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Design of Lithium Battery Equalization Circuit for Energy Multipath Transmission

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ABSTRACT

Aiming at the large-scale power battery series energy storage battery pack, the topology of the equalization circuit is studied to reduce the equalization loss, improve the equalization speed and efficiency, simplify the equalization system structure, save cost and save energy. A combined equalization topology based on centralized and distributed switching power supplies and capacitors is proposed, and the feasibility of equalizing the main circuit is verified in the MATLAB/SIMULINK.

1. INTRODUCTION

With the use of lithium-ion batteries and the increase in the number of battery cells in electric vehicles, more engineers are aware of the importance of equalization technology for battery stacking. The equalization circuit topology is the basis of the research on equalization technology. The purpose of the research is to find an equalization circuit with high equilibrium energy efficiency, fast equalization speed, small size, low cost and simple design structure. In recent years, the United States, Europe, Japan, Taiwan and other places have conducted a lot of research on the topology of equalization circuits, and proposed a variety of new equalization circuit structures. Jong-Won Shin [1] and Dorin V [2] studied the equalization topology based on a single-side coaxial transformer. The two ends of the battery cell can realize the transfer of energy between the battery cell and the battery pack by controlling the conduction of the MOS tube. The topology is large in size and

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complicated in structure, and the expandability is poor. Hao Xiaowei [3] of Jilin University and others studied the control of the closure of the switch. The structural feature is that the two-way transmission of energy can be realized, and the equalization current is large, and the equilibrium speed is also fast; the disadvantage is that when the monomers that need to be balanced are far apart, the energy needs to be balanced after multiple transfers to make the equilibrium time change. Kobzev G A [4] and A.C. Baughman [5] have studied the balanced topology based on switched capacitors. This structure has simple control and high efficiency, but it is easy to generate large switching current shock and loss of device life. A variety of circuit structures are also derived from these basic circuits, and combinations between different structures can derive more balanced topologies. The various balanced topologies that are still being developed indicate that the current equalization scheme is not perfect, and the ideal circuit structure has yet to be developed.

2. EQUALIZATION CIRCUIT DESIGN

2.1 Equalization Circuit Topology Design

Combining the advantages and disadvantages of the centralized and decentralized equalization circuit topology based on the switching power supply and the balanced topology of the switched capacitor, the above three equalization circuit topologies are combined to propose an equalization circuit topology (Fig. 1).

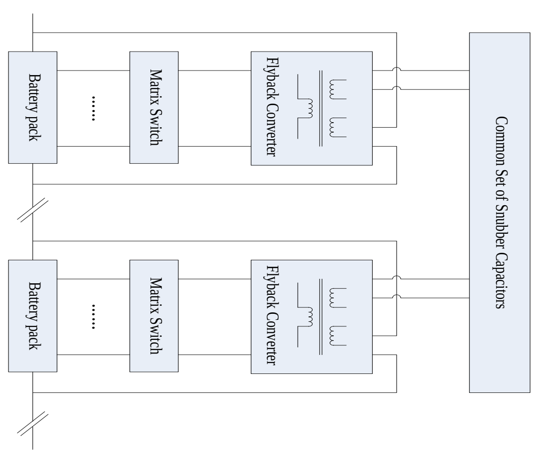


Figure 1. Combined equalization circuit topology.

The combined equalization topology is to divide one battery into several battery groups, and one battery group is composed of several battery cells, and each battery group corresponds to an equalization circuit structure based on a centralized DC/DC converter. The secondary of the multi-winding isolated flyback transformer is connected to both ends of the battery pack and a common set of snubber capacitors, and the battery cells can be charged and discharged through the matrix switch, and the energy at both ends of the transformer can be transmitted in both directions.

2.2 Design of Coaxial Multi-winding Bidirectional Flyback Converter

The core of the equalization circuit topology used in this design is a bidirectional flyback converter based on coaxial multi-winding, through which bidirectional transfer of energy is performed. The circuit structure of the isolated flyback DC/DC converter based on the transformer is shown in Fig. 2. The switch Q is a power MOS transistor controlled by PWM.

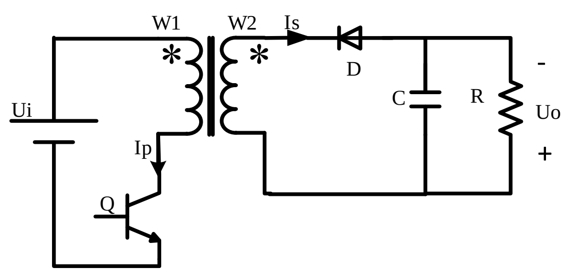
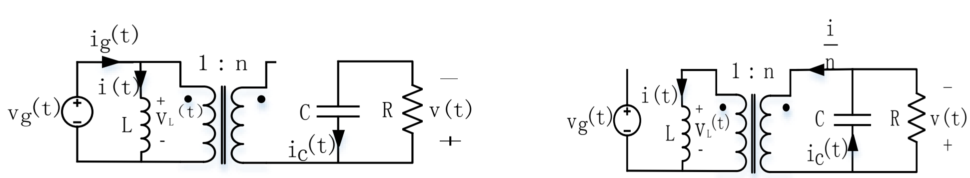


Figure 2. Flyback DC/DC converter schematic.

2.3 Modeling of Flyback DC/DC Converter

The flyback transformer can be replaced by a model in which the primary side excitation inductance is L and the ideal transformer with a turns ratio of 1:n is connected in parallel [6]. Regardless of the leakage inductance and other losses of the transformer, the equivalent circuit when the switch Q is turned on and off in the CCM mode can be obtained (Fig. 3).

Let the input voltage and current of the flyback converter be $v_g(t)$ and $i_g(t)$, the output voltage and the inductor current are $v(t)$ and $i(t)$ respectively, and the terminal voltage of the diode is $v_D(t)$. By analyzing the DC and AC small signal equivalent circuits of the flyback DC converter, the steady-state characteristics and dynamic characteristics of the converter are obtained [6].



（a）When the switch Q is turned on （b）When switch Q is turned off

Figure 3. Two working states of an ideal flyback converter.

According to the equivalent transformation, the DC equivalent circuit and the AC small signal equivalent circuit of the ideal flyback converter can be obtained, as shown in Fig. 4 and Fig. 5.

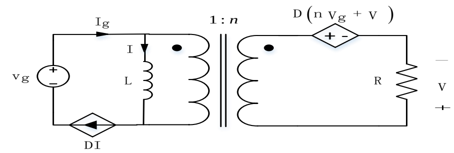


Figure 4. DC equivalent circuit.

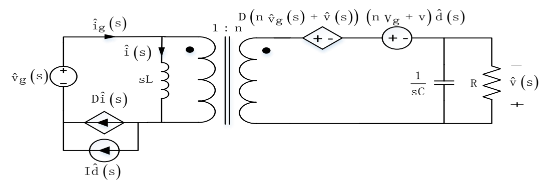


Figure 5. AC small signal equivalent circuit.

According to the theoretical analysis, the control-output voltage transfer function of the flyback converter can be obtained:

$$G_{vd}(s)=\left.\frac{\hat{v}_s}{\hat{d}_s}\right|_{\hat{v}_g(s)=0}=\frac{-nRLIs+(1-D)R(nv_g+v)}{n^2LRCs^2+n^2Ls+(1-D)^2} \tag{1}$$

Converter Control - Primary Side Inductor Current Transfer Function:

$$G_{id}(s)=\left.\frac{\hat{i}_s}{\hat{d}_s}\right|_{\hat{v}_g(s)=0}=\frac{1}{Ls}\left[v_g+\frac{v}{n}-\frac{1\text{-}D}{n}\frac{-nRLIs+(1-D)R(nv_g+v)}{n^2LRCs^2+n^2Ls+(1-D)^2}\right] \tag{2}$$

2.4 Structure of Bidirectional Flyback Multi-Winding Converter

The two-way flyback converter can realize the bidirectional transfer of energy, and the structure of the coaxial multi-winding transformer can further realize the multipath transmission of energy. The bidirectional flyback converter based on the coaxial multi-winding transformer is designed (Fig. 6). The primary side of the transformer in the circuit contains one winding and the secondary side contains two windings for energy transfer in six directions. The A terminal is connected to the battery cell through a matrix switch, the B terminal is connected to the buffer capacitor, and the C terminal is connected to the positive and negative poles of the battery pack.

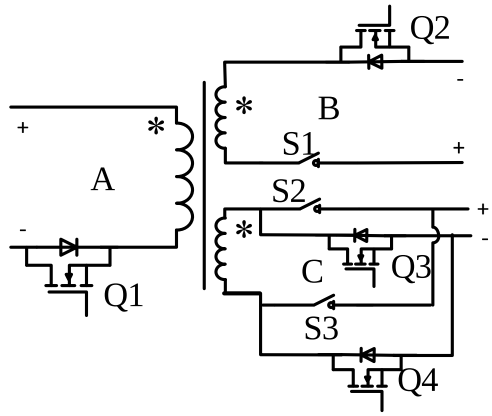


Figure 6. Main circuit of bidirectional flyback converter based on coaxial multi-winding transformer.

3. EQUILIBRIUM MAIN CIRCUIT SIMULATION

An equalization main circuit model based on bidirectional multi-winding isolated flyback converter is built, as shown in Figure 7. The simulation circuit model is mainly composed of a multi-winding transformer, a voltage-current double closed-loop feedback controller, a PWM output selection and a voltage-current feedback selection control sub-module. The multi-winding transformer has one winding on the primary side and two windings on the secondary side. The turns ratio of the transformer is 1:6:6. The voltage-current dual closed-loop controller V_I_FeedBack internally includes two error amplifiers. Firstly, the feedback rms current value and voltage value are compared with the set equalization current value and voltage threshold value, and then the PWM wave of the driving MOSFET is obtained by comparing the difference with the sawtooth wave. PWM output selection module PWM_Control, The voltage feedback selection control module U_FED_Select and the current feedback selection module I_FED_Select are set according to the equalization control strategy and different energy transfer directions, thereby controlling the energy transfer path and stabilizing the input current and the output voltage.

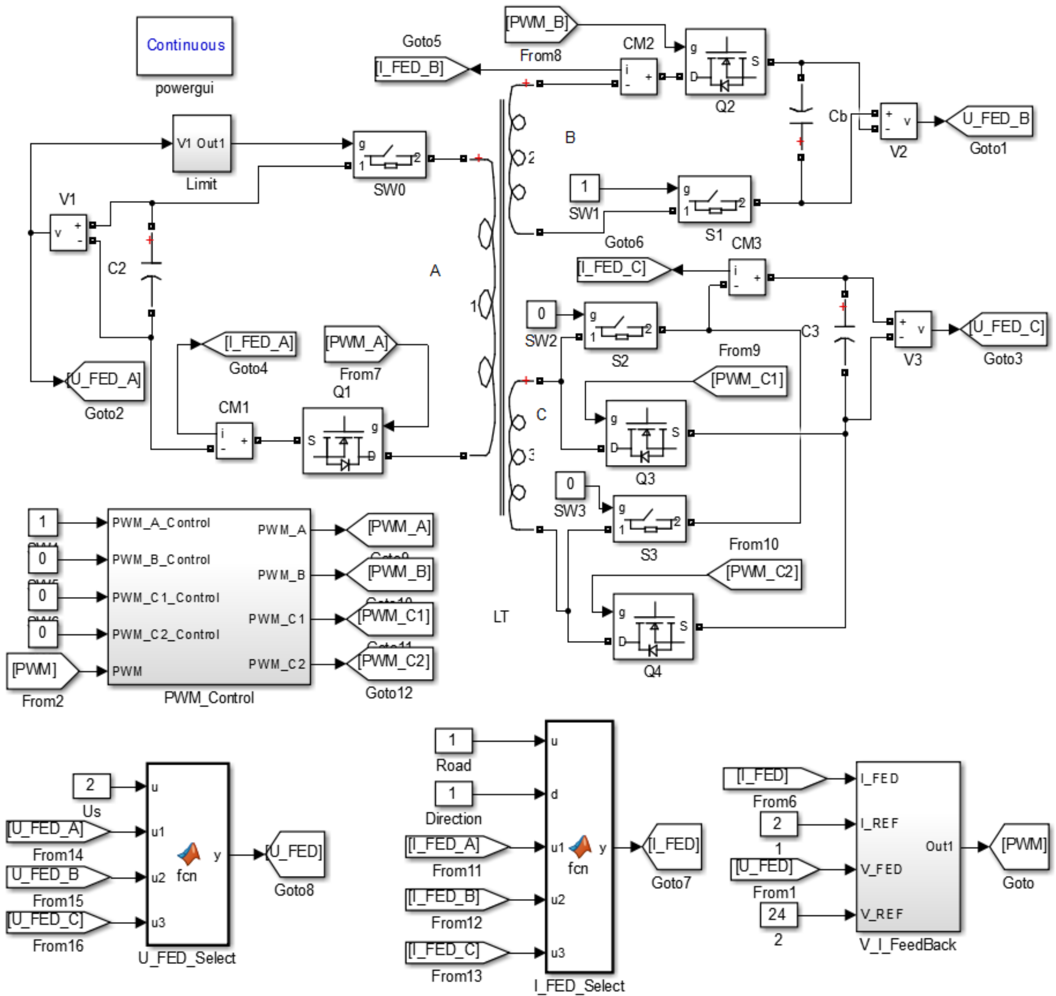


Figure 7. Equilibrium main circuit model based on bidirectional multi-winding isolated flyback converter.

Based on the equalization main circuit model of the bidirectional multi-winding isolated flyback converter, the simulation experiments of six energy transfer paths are carried out to verify the feasibility of energy transfer for each path.

Verify that energy is transferred from the A terminal to the B terminal. Set switch SW1=1; Road=1 of I_FED_Select module, Direction=1, select input current of A terminal as feedback current, and the direction of current is positive; Us=2 of U_FED_Select module, select B output voltage as feedback voltage; PWM_A_Control=1, the other three are set to 0, only the A-side MOSFET has PWM wave drive; the equalization current of the V_I_FeedBack module is I_REF=2A, the output voltage is V_REF=24V; the initial voltage of the A-side capacitor is set to 3.5V, The initial voltage of the B-terminal capacitor is set to 20V. The simulation results are shown in Figure 8, Figure 9, and Figure 10.

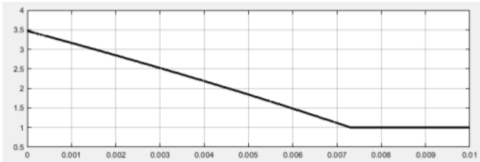


Figure 8. Voltage change curve at terminal A.

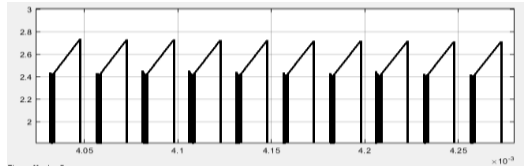


Figure 9. current change curve at terminal A.

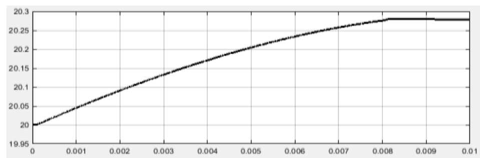


Figure 10. Voltage change curve at terminal B.

Verify that energy is transferred from the A terminal to the C terminal. Set switch SW3=1; Road=1 of I_FED_Select module, Direction=1, select input current of A terminal as feedback current, and the direction of current is positive; Us=3 of U_FED_Select module, select C output voltage as feedback voltage; PWM_A_Control=1, the other three are set to 0, only the A-side MOSFET has PWM wave drive; the equalization current of the V_I_FeedBack module is I_REF=2A, the output voltage is V_REF=24V; the initial voltage of the A-side capacitor is set to 3.5V, The initial voltage of the C-terminal capacitor is set to 20V. The simulation results are shown in Figure 11 and Figure 12.

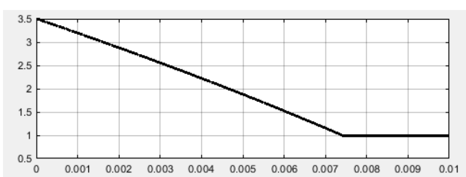


Figure 11. Voltage change curve at terminal A.

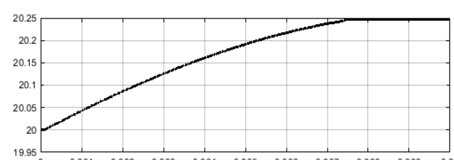


Figure 12. Voltage change curve at terminal C.

Verify that energy is transferred from the B terminal to the A terminal. Set switch SW1=1; Road=2 of the I_FED_Select module, Direction=-1, select the input current of the B terminal as the feedback current, and the direction of the current is reversed; Us=1 of the U_FED_Select module, select the output voltage of the A terminal as the feedback Voltage; PWM_B_Control=1, the other three are set to 0, only the B-side MOSFET has PWM wave drive; V_I_FeedBack module equalization current I_REF=2A, output voltage V_REF=4V; the initial voltage of the A terminal capacitor is set to 3.2V The initial voltage of the B-terminal capacitor is set to 20V. The simulation results are shown in Figure 13 and Figure 14.

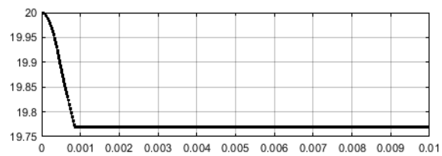


Figure 13. Voltage change curve at terminal B.

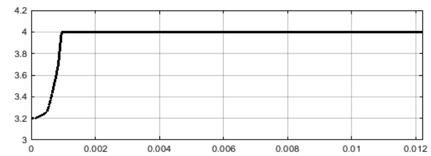


Figure 14. Voltage change curve at terminal A.

Verify that energy is transferred from the B terminal to the C terminal Set switch SW1=SW2=1; Road=2 of the I_FED_Select module, Direction=-1, select the input current of the B terminal as the feedback current, and the direction of the current is reversed; Us=3 of the U_FED_Select module, select the output voltage of the C terminal As the feedback voltage; PWM_B_Control=1; equalization current I_REF=2A of the V_I_FeedBack module, output voltage V_REF=24V; initial voltage of the B terminal and C terminal capacitance is set to 20V. The simulation results are shown in Figure 15.

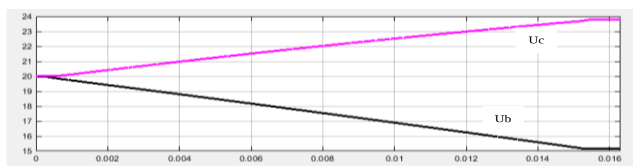


Figure 15. Voltage change curve at terminal B and terminal C.

Verify that energy is transferred from C terminal to A terminal. Set switch SW3=1; Road=3 of the I_FED_Select module, Direction=1, select the C input current as the feedback current, and the direction of the current is positive; Us= of the U_FED_Select module, select the output voltage of the A terminal as the feedback voltage PWM_C1_Control=1; equalization current I_REF=2A of V_I_FeedBack module, output voltage V_REF=4V; initial voltage of A terminal capacitor is set to 3.2V, and initial voltage of C terminal capacitor is set to 20V. The simulation results are shown in Figure 16 and Figure 17.

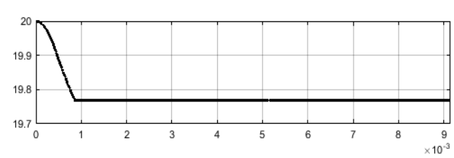


Figure 16. Voltage change curve at terminal C.

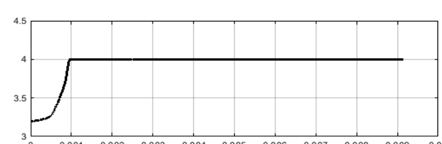


Figure 17. Voltage change curve at terminal A.

Verify that energy is transferred from C terminal to B terminal. Set switch SW1=SW2=1, Road=3 of I_FED_Select module, Direction=1; Us=2 of U_FED_Select module, PWM_C2_Control=1, equalization current I_REF=2A of V_I_FeedBack module, output voltage V_REF=24V, B The initial voltage of the terminal and C-terminal capacitors is set to 20V. The simulation results are shown in Figure 18 and Figure 19.

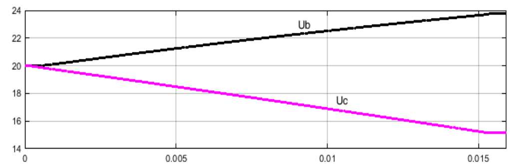


Figure 18. Voltage change curve at terminal B and terminal C.

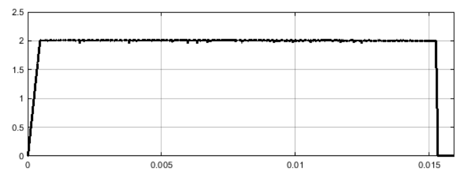


Figure 19. Current change curve at terminal C.

3. CONCLUSIONS

From the waveforms of the input voltage and output voltage of the six energy transfer paths, it can be seen that the input voltage is decreasing and the output voltage is rising, which indicates that the six energy transfer paths based on the bidirectional flyback multi-winding converter are feasible. In addition, the output voltage of the A terminal can be seen from the waveform of the output voltage. It can be stabilized after rising to 4V, and the output voltage of B and C terminals can reach stable when it rises to 24V. This shows that the voltage and current double closed-loop feedback controller is also effective, which can control the equalization voltage and current to achieve stability. In summary, the equalization main circuit design based on the bidirectional multi-winding isolated flyback converter is feasible, and the voltage and current double closed loop feedback control can better control the equalization voltage and current to achieve stability.

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