Buck-boost Equalizer for Super-capacitor Modules

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***Abstract*-An equalization management system based on buck-boost converters is proposed. This system uses pulse width modulation (PWM) signal to control the voltage balance between adjacent cells in super-capacitor modules connected in series, which can effectively balance cells' voltage during the charge-discharge process, and avoid the weak cells from being overcharged or over discharged. Thus enhance the profitability of limited capacitance.**

***Keywords*-buck-boost converter; pulse width modulation; equalization; super-capacitor**

I. INTRODUCTION

Because the super-capacitor has the features of high power density, fast charging and long service life, it attracts much attention as the energy storage device of the electric vehicle power system in recent years[1-5]. In actual applications, since the single super-capacitor voltage is not high (typically less than 3V), dozens or even hundreds of cells are connected in series to achieve the required voltage. The performance of each capacitor (capacity, internal resistance, leakage current, etc.) in the series connected module is inconsistent (even if the selection of the consistency is done, the bias exist inevitably), which will decrease the energy of super-capacitor module or the energy can not be used sufficiently[1]. The battery balancing technology can effectively solve this problem. At the same time this technology also plays an important role in extending its life and avoiding overcharge and over discharge[1,2]. The dynamic equalization technology is that each cell in the battery group or super-capacitor module can simultaneously achieve the maximum or minimum voltage in the charge-discharge process by some devices and certain control methods, which can thus avoid the overcharge or over discharge of cells. If the upper limit or lower limit of the total capacitor module voltage is used to judge whether the energy storage is fully charged or totally discharged without equalization management, the cells with a lower capacity will be overcharged or over discharged, as a result this will reduce its service life. Moreover, along with the increasing charge-discharge cycles, the individual cell performance will drift apart, which will further damage capacitor components. If the upper limit or lower limit of the single cell voltage is considered as the sign of the end of charge or discharge, lower capacity cells will reach the upper limit voltage first during charge but other cells have not been totally charged. Also, lower capacity cells will reach the lower limit voltage first during discharge, but some surplus energy in high capacity cells has not been used yet. To maintain the performance of electric vehicles (acceleration, driving range, etc.), it is necessary to increase the number of capacitors, which will increase the cost of electric vehicles. If the battery equalization technology is used, the equalization system can reduce the charge-discharge speed of the lower capacity cells, thus avoid the overcharge or over discharge. Meanwhile, the charge-discharge time of the whole capacitor module will extend in the condition of the same charge-discharge current, which ensure that high capacity capacitors can be charged or discharged as much as possible in the charge-discharge process. Reference [3] has compared the results between equalization and non-equalization tests of several battery packs. The tests show that even if the equalization system doesn't achieve the ideal results, the individual differences are reduced, which is helpful for the battery life and capacity. It is the same for the super-capacitor modules; the equalization management will play an active role. Therefore, the equalization management for the super-capacitor is significant for short-distance electric car. According to the ideas above, we have researched the equalization management system based on the buck-boost converters for the super-capacitor modules. The road experiments show that the system achieves the expected effect.

II. THE MAIN EQUALIZATION CIRCUIT AND PRINCIPLE

The main equalization circuit uses buck-boost converter (as shown in Figure 1). The waveforms of various parameters of the equalization circuit are shown in Figure 2. T1 and T2 are the FET switches, D1 and D2 are the freewheeling diodes, L is the energy storage inductor, C1 and C2 are two adjacent capacitors in the series super-capacitor module. The work principle is:

When the voltage U_{C1} of the capacitor C1 is greater than the voltage U_{C2} of the capacitor C2, the FET T2 is cutoff, the T1 is exerted by the pulse width modulation signal (PWM). As shown in Figure 1 (a), the capacitor C1, the FET T1 and the inductor L constitute a loop during the time T_{ON} that T1 is turned on, the loop current is I_{C1}, the energy of the capacitor C1 is transferred into the inductor L. The inductor L, the capacitor C2 and the diode D2 form a loop during the time T_{OFF} that T1 is turned off. The loop current is I_{C2}, and the

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energy of the inductor L is transferred into the capacitor C2. The waveforms of the PWM signal, the inductor current IL, the current I_{C1}, I_{C2}, the voltage U_{C1} of the capacitor $_{C1}$ and the voltage U_{C2} of the capacitor C2 are shown in Figure 2 (a).

When the voltage U_{C2} of the capacitor C2 is greater than the voltage U_{C1} of the capacitor C1, the FET T1 is cutoff, the T2 is exerted by the PWM signal, as shown in Figure 1 (b). The current and voltage waveforms of components in the circuit are in Figure 2 (b).

According to the analysis of the working process, thePWM signal can control the circuit to achieve the voltage equalization between adjacent capacitors in the series connected capacitor modules. To achieve the voltage equalization of all of the cells, each two adjacent capacitors have a buck-boost converter in parallel, and the equalization system will determine an equalization control strategy depending on the voltage of every cell, and then control PWM signal to drive different FET switches in a reasonable order to balance the capacitor voltage. High voltage and low voltage cells may be not adjacent to each other. Other capacitors between them will become intermediary components that transfer the energy.

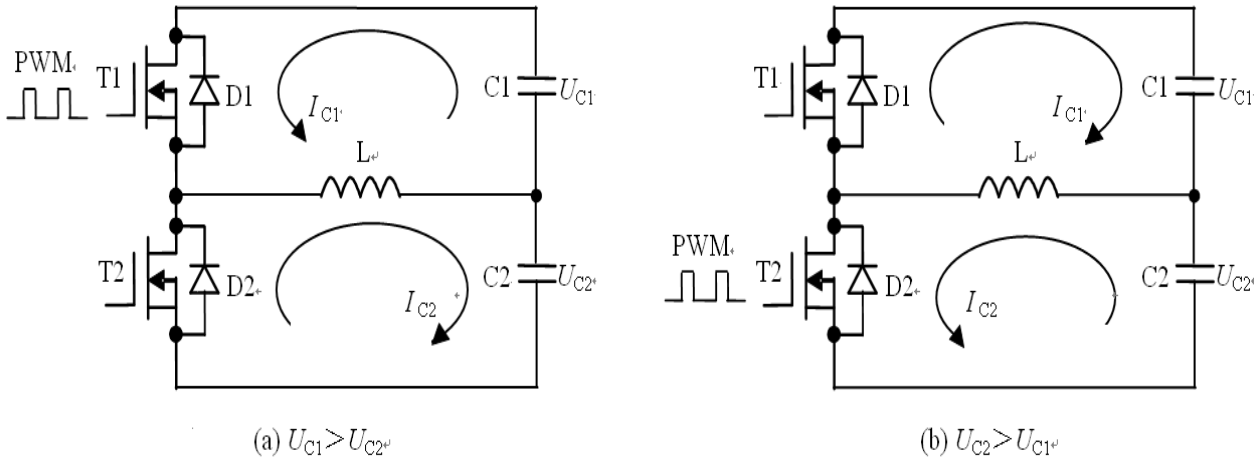

Figure. 1. The main equalization circuit based on the buck-boost converter

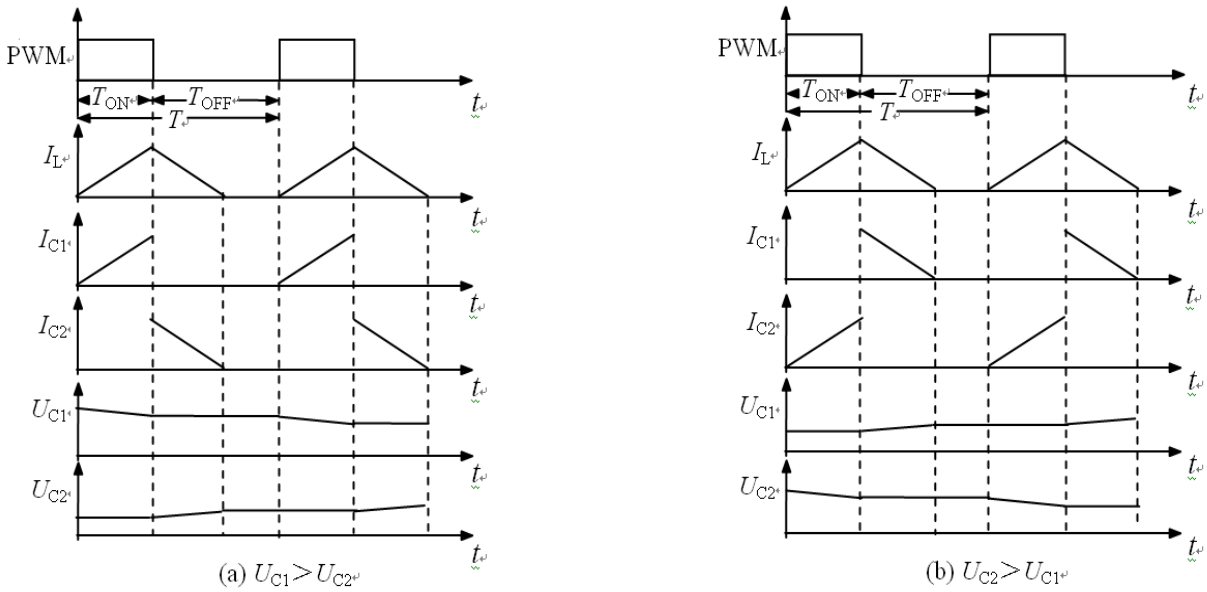

Figure. 2. The waveforms of circuit parameters in the equalization process

III. THE EQUALIZATION MANAGEMENT SYSTEM

A. The Super-capacitor Module for Electric Vehicle

The bus we researched uses 600 capacitors in serial and parallel connection as power supply. Each capacitor's voltage is 0.8 ~ 1.6V, and its capacity is 80,000F. First, 10 capacitors with similar performance are connected together in series, which are packaged as a group, and there are 60 groups in all; 20 groups constitute one big group, so there are three big group altogether; Finally, three series groups are connected in parallel providing power for electric bus, as shown in Figure 3.

In this way, the super-capacitor module provides the voltage range of 160 ~ 320V for the vehicles and the total output energy is 12.8kWh.

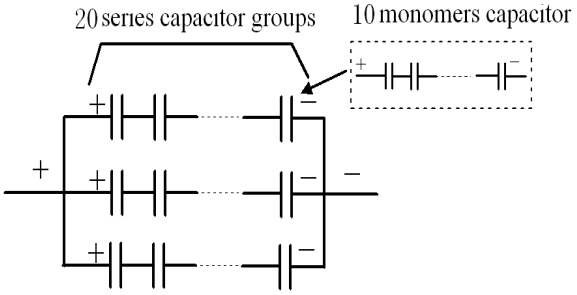

Figure. 3. The series-parallel super-capacitor module

B. The Capacitor Module Management System

In order to monitor the state and control the equalization of each capacitor, the distributed equalization management system is designed. 60 capacitor modules are installed respectively on the lower-level capacitor equalization management unit (CMU). These CMUs are connected to the host computer by CAN bus, then the host computer accomplishes the management to the capacitor modules. In addition, the host computer completes the data acquisition of the total voltage and current of the capacitor module, the equalization between the capacitor modules and the communication with the vehicle management unit. The system diagram is shown in Figure 4.

C. The Lower Capacitor Equalization Management Unit (CMU)

The task of CMU is to acquire the data of each cell and equalize 10 cells that connected in series of a capacitor module and communicate with the host computer. PIC18F458 MCU is designed as the core of the lower-level capacitor equalization management unit, as shown in Figure 5. The PIC18F458 MCU has 8-channel 10-bit A / D, 4K bytes of EEPROM data memory, 2M bytes of FLASH program memory, PWM outputs and CAN2.0 serial communication interface. The voltage measurement part completes the voltage inspection of 10 capacitors. The MCU sends PWM signal to FET to drive the control circuit through the multi-switch in order to achieve the voltage equalization of 10 cells.

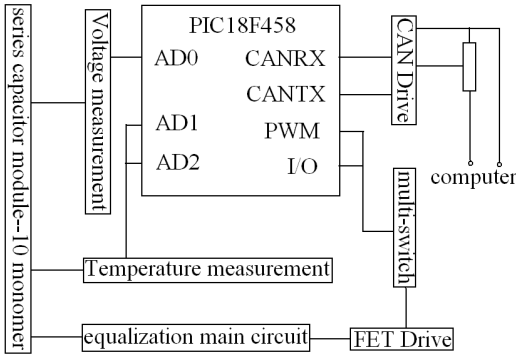

Figure.5. The diagram of CMU

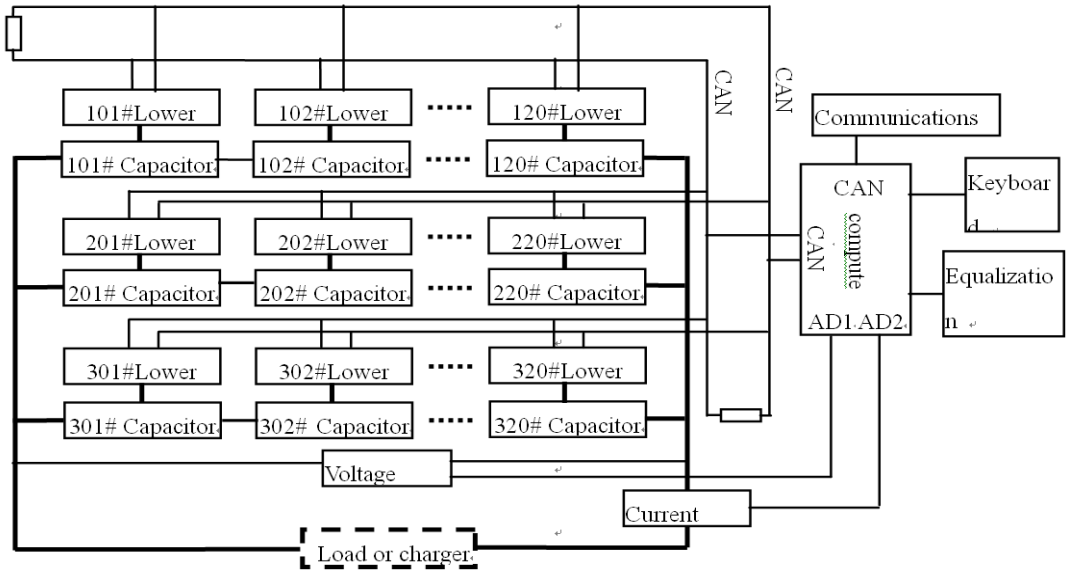

Figure. 4. The diagram of the capacitor module management system

IV. THE EQUALIZATION EXPERIMENTS

A. The Experiment Description

Four capacitors of 30,000F in series are tested by the Arbin BT-2000 battery test equipment. 40 circular charge-discharge experiments without equalization management and with equalization management are carried out. The voltages of the four capacitors are recorded at 5 minutes after the end of each charge-discharge cycle.

B. Analysis

- *The Qualitative Analysis of the Equalization Management*

According to the experimental data, the voltage curves of four cells without the equalization management and with the equalization management are drawn at 5 minutes after the end of each charge-discharge cycle, as shown from Figure 6 to Figure 9. Among them, Figure 6 and Figure 7 are four cell voltage curves of 40 charge-discharge cycles without the equalization management. Due to the different performances between cells, the differences will be greater during the charge-discharge process, which eventually leads to overcharge or over discharge of some cells. Meanwhile, some cells can not be fully charged or utilized. The overcharge or over discharge will reduce the life of the capacitor; and the latter situation will affect driving range. Figure 8 and Figure 9 are four cell voltage curves of 40 charge-discharge cycles with the equalization management. The different performances between cells with equalization management are greatly improved. Equalization management can avoid overcharge or over discharge in order to prolong the life of the capacitors. Meanwhile, the equalization management also increases the profitability of limited capacitance.

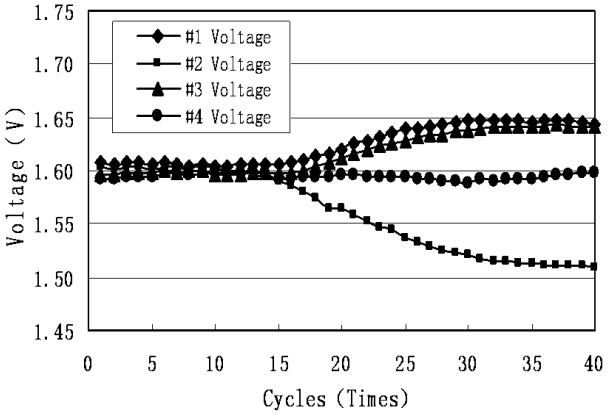

Figure.6. The cell voltage at the end of charge without the equalization management

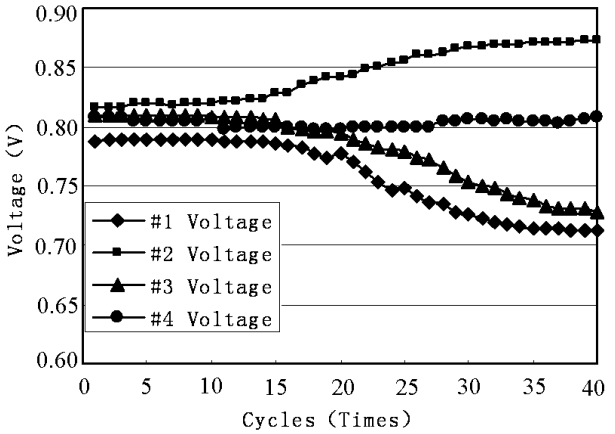

Figure.7. The cell voltage at the end of discharge without the equalization management

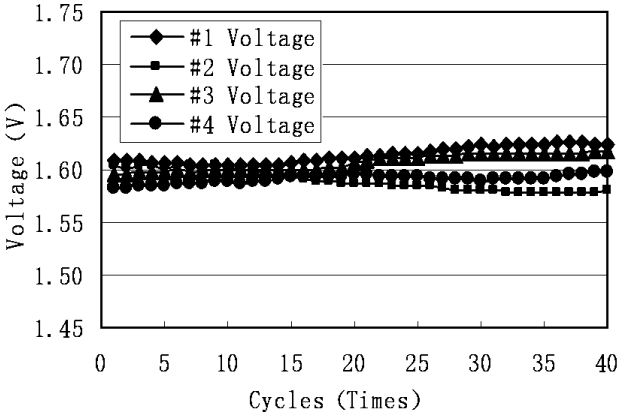

Figure.8. The cell voltage at the end of charge with the equalization management

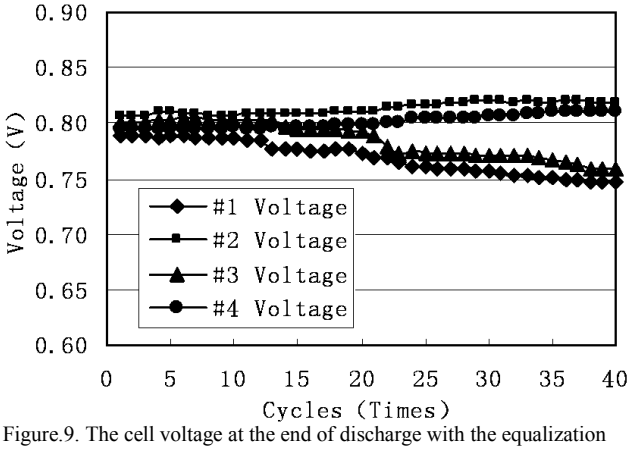

Figure.9. The cell voltage at the end of discharge with the equalization management

- *The Quantitative Analysis of the Utilization Rate of the Capacitor*

Take #1 capacitor and #2 capacitor (with the capacity of 30,000F) in the experiment as an example, the voltage at 5 minutes after the end of the 40th charge-discharge, the initial voltage and the charge-discharge energy calculated by theory without the equalization management and with the equalization management are shown in table 1.

Table□. THE COMPARISION OF EQUALIZATION EFFECT

Parameter		No equalization	Equalization
Initial voltage /V	#1	0.7121	0.7461
	#2	0.8720	0.8181
Charge end voltage /V	#1	1.6435	1.6245
	#2	1.5092	1.5803
Discharge end voltage /V	#1	0.7127	0.7468
	#2	0.8730	0.8193
Charge total energy/kJ		55.726	58.680
Discharge total energy /kJ		55.688	58.636

According to the table, the equalization management not only reduces the differences between capacitors but also improves the utilization rate of the series connected capacitor module at the same charge-discharge condition. The energy charged or discharged from the capacitor module with the equalization management system increases by 5.3%.

V. CONCLUSIONS

The different performances between cells in the series connected super-capacitor modules are the main factors affecting the capacitors' service life and their high failure rate. Therefore, the equalization management for the series connected super-capacitor module is of great significance. Experimental results show that the equalization management based on the buck-boost converter can effectively achieve the voltage equalization in the charge-discharge process, and avoid the weak cell being overcharged or over discharged and improve the utilization rate of the capacitor. This system is applied to the super-capacitor electric bus, and obtains good effect.

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