Research on Symmetry Half-Bridge Switched Capacitor Active Equalization Circuit of Vehicle Power Lead-Acid Battery

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Abstract –In view of the complex battery equalization control in the traditional active equalization strategy of lead-acid batteries. In the traditional lead-acid battery active equalization strategy, the isolated drive circuit of the power switch is complicated and its stability is poor. A new equalization strategy based on half-bridge switch structure, moderate cost, easy to control, and high stability is proposed. The proposed scheme is suitable for equalization applications with a small number of battery cells , and the battery capacity is large , similar to lead acid battery. The proposed scheme is simulated and verified by Simetrix-Simplis 8.20 , and the working conditions of the power battery in vehicles are analyzed and demonstrated, and the complete control strategies are developed for various working scenarios, and they are verified by experiment. The experimental results demonstrate that the proposed equalization scheme can accomplish the equalization work continuously, stably and efficiently.

Keywords – Lead-Acid battery equalization, Symmetry half-bridge driver, Switched capacitor

I. INTRODUCTION

Lead-acid batteries are still widely used in low-end areas of power batteries [1], which have a high cost-effective ratio compared to lithium batteries, and they have no memory effect as lithium batteries. The lead-acid battery cell rated voltage is 12V and requires multiple lead-acid battery cells in series to meet the needs of different applications in practice [2]. Similar to other types of batteries, lead-acid cells can be skewed in the manufacturing process, although factory-specific battery cells are distributed in a group through schemes such as battery packing, the differences between cells are inevitable. As usage time increases, similar batteries can be in different states due to complex usage. As the degree of imbalance increases, directly back to the lead-acid battery pack where individual batteries cannot be fully charged due to the "barrel effect" [3]. Lead-acid batteries over discharge or overcharge for a long time will eventually lead to the battery plate vulcanization [4]. Vulcanization is the main factor to reduce the capacity and shorten the life of lead-acid battery. To extend battery life, imbalances must be suppressed as much as possible over the life period of the battery [5]. An effective way to reduce imbalances is equalization. The passive equalization method narrows the difference between the cells by dissipation of energy [6]. For large-capacity lead-acid battery cells, it is unreasonable to achieve equalization by passive equalization because it wastes a lot of energy and generates a lot of heat. This method is not appropriate from an efficiency and security perspective [7]. Active equalization is also known as energy transfer equalization. The method is to transfer the unbalanced energy in some way until the balanced state is reached [8]. According to the critical devices used in active equalization to classify, active equalization mainly includes: inductive equalization, capacitive equalization, bidirectional Buck-Boost topology equalization, bidirectional flyback topology equalization [9], resonant equalization [10], etc. Capacitive equalization is more flexible than inductive equalization, and circuit topology has more research value [11]. In this paper, the method of active equalization of symmetric half-bridge switching capacitors is proposed, and a simple and reliable driving method is proposed for the key problem of switch isolation drive. The feasibility of the method is proved through theoretical analysis, simulation and actual circuit test.

II. TECHNICAL INFORMATION

A. Equalization system block diagram

As shown in Fig. 1, the system is divided into two parts: the control circuit and the equalization circuit. The control circuit collects the battery voltage data through the ADC channel and outputs PWM waveform for control. This part provides the consumer with a control interface and status indication. The equalization circuit consists of a symmetrical half-bridge switch array, a switch array drive circuit and a equalization capacitor array.

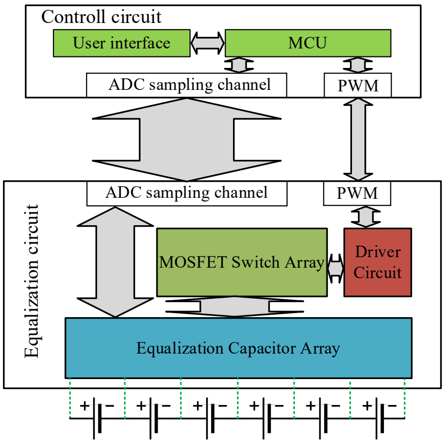


Fig. 1: equalization system block diagram

B. Symmetry half-bridge switch circuit and drive circuit

In this paper, a half-bridge switch structure is proposed to realize the function of capacitive charge and discharge circuit switching, and the local circuit structure diagram is shown in Fig. 2. Take the B5 and B6 battery cells in Fig. 1 as an example.

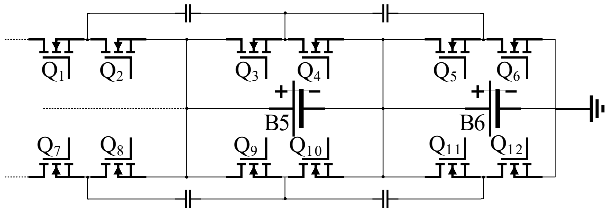


Fig. 2: Symmetry half-bridge switch circuit

The common drive circuit of the half-bridge structure only needs to float the upper half-bridge switch, but the float drive between each set of half-bridges in this particular structure of the battery pack is also a key point in the design. The float drive of the switch between the battery packs is also difficult. In this paper, a simple structure and moderate cost drive circuit are proposed for the complexity and high cost of traditional methods, the circuit structure is shown in Fig. 3, the corresponding control signal is shown in Fig. 4.

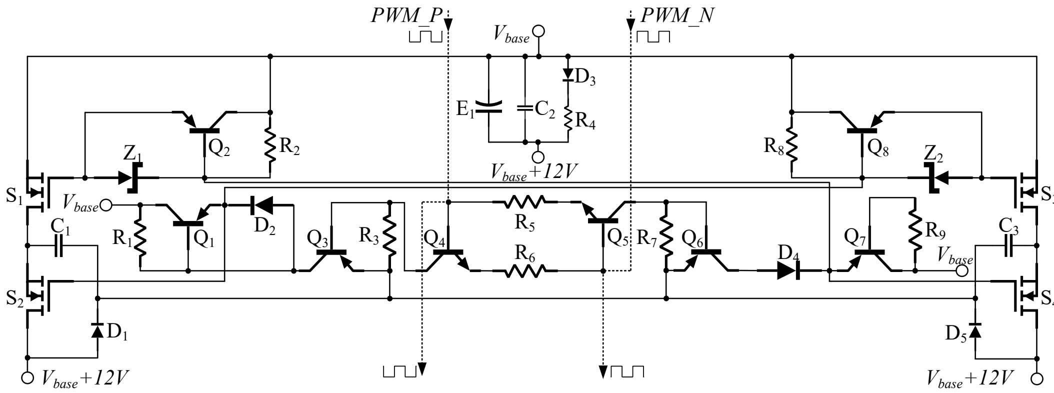


Fig. 3: Float half-bridge drive circuit

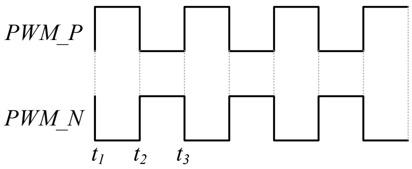


Fig. 4: Half-bridge drive circuit control signal

C. Equalization circuit parameter calculation

The method proposed in this paper is based on the traditional single-layer switched capacitor equalization topology. The theoretical analysis needs to pay attention to the process of voltage and current change during capacitor charging and the process of voltage change during capacitor discharge.

- *Capacitor charging process*

Ignore the loss caused by parasitic resistances such as transmission wires and switching devices, firstly analyze and calculate the charging process of the capacitor in the zero initial state. Assume that battery B5 in Fig. 5 is the source battery with a higher energy level, and B6 is the target battery with lower energy level.

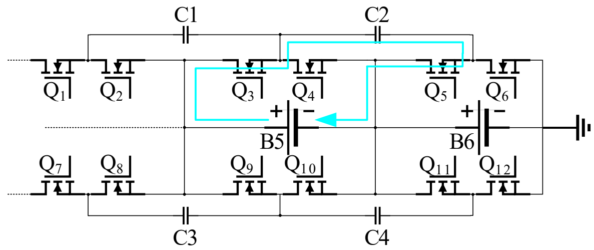


Fig. 5: Capacitor charging loop

The on resistance of single mosfet switch is R_{dson}, and the internal resistance of the battery is R. The discharge current of battery B5 passes through the two mosfet switches Q_4 and Q_5. In this case, the equivalent circuit model of the charging loop is shown in Fig. 6.

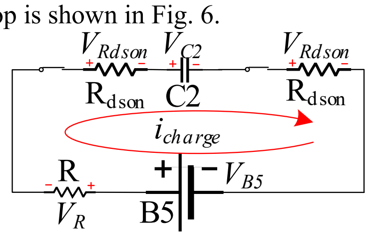


Fig. 6: Capacitor charging equivalent circuit

Because the charge and discharge are switched quickly, the battery voltage can be regarded as constant for a short time, equation (1) is obtained according to Kirchhoff's law.

$$V_{B5} = V_{C2} + 2V_{R_{dson}} + V_R \qquad (1)$$

The voltage on the equivalent resistance is calculated according to equation (2). The charging current value i_{charge} is calculated according to equation(3).

$$2V_{R_{dson}} + V_R = i_{charge}(2R_{dson} + R) \qquad (2)$$

$$i_{charge} = C\frac{dV_{C2}}{dt} \qquad (3)$$

Combine equation (2) and equation(3) to get equation (4), which is a first-order linear differential equation with constant coefficients.

$$V_{B5}=V_{C2} + C(2R_{dson} + R)\frac{dV_{C2}}{dt} \qquad (4)$$

The differential equation solving result is shown in equation (5),

$$-ln(V_{B5} - V_{C2}) = \frac{t}{C(2R_{dson} + R)} + k \qquad (5)$$

In equation (5), k is an arbitrary constant. Substitute boundary conditions $t=0, V_{C2}=0$, find $k = -lnV_{B5}$, Substitute k into the last equation of equation (5), the capacitor voltage expression is obtained as shown in equation (6).

$$V_{C2} = V_{B5} - V_{B5}e^{-\frac{t}{C(2R_{dson}+R)}} \qquad (6)$$

Then the change of the capacitor voltage with time is shown in Fig. 7.

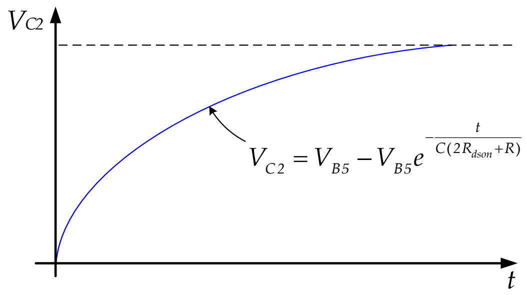


Fig. 7: Voltage curve of capacitor charging in zero state

Substitute the capacitor voltage into equation (3) to solve the loop current, the process is shown in equation (7),

$$V_{R_{total}} = V_{B5} - V_{C2} = V_{B5}e^{-\frac{t}{C(2R_{dson}+R)}}$$
$$i_{charge} = C\frac{dV_{C2}}{dt} = \frac{V_{B5}}{2R_{dson} + R}e^{-\frac{t}{C(2R_{dson}+R)}} \qquad (7)$$

The current decay curve is shown in Fig.8,

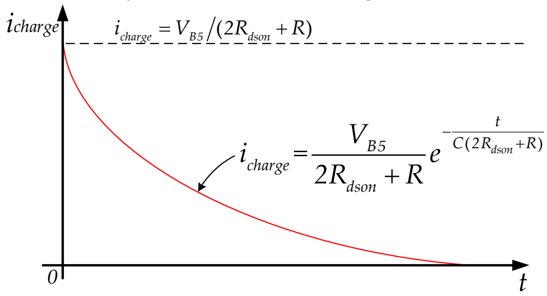


Fig. 8: Current decay curve of capacitor charging loop

The maximum current value that can be reached during the charging of the capacitor is $i_{charge} = V_{B5}/(2R_{dson}+R)$.The capacitance value of the capacitor needs to be estimated based on the capacitor charging time constant and the selected switching frequency. The capacitor charging time constant is $\tau=C(2R_{dson}+R)$, ignoring the ESR of the capacitor. According to the selected on-resistance of the mosfet and the internal resistance of the lead-acid battery, the approximate capacitor charging time can be estimated. If the switching period is satisfied, the charging and discharging time requirement of the capacitor can be met.

- *Capacitor discharge process*

The process of capacitor C2 charging battery B6 is similar to the process mentioned above, the discharge equivalent circuit is shown in Fig. 9.

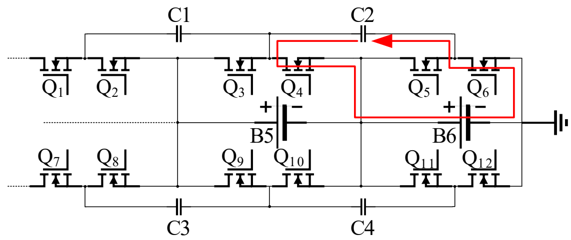


Fig. 9: Capacitor discharging loop

The capacitor will continue to discharge until the capacitor voltage is equal to the battery voltage. Suppose the voltage of battery B6 is V_{B6}. The equivalent circuit diagram of the discharge circuit is shown in Fig. 10.

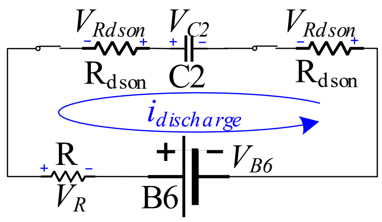


Fig. 10: Equivalent circuit of capacitor discharge

According to Kirchhoff's law, list the equation as shown in equation (8). The voltage symbols used are redefined here,

$$V_{C2} = -2V_{R_{dson}} - V_R + V_{B6} \qquad (8)$$

The capacitor discharge current is calculated according to equation (9),

$$2V_{R_{dson}} + V_R = i_{discharge}(2R_{dson} + R)$$
$$i_{discharge} = C\frac{d(V_{C2} - V_{B6})}{dt} \qquad (9)$$

Write the differential equation as shown in equation (10),

$$V_{C2}=V_{B6} + C(2R_{dson} + R)\frac{d(V_{C2} - V_{B6})}{dt} \qquad (10)$$

The process of solving this differential equation is similar to the process mentioned above, and equation (11) is obtained,

$$-ln(V_{C2} - V_{B6}) = \frac{t}{C(2R_{dson} + R)} + k \qquad (11)$$

k is an arbitrary constant, and the boundary condition $t=0$, $V_{C2}=V_{B5}$, find $k=-ln(V_{B5}-V_{B6})$. Substituting k into equation (11) and solving, the capacitor voltage expression is obtained as shown in equation (12).

$$V_{C2} = V_{B6} + (V_{B5} - V_{B6})e^{-\frac{t}{C(2R_{dson}+R)}} \qquad (12)$$

The voltage change curve of the capacitor is shown in Fig.11.

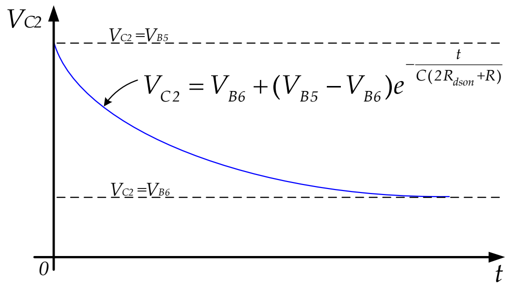


Fig. 11: Capacitor discharge voltage curve

The final capacitor voltage is equal to the battery voltage. The capacitor discharge current does not need to be concerned, only the maximum current peak value during the charging process needs to be estimated.

III. Implementation And Experimental Results

A. Experimental Parameters

The lead-acid batteries used in the experiment and the types and parameters of the devices are shown in Table 1.

Table 1: Devices and parameters

Item	Name	Parameters
Battery	6-DZF-12.2	12V 12.2Ah
Mosfet	VBE1307	R_{dson}=10mΩ
Capacitor	16SEPC270MX	16V 270uf
Controller	STM32F030C8T6	-
Switching Freq.	-	16kHz

A total of 6 batteries were used in the experiment, and the maximum instantaneous peak current that the mosfet used as a switch can withstand is 250A.

B. Control Algorithm

Equalization algorithm is the key factor for efficient work of equalization system, most of the traditional algorithms are equalization algorithms for static battery systems, the equalization of the battery pack in actual use is not taken into account. For example, the status of vehicle start, vehicle stop and battery charging encountered in actual use of the power battery, this paper presents a dynamic equalization algorithm that include the operating status of the vehicle. The control algorithm is shown in Fig. 12.

The proposed equalization algorithm includes the starting and stopping of the vehicle, and the state of charging when the battery charging, which is closer to the actual working condition of the power battery equalization system.

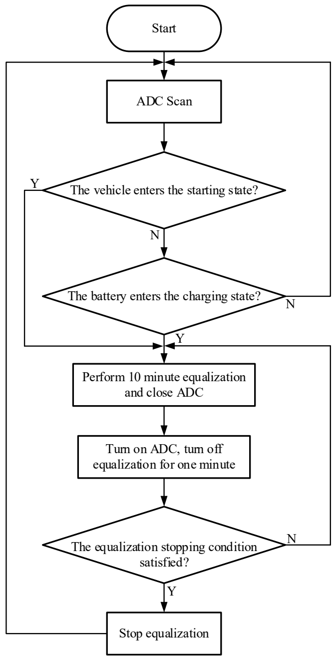
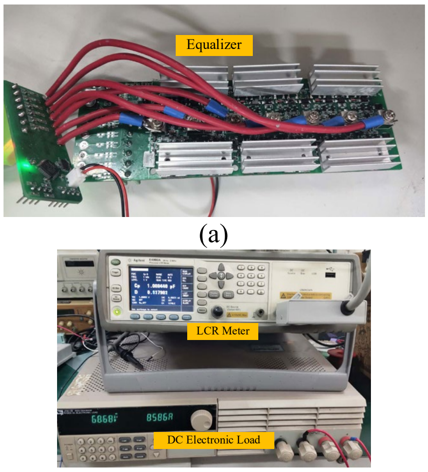


Fig. 12: Equalization strategy flowchart

C. Prototype of equalization circuit

The prototype and test equipment of the equalization system are shown in Fig. 13.



(a)

(b)

Fig. 13: Prototype and test equipment, (a) symmetrical half-bridge equalization board (b) LCR meter and electronic load.

In the experiment, six unbalanced 12V-12.2Ah lead-acid batteries were balanced. Artificially used chargers and electronic loads to create the required unbalanced state. The open circuit voltage state of the battery cell before equalization is shown in Table 2.

Table 2: Cell voltage before equalization

Cell number	Voltage
Cell1	13.824V
Cell2	12.928V
Cell3	12.514V
Cell4	11.514V
Cell5	11.092V
Cell6	10.768V

The signal waveforms of PWM_P and PWM_N in Fig. 3

are shown in Fig. 15.

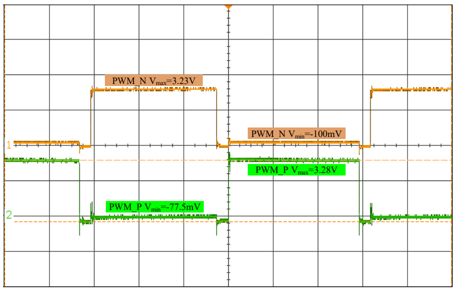


Fig. 15: Half-bridge drive circuit control signal

During the process, the relevant waveform of switch S4 in Fig. 3 is shown in Fig. 16.

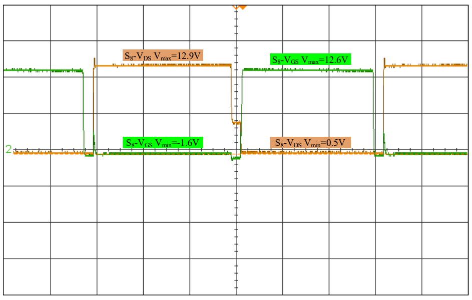


Fig. 16: GS and DS waveforms corresponding to switch S4 in Fig. 3

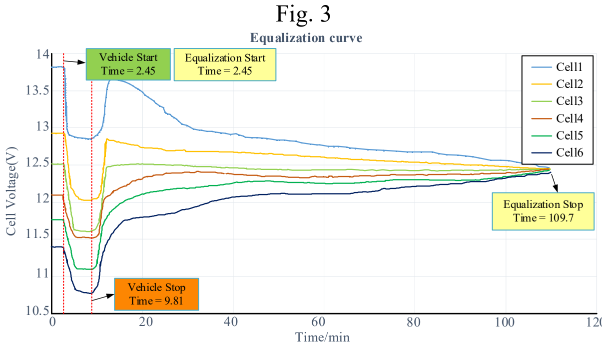


Fig. 17: Equalization curve

Table 3: Cell voltage after equalization

Cell number	Voltage
Cell1	12.463V
Cell2	12.449V
Cell3	12.439V
Cell4	12.441V
Cell5	12.425V
Cell6	12.414V

As shown in Fig. 17, the equalization circuit did not start before the vehicle started. The equalization circuit starts at Time = 2.45, and the vehicle stops at Time = 9.81. The equalization lasted for about 109.7 minutes and then stopped, after the equalization completed, the battery cell voltage is shown in Table 3.

IV. CONCLUSION

This paper proposes a symmetrical half-bridge switched capacitor balancing circuit topology. Aiming at the problem of floating drive of traditional battery pack power switch, the paper proposes a simple, reliable and easy-to-control half-bridge drive circuit. The equalization circuit proposed in the paper is suitable for the equalization of batteries with higher cell voltage and larger capacity, typical applications such as the equalization of power lead-acid battery. Energy is transferred through the symmetrical half-bridge structure with equalizing capacitors as the medium. The paper gives the necessary theoretical analysis of the capacitor charge and discharge process in the equalization system. A prototype of the equalization circuit was made to verify the method proposed in this paper, the test results prove the rationality and high efficiency of the proposed symmetrical half-bridge switch structure and corresponding drive circuit. Compared with the traditional complicated power switch driving method, the power switch driving circuit proposed in the paper is more stable and the control method is simpler.

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