A Novel Space Active Balance System for Lithium-ion Battery Packs

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Abstract. In regard to the balance management for high capacity Lithium-ion battery packs in space, an active balance circuit based on the topology of multi-winding transformer is proposed in the article. The circuit can control the magnitude of the balance current by fixed duty cycle control, to achieve charge balance function. The circuit can effectively improve the balance speed of the high-capacity battery packs, meeting the requirement of balance function and reducing the energy loss of the battery packs, Meanwhile, increasing the service life of the battery packs. The novel balance system can realize modular and scalable. A Simulink model was built for the program. The simulation results prove the correctness and effectiveness of the circuit.

1. Introduction

Lithium-ion batteries have high specific energy, high voltage, and low self-discharge rate, and have been used more and more widely. They have become the third-generation space energy storage sources after nickel-cadmium batteries and nickel-hydrogen batteries. Lithium-ion battery packs cannot be over-charged or over-discharged. If balance control is not performed during charge or discharge for batteries, Individual cell voltages differentiate as the number of charge-discharge cycles increases, which greatly reduces the battery pack's service life[1-2].

At present, the domestic space lithium-ion battery packs generally adopt the passive balance method of the parallel connection resistance of the batteries, and consume excess energy on the resistors. As the capacity of the used battery packs increases, it is required to increase the balance current, which will cause problems for the heat dissipation of the balance circuit [3]. Relevant data shows that some countries have already applied active balance on GEO and LEO satellites. The active balance speed is fast, and the balance current changes with the battery voltage error. Compared with passive balance, there is no heat dissipation problem, and it is especially suitable for the balance of space high-capacity lithium-ion battery packs [4].

The application environment of space lithium-ion battery packs is special, and the balance circuit control method design and component selection need to consider more limiting factors, which objectively increases the design difficulty of active balance circuit. Therefore, the active balance technology for large-capacity lithium-ion battery packs in space has attracted more and more attention. At present, commonly used active balance circuit mainly include capacitor balance [5-6], inductance balance [7]. There are typical shortcomings in space applications. Take the capacitor balance circuit as an example. On the one hand, when the balance starts, the balance capacitor will constantly switch between the adjacent two cells, which will cause the voltage of the balance capacitor to fluctuate, which will cause the battery voltage to fluctuate by a certain extent. The phenomenon affects the voltage sampled signal during active balance circuit. On the other hand, as the batteries voltage error...
decrease, the capacitive balance speed will be slower and slower. Because of the balance control strategy is relatively complex and requires multiple transmissions for inductive balance circuit, the transmission efficiency are low, and it is difficult to meet the requirements of space applications for reliability and efficient and rapid balance.

In conclusion, in order to deal with the problems of balanced speed, high reliability design and other issues faced by high-capacity lithium-ion battery packs in space, this paper proposes a multi-winding balanced transformer and active switching (MOSFET) topology to build an efficient, highly reliable active balance circuit. The topology can realize the flow of energy between the single battery and the battery packs. Rapid balance of the battery packs can be achieved by discharging of the high-voltage batteries to large-capacity lithium-ion battery packs, thereby ensuring the safe operation of large-capacity lithium-ion battery packs in orbit.

2. Active balance principle of multi-winding transformer

Figure 1 show an active balance circuit based on multi-winding transformers. It can be seen from the figure that, through reasonable design, each multi-winding transformer unit corresponds to 6 battery cells, and it is defined as a balance module. The balance system can realize the cascade of multiple modules so that facilitate larger battery packs in greater scales. In addition, all balance modules can be equilibrated at the same time, which is very advantageous for high-capacity lithium-ion battery packs with high requirements for balance speed.

Fig 1. Active balance topology based on multi-winding transformers
In Figure 1, the transformers realize interleaved parallel. One side of the connecting single cell is the primary side of the balanced transformer, and the side of the connecting battery packs is the secondary side of the balanced transformer. The balance topology adopts a multi-winding balanced
transformer. There are six windings on the primary side of the transformer, corresponding to six battery cells, one winding on the secondary side, and connected to twelve batteries. The circuit can achieve simultaneous balance of several cells in different modules, and can achieve balanced battery string expansion through multiple multi-winding balance transformers in series. Each secondary winding of a multi-winding transformer has a freewheel diode connected to enable the secondary winding to charge the part battery packs.

In the charging process of large-capacity lithium-ion battery packs, if the voltage of a certain cell is greater than the balance voltage threshold, the switch in the primary side of the balance transformer connected in parallel to the battery is controlled to work a fixed duty cycle. The equivalent balance circuit is shown in Figure 2. Taking the battery CELL1 as an example, during the on-time period of the MOSFET, the cell CELL1 discharges for the primary winding of the balance transformer, and the primary side magnetize inductance stores energy; during the off-time of the MOSFET, the secondary winding of the balance transformer charge to the corresponding lithium-ion battery packs by the freewheeled diode. This cycle can quickly achieve the balance of large-capacity imbalance cell packs. The balanced current waveform is shown in Figure 3. The transformer operates in discontinuous mode and maximum balance current can be controlled by adjusting the duty cycle.

![Balance process diagram](Fig 2)
3. The design of active balance circuit for multi-winding transformer

Active balance circuit of multi-winding transformer showed in Figure 4. The circuit can be divided into power module and control module. The power module consists of battery unit, balance transformer, and switching transistor (MOSFET), and the module can be expanded. Each battery is connected in series with a battery pack through MOSFET, and fixed duty cycle control is used to discharge for batteries with the higher voltage. Control module includes FPGA control unit, AD sampling unit. Each battery voltage signal enters AD sampling through a first-order low-pass filter. The AD sampling signal of all battery voltages is processed into the FPGA, and the balance algorithm inside the FPGA is used to achieve the battery pack’s balance control. The relationship between the switching period of the MOSFET and the peak current of the balance transformer as follows:

\[ T_S = T_{ON} + T_{OFF} = L_{pri} \frac{I_{pri-peak}}{U_{bat}} + L_{sec} \frac{I_{sec-peak}}{U_{OFF}} \]  

\( T_S \) - Switching cycle; \( T_{ON} \) - turn on time of MOSFET; \( T_{OFF} \) - turn off time of MOSFET; \( L_{pri} \) - Primary magnetizing inductor; \( I_{pri-peak} \) - Primary peak current; \( U_{bat} \) - Single battery voltage; \( L_{sec} \) - second magnetizing inductor; \( I_{sec-peak} \) - Second peak current; \( U_{OFF} \) - Total voltage of battery packs.

The design for balance transformer is related to the working performance of the balance circuit. Therefore, the transformer parameters must be properly designed. During charging of the battery packs, once the active balance circuit detects that the voltage of certain cell is too high, it starts the corresponding balance switch to discharge for the cell. The average discharged current for the primary side of balance transformer is:

\[ I_{pri-ave} = \frac{I_{pri-peak}}{2} \frac{n \times k}{n \times k + 1} \]  

Similarly, the average charge current of the secondary battery of the balance transformer can be obtained as:

\[ I_{sec-ave} = \frac{I_{pri-peak}}{2} \frac{k}{n \times k + 1} \]  
n-number of cells in series; \( k \) - the ratio of turns of the primary and secondary sides of the transformer.

Analyzing equations (1) to (3), we can conclude that with a fixed duty cycle control method, the balance average current is only related to the turn’s ratio of the primary and secondary winding of the transformer, the number of batteries, and the current peak value.
According to the above physical quantity relationship, the design parameters of the balance transformer can be calculated by combining the actual requirements of the task, thereby providing guidance for the optimization design of the multi-winding balanced transformer. With a fixed duty cycle control, the maximum duty cycle is 50%. Since the operating voltage range of a single cell is between 3.6V and 4.2V, it is possible to obtain balance current at a maximum cell voltage of 4.2V with the transformer operating at 50% duty cycle. This current is maximum balance current of the active balance system.

Fig 4. Active balance system
The MOSFET of the active balance circuit needs to use the floating driving method, and it is necessary to consider the space application requirements with emphasis. For this reason, this paper designs a totem pole plus transformer isolation driving method, in which the totem pole serves the purpose of increasing the driving current. At the same time, magnetic isolation ensures floating drive. The drive circuit has a simple structure and can meet the requirements of the space applications. The drive circuit for active balance circuit is shown in Figure 5.

3.1. Simulation results

In order to verify the balance function of the multi-winding transformer, three Li-ion batteries charge balance circuit was built based on Simulink simulation software. Simulink consists of a battery simulation model. Set the capacity of the three cells to 1.2Ah, the standard voltage of three cells is 3.6V, and the initial capacity of the three cells is set to 20%, 20%, and 80%, respectively. Different initial voltages are set by setting different initial capacities. Given a fixed duty cycle of 50%, the switching frequency is set to 10 kHz.
As shown in Figure 6, the battery balance module is built using Simulink software. Using the existing battery model in Simulink, the transformer secondary winding connects diode freewheeling. The transformer has three windings on the primary side and one winding on the secondary side. The maximum voltage of the battery discharge to achieve the balance between batteries.

The balance current waveform is shown in Figure 7. Given a fixed 50% duty cycle signal, the maximum primary current of the transformer can reach 20A, and the peak value of the secondary current of the transformer can reach 15A. The transformer works in discontinuous mode. Analysis of Figure 7 shows that the active balance can realize function with a large current, and the average discharge current can reach 5A or more for single battery.

The three battery voltage waveform is shown in Figure 8. The active balance can realize function with a large current, and the average discharge current can reach 5A or more for single battery.
As shown in Figure 8, the initial capacity of two battery voltages is 20%, the initial capacity of one battery voltage is 80%, and the maximum error between the initial voltages of three batteries is more than 100mV. After about 14s balance process, three battery voltages are balanced, and the three battery voltages error is very small, which shows the feasibility of this strategy.

4. Conclusion

This paper proposes an active balance circuit that can be applied to space high-capacity lithium-ion battery packs. The balance scheme is based on a multi-winding balance transformer design, which can achieve rapid balance in the charging process of lithium-ion battery packs, with a fixed duty cycle control to simplify the control system design. Based on Simulink simulation analysis, the basic principle and function of the circuit are verified, and the advantages of the multi-winding transformer-based active balance circuit can be obtained as follows:

(1) The active balance method reduces the energy loss, improves the balance speed (the balance current can reach 5A or more), and can better meet the balance requirements of large-capacity lithium-ion battery packs;

(2) The multi-winding transformer is used in the active balance circuit, and the operating frequency is designed to be more than 10 kHz, which is beneficial to the high integration and light weight design of the balance circuit;

(3) Using a fixed duty cycle control method, the control strategy is simple, and it is conducive to meeting the high-reliability design requirements of space high-capacity lithium-ion battery packs.

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