Two-stage energy storage equalization system for lithium-ion battery pack

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Abstract. How to raise the efficiency of energy storage and maximize storage capacity is a core problem in current energy storage management. For that, two-stage energy storage equalization system which contains two-stage equalization topology and control strategy based on a symmetric multi-winding transformer and DC-DC (direct current-direct current) converter is proposed with bidirectional active equalization theory, in order to realize the objectives of consistent lithium-ion battery packs voltages and cells voltages inside packs by using a method of the Range. Modeling analysis demonstrates that the voltage dispersion of lithium-ion battery packs and cells inside packs can be kept within 2 percent during charging and discharging. Equalization time was 0.5 ms, which shortened equalization time of 33.3 percent compared with DC-DC converter. Therefore, the proposed two-stage lithium-ion battery equalization system can achieve maximum storage capacity between lithium-ion battery packs and cells inside packs, meanwhile efficiency of energy storage is significantly improved.

1. Introduction

Energy storage technology is a crucial part of six steps containing adoption- generate power-transmission- distribution- utilization of power- energy storage in power grid operation, implementing effectively management of supply side, peak shaving and load shifting, which can efficiently utilize power equipment and reduce the power cost. The development of lithium-ion battery for large-scale energy storage systems enable this technology to address high energy density, long cycle life, high standard voltage, and other factors, which are in line with the current green requirements of sustainable development. Energy storage technology is available for large-scale applications, such as electric vehicle, light railway vehicle, smart building, etc [1-3]. The success of these applications of energy storage will depend on how to maximize storage energy and raise the efficiency of stored energy [4], therefore, energy storage equalization technology is a key expectation at present.

Many scholars have made in-depth research and design for energy storage equalization topology of the Lithium-ion battery at home and abroad. Two main categories are as follows: dissipative equalization and non-dissipative equalization. The dissipative equalization refers to dissipate redundant energy in the form of heat through the parallel resistance on both ends of the battery, and it is with advantages of simplicity, speediness, high reliability, but low energy efficiency and thermal management issues [5,6]. Non-dissipative equalization is that energy is transferred between the cells through the inductor or capacitor, which has various circuit forms: Ye Y M [7], Bruen T [8] and their fellows have proposed the combination usage of switch and capacitor to achieve energy transfer.
between the cells. Guo X W [9] used energy storage inductors as energy storage devices, the redundant energy of cells are transferred to the necessarily balanced cells, in order to achieve the consistent battery energy. Zhu H [10], etc. took into account the characteristics of reliable passive equalization and active equalization without energy loss, and proposed the balanced solution of combination of passive equalization and active equalization under the low cost. Gui Y [11] and Park H S [12] designed a balanced circuit topology based on fly-back transformer, redundant energy among cells is transferred through the conversion between electric energy and magnetic energy. All these research results about the equalization topology are accomplished under the conditions of less cells, however, large-scale energy storage equalization systems often need to load thousands of series cells, which can bring quite complex control strategies in the course of energy transfer [13].

From what has been discussed above, there are obvious advantages of hierarchical equalization for simplifying the control process based on large scale cells. Therefore, this paper proposes two-stage energy storage equalization system which contains two-stage equalization topology and control strategy based on a symmetric multi-winding transformer and DC-DC converter, in order to realize the objectives of consistent lithium-ion battery packs voltages and cells voltages by using a method of the Range. Equalization effect of the two-stage energy storage equalization system will be verified compared with DC-DC converter finally.

2. Design of energy storage equalization system

2.1. Structure of energy storage equalization system

Application pattern of energy storage technology for the lithium-ion battery pack in the field of distributed generation of micro-grid is shown in figure 1, where energy storage system based lithium-ion battery pack is an imperative part.

![Figure 1. Application pattern of energy storage technology for the lithium-ion battery pack in the micro-grid.](image)

The energy storage equalization system proposed in this paper consists of lithium-ion battery pack, first-stage equalization circuit, second-stage equalization circuit, voltage acquisition module and controller, as shown in figure 2. The whole lithium-ion battery pack is composed of a number of single cells, of which four single cells form a lithium-ion battery pack. The first-stage equalization circuit between the lithium-ion battery packs is used for energy equalization of lithium-ion battery packs; The second-stage equalization circuit between cells in the pack acts as energy equalization of cells in the
pack; The voltage acquisition module collects the voltages of the single cells in real time and transmits the voltage signals to the controller; The controller calculates and processes the voltage signals collected by the voltage acquisition module. If it is judged that the energy between the lithium-ion battery packs and the cells in the pack is not consistent, the controller outputs the control signals according to the two-stage energy storage equalization control strategy, the energy equalization is achieved between the lithium-ion battery packs and the cells in the pack.

2.2. The first-stage equalization circuit

The first-stage equalization circuit is characterized by a symmetrical multi-winding transformer possessing an iron core, a primary winding and three secondary windings. Each secondary winding connects to two ends of lithium battery pack, a MOSFET (metal-oxide semiconductor field-effect transistor) Sp and a filter inductor Lf correspondingly, and the number of turns of winding ratio of 1: 1: 1 symmetrical design. The circuit has the advantages of accurate equalization, high efficiency, and low magnetic loss. The equalization circuit schematic diagram is shown in figure 3.

Course of pack1 energy release: symmetrical multi-winding transformer uses for energy equalization of the lithium-ion battery packs, if the controller judges minimum voltage lithium-ion battery pack3 by processing voltage signals collected and meet the condition of $V_{pack1} - V_{pack3} > \Delta$, where the difference of lithium-ion battery pack1 voltage and lithium-ion battery pack3 voltage is greater than the equalization threshold $\Delta$, the lithium-ion battery pack1 externally releases energy to maintain the energy equalization between the lithium-ion battery packs, then the MOSFET Sp1 is on.

During the Sp1 switched on, the current flowing through Sp1 is given by:

$$I_{sp(t)} = \frac{V_{pack1}}{T_{pl}} - I_s, \quad (0 \leq t \leq t_{on})$$  \hspace{1cm} (1)

When $t = t_{on}$, the current of secondary winding $T_{pl}$ reaches the maximum:

$$I_{sp_{max}} = \frac{V_{pack1}}{T_{pl}} I_{on}$$  \hspace{1cm} (2)

Transformer secondary winding $T_{pl}$ energy stored is marked as $W_{pl}$:

$$W_{pl} = \frac{V_{pack1} I_{sp_{max}}}{2} t_{on}$$  \hspace{1cm} (3)

Where $T_{pl}$ is the secondary winding inductance, and $t$ is the time of secondary winding $T_{pl}$ storage energy.

Course of pack3 energy storage: When the lithium-ion battery packs voltages meet the condition of $V_{pack1} - V_{pack3} > \Delta$, the lithium-ion battery pack3 needs to receive energy from other lithium-ion battery pack to keep the system balanced, then commutating diode conducts in the MOSFET Sp3, and secondary winding $T_{pl}$ generates current. $T_{pl}$ winding current peak is:
The energy absorbed by the lithium-ion battery pack3 is:

\[ W_{p3} = \frac{V_{\text{pack1}} + V_{\text{pack2}} + V_{\text{pack3}}}{2} I_{\text{tpmax}} \left( t_s - t_{on} \right) = \frac{(V_{\text{pack1}} + V_{\text{pack2}} + V_{\text{pack3}})^2}{2T_{p3}} n^2 \left( t_s - t_{on} \right)^2 \]  

(5)

Where \( n \) is the winding turns, \( T_{p3} \) is the secondary winding inductance, \( t_s - t_{on} \) is the time of secondary winding \( T_{p3} \) energy released.

2.3. The second-stage equalization circuit

The second-stage equalization circuit is characterized by a DC-DC converter containing a storage energy inductor \( L \), a MOSFET \( S \) and a commutating diode \( D \). The equalization circuit has a complex energy storage equalization control strategy for large numbers of single cells, but with the advantage of modularity. Equalization schematic diagram is shown in figure 4.

**Figure 4.** Schematic diagram of the second-stage equalization circuit. (a) B1 release energy, (b) B2, B3, B4 storage energy, (c) B2 release energy and (d) B1 storage energy.

DC-DC converter uses for energy equalization of cells in the pack, the principle of specific equalization shown in figure 4. Taking the lithium-ion battery pack1 for example, voltage signals collected by the data acquisition module from the cells are transmitted to the controller, which judges the state of cells according to voltage signals. If the minimum cell voltage meets the condition of \( V_{B1} - V_{\text{bmin}} > \Phi \), where \( \Phi \) is equalization threshold of cells in the pack, that is, the difference of B1 voltage and the minimum cell voltage is greater than the equalization threshold, the MOSFET S1 is on, and then B1 releases energy that is transferred to inductor \( L_1 \), as shown in figure 4(a).

Voltage transferred by B1 can be expressed as [15,16]:

\[ \Delta V_{B1} = L_1 \frac{di}{dt}, \quad \begin{cases} \frac{di}{dt} = I_1 \\ dt = DT \end{cases} \]  

(6)

The peak current of inductor \( L_1 \), \( I_1 \), is gave by:

\[ I_1 = \frac{\Delta V_{B1} DT}{L_1} \]  

(7)

The energy released by B1 is deduced from the formula \( W = UI_t \):
Where $L_1$ is the energy storage inductance, $T$ is the circuit work cycle, $D$ is MOSFET duty ratio.

As shown in figure 4(b), if the any voltage of B12, B13, B14 is less than the equalization threshold, the energy stored in inductor $L_1$ is transferred to B2, B3 and B4 during the S1 switch-off period. In order to release completely the energy stored in the inductor and avoid saturation hysteresis, DC-DC converter operates under the condition of the DCM (discontinuous current mode). As shown in figure 4(c), if the controller judges that the voltage difference between the cell B2 and the minimum voltage cell is larger than the equalization threshold, the MOSFET S2 is turned on, then B2 releases energy in the period of storing energy of $L_2$. As shown in figure 4(d), if B1 voltage is less than the equalization threshold, B1 stores energy in the period of releasing energy of $L_2$. If the controller determines that the cell B3 voltage meets the equalization condition, the MOSFET S3 is turned on, then B3 releases energy in the period of storing energy of $L_3$; if any voltage of B1, B2 is less than the equalization threshold, $L_3$ releases energy towards B1, B2. If the controller determines that the cell B4 voltage meets the equalization condition, the MOSFET S4 is turned on, then B4 releases energy in the period of storing energy of $L_4$; if any voltage of B1, B2, B3 is smaller than the equalization threshold, $L_4$ releases energy to B1, B2, B3. When all the cells in the lithium-ion battery pack1 are equalized, the energy released by the cells during each switching cycle is equal to the energy absorbed from the other cells.

3. Equalization control strategy

Two-stage energy storage equalization control strategy for lithium-ion battery pack is divided into two stages, the specific process shown in figure 5.

**Figure 5.** Flow diagram of two-stage energy storage equalization control strategy.

Phase 1: Firstly, initializing the equalization system, and then sorting the lithium-ion battery packs voltages collected by the voltage acquisition module. If the Range between the maximum lithium-ion battery pack voltage and the minimum lithium-ion battery pack voltage is more than 0.01 V, the first-stage equalization is activated. The controller outputs pulse width signal to drive the
corresponding MOSFET Spi, performing energy transfer for lithium-ion battery packs based on symmetrical multi-winding transformer. If the Dispersion is greater than 2%, the system will continue the energy equalization between the lithium-ion battery packs; if the Dispersion is less than 2%, the system will complete the energy equalization for lithium-ion battery packs.

Define the Dispersion $\delta$:

$$\delta = \sqrt{\frac{\sum_{i=1}^{n} (V_i - \bar{V})^2}{n - 1}}, \quad \bar{V} = \frac{1}{n} \sum_{i=1}^{n} V_i$$  \(9\)

where $\bar{V}$ is the average value, $V_i$ is voltage of lithium-ion battery pack or cell, and $n$ is the number of lithium-ion battery pack or cell.

Phase 2: After finishing the first-stage energy storage equalization for lithium-ion battery packs, the voltage acquisition module collects the single cells voltage, which are sorted in the meantime. If the Range of maximum cell voltage and the minimum cell voltage is greater than 0.005 V, the second-stage equalization is activated, the controller outputs pulse width signal to drive the corresponding MOSFET Si, equalizing energy for cells based on DC-DC converter. If the Dispersion is greater than 2%, the system will continue the energy equalization between the cells; if the Dispersion is less than 2%, the system will complete the energy equalization for the cells in the pack.

4. System simulation and results analysis

4.1. Establish of simulation model

In order to verify the feasibility and effectiveness of the two-stage energy storage equalization system designed in this paper, lithium-ion battery model and equalized topology circuit model are set up in the simulation environment of MATLAB / SIMULINK \[17,18\], where Bi, packi are cells and battery pack modules respectively, Vi/ Ci collects battery voltages or current in real time on behalf of voltage/current acquisition modules, Si represents MOSFET switch that are used for controlling the state of circuit model, Strategy is the same as controller which processes the voltage signals collected by Vi. If it is judged that the energy between the lithium-ion battery packs and the cells in the pack is not consistent, the controller outputs the control signals according to control strategy. In order to simulate energy release and energy storage characteristics and reduce the non-linear characteristics of the lithium-ion battery, RC equivalent circuit are selected, where $R$ is the internal resistance of the lithium-ion battery, the capacitor $C$ is the open circuit voltage of the lithium-ion battery. The different capacitance values in the circuit simulate the energy differences of the cells in practice.

The first-stage energy storage equalization circuit model is built in the simulation environment as shown in figure 6. The three lithium-ion battery pack models are composed of four cells in series respectively, the initial voltages of which are 13.6 V, 13.4 V, and 13.2 V, respectively. Symmetrical multi-winding transformer is characterized by rated power, frequency, winding leakage inductance, transformer inductance, filter inductance with 24 W, 20 kHz, 20.8 $\mu$H, 30 H, and 20.7 $\mu$H, correspondingly, regardless of core saturation. The simulation step length is set to ode23tb, and powergui is continuous. The first-stage energy storage equalization circuit model is simulated in the process of energy storage and energy release by using a controlled constant current source and a 100 $\Omega$ resistive load for the lithium-ion battery packs respectively.
Figure 6. The first-stage equalization circuit model.

Figure 7. The second-stage equalization circuit model.

The second-stage energy storage equalization circuit model is built in the simulation environment as shown in figure 7. The lithium-ion battery models are composed of four cells in series in the pack1, the initial voltages of which are 3.4 V, 3.3 V, 3.0 V and 2.9 V. The energy storage inductance are 11.1 μH, 16.7 μH, 12.5 μH, and 11.1 μH correspondingly, meanwhile, the parasitic resistances of MOSFET and diode are set as the default value. The simulation step length is set to ode23tb and powergui is continuous. The second-stage energy storage equalization circuit model is simulated in the process of energy storage and energy release by using a controlled constant current source and a 100 Ω resistive load for the cells in the pack1 respectively.

4.2. Analysis of simulation results

The voltage variation curves for the lithium-ion battery packs and the cells in the pack1 are obtained about the simulation results, as shown from figure 8 to figure 12.

As shown in figure 8, voltage curves of the 12 cells which contain B1, B2, B3...B12 are acquired based on DC-DC converter in the process of energy storage, where voltage fluctuations are fairly
obvious. Voltage values of 12 cells have achieved a consistent state simultaneously after equalization time of 0.75 ms.

**Figure 8.** Voltage curves of the 12 cells based DC-DC converter.

**Figure 9.** Voltage curves of three battery packs based the first-stage equalization in the period of energy storage.

**Figure 10.** Voltage curves of three battery packs based the first-stage equalization in the period of energy release.

**Figure 11.** Voltage curves of 4 cells in the pack1 based the second-stage equalization in the period of energy storage.

**Figure 12.** Voltage curves of 4 cells in the pack1 based the second-stage equalization in the period of energy release.
As shown in figures 9 and 10, the voltage differences between the lithium-ion battery pack1, pack2, and pack3 have been eliminated within equalization time of 0.1 ms, and voltage curves change smoothly. As shown in table 1, the Dispersion of the lithium-ion battery packs is reduced from 20% to 0.07% and 0.47% respectively in the process of energy storage and energy release, and the Range of voltages is also kept within 10mV, therefore, the two parameters of dispersion and range reaches the evaluation index.

Table 1. The state of lithium-ion battery packs and cells in the pack1.

| State                | The lithium-ion battery packs | Cells in the pack1 |
|----------------------|-------------------------------|--------------------|
|                      | Range/V  Dispersion /%        | Range/V  Dispersion /% |
| Initial state        | 0.4000  20.00                 | 0.5000  23.00      |
| After energy storage | 0.0049  0.07                  | 0.0046  0.22       |
| After energy release | 0.0094  0.47                  | 0.0051  0.27       |

As shown in figures 11 and 12, volumes of four cells in the pack1 are stored energy fully when equalization time is 0.5 ms. Voltage fluctuations are smaller than that 12 cells based on DC-DC converter shown in figure 8, meanwhile, equalization time is shorter significantly. As shown in table 1, the Dispersion of the cells in the pack 1 is reduced from 23% to 0.22% and 0.27% respectively in the process of energy storage and energy release, and the Range of voltages is also maintained at 5 mV, therefore, the evaluation indexes of dispersion and range are met totally.

From what has been analyzed above, the two-stage energy storage equalization system can achieve the equalization control objective accurately and quickly. The transfer energy for the lithium-ion battery packs and the cells in the pack is accomplished within equalization time of 0.5 ms, which eliminates the problem of voltage inconsistency and achieves maximum storage capacity.

5. Conclusion
Two-stage energy storage equalization system proposed which contains two-stage equalization topology and control strategy based on a symmetric multi-winding transformer and DC-DC converter is designed to reach consistent lithium-ion battery packs voltage and cells voltage during energy storage and energy release, and that raises the efficiency of energy storage and maximize storage capacity. The simulation results show that the method achieves an efficient and quick equalization with the Dispersion of 2% and equalization time of 0.5ms for the lithium-ion battery packs and the cells in the pack. The idea of hierarchical energy storage equalization simplifies the control process and shortens the equalization time of 33.3% compared with the DC-DC converter, therefore, the efficiency of energy storage is improved further.

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