the MOSFETs of the two balancers and the output/input current to the AC bus.

One balancer is master and the other is slave. The PWM for controlling the MOSFETs were generated by the master device. Because all the devices must keep synchronous in AC frequency and phase, the PWM signal were delivered to the slave device by communication lines. Fig.10 shows the waveforms of MOSFET drain-source voltage (V_{ds}) and AC bus current. CH1 is V_{ds} of the master device, CH2 is the PWM to drive MOSFET, CH3 is V_{ds} of the slave device and CH4 is the secondary winding current of the master device transformer.

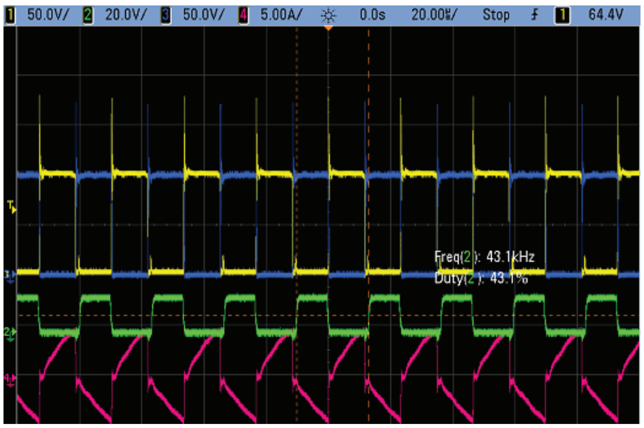

Fig. 10. MOSFET drain-source voltage and AC bus current

The main purpose of this experiment is to obtain the relation between the module voltage difference and the balance current. Meanwhile, track the efficiency curve versus the changing current. The experiment result is shown in Table II and Fig.11.

It shows that larger voltage difference causes large balance current and the relationship is approximately linear. The balance efficiency is higher than 96% as the current changes around 3A to 10A.

TABLE II. RELATIONSHIP BETWEEN VOLTAGE DIFFERENCE AND BALANCE CURRENT

Balance Current/A	Module A		Module B	
	Voltage/V	Current/A	Voltage/V	Current/A
3	49.123	3.011	48.528	2.811
3.5	49.097	3.502	48.382	3.318
4	49.063	3.999	48.253	3.813
4.5	49.026	4.498	48.129	4.311
5	48.988	5.002	48.004	4.813
5.5	48.950	5.499	47.876	5.313
6	48.905	5.962	47.749	5.775
6.5	48.923	6.515	47.689	6.274
7	48.960	7.023	47.624	6.778
7.5	48.988	7.498	47.538	7.310
8	49.585	8.003	47.985	7.810
8.5	49.633	8.502	47.94	8.278
9	49.632	9.010	47.872	8.764
10	50.469	9.905	48.534	9.658

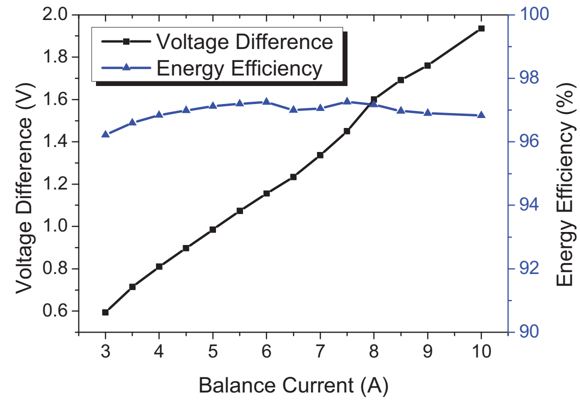

Fig. 11. Voltage difference and balancer energy efficiency at different balance currents

B. Four Modules Balance

Two more battery modules added in the balance experiment. Two situations of imbalance have been analyzed. The first one was that one battery module voltage was high and another was lower. On the balance process, the high module voltage decreased slowly while the low voltage increased. As shown in Fig.12, among the three low module voltages, the lowest one increased sharply. However, the other two remained fairly unchanged. As time went on, the voltage changed more and more slowly. After balancing for 2 hours, the voltage difference was very small and the balance current was almost zero. A longer time was taken to achieve a smaller voltage difference by a low efficiency balancing process, which was not advisable.

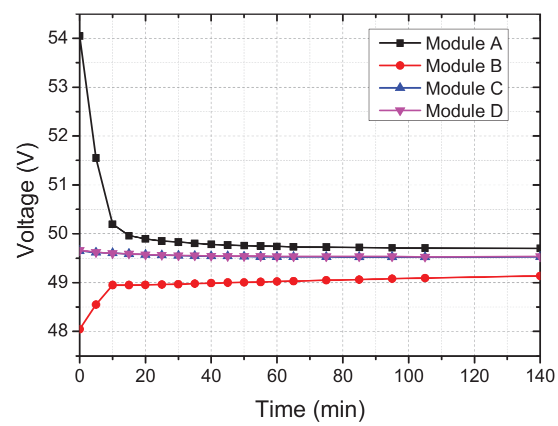

Fig. 12. Voltage curves of different modules during balancing for the first imbalance situation

The second situation was that one module voltage is lower than the average value. It was a common imbalance which was usually caused by battery self-discharge rate increasing or acceleration of aging. The trend of voltages changing was shown in Fig.13. During the balancing time, the lowest voltage increased quickly when the other three voltages slowly decreased. The reason for the different voltage changing rates was that the charge transferring to the low voltage module was supplied by the other three modules averagely. Therefore, the output charge from one of the three modules is quite small.

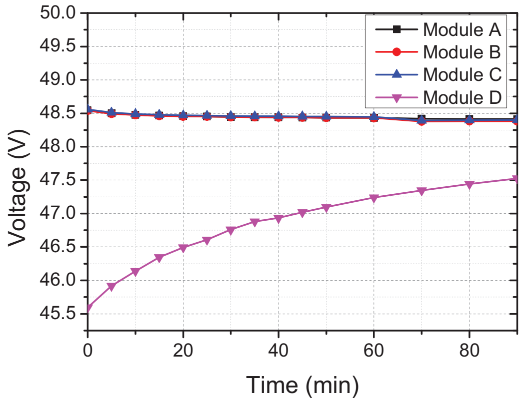

Fig. 13. Voltage curves of different modules during balancing for the second imbalance situation

V. Conclusion

To cope with the battery module imbalance, which leads to reduction of available capacity for the BESS, the isolated DC/AC inverter of $LiFePO_4$ battery modules is proposed. The short chain and simple structure of the inverter make it high-efficiency in energy transfer. The circuit topology of AC bus is suitable for modulation and extension. With balance inverters, any number of battery modules can be connected together for balancing. Energy transfers from one module to another directly and the balance current is auto-adjusted according to the voltage differences of the balancing battery modules. The experiments verify that the AC/DC balancers can balance two or more battery modules synchronously with current up to 10A and efficiency higher than 96%

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