Paper number: #131
Topical area: Energy Storage

Super-capacitor Stacks Management System with Dynamic Equalization Techniques

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Abstract: Super-capacitor has the advantage of quick charge, large power density and long cycle life. The shortage is the lower energy density compared with electrochemistry batteries. These features make it suitable for short distance electric bus used in the city.

Because of the capacitance difference between the capacitor cells, after a number of deep discharging/charging cycles, the voltage difference between cells will be enlarged. This will accelerate the aging of the weak super-capacitors and affect the output power. So a management system with equalization function is essential. In this paper a practical super-capacitor stacks management system with dynamic equalization techniques is proposed.

The function of the management system includes: monitoring the current, voltage and temperature of the stacks, control of charge and discharge with equalization on line. A switched-capacitor equalization approach is adopted showing a low-cost way to meet the accuracy requirements. The dynamic equalized charging and discharging circuit is described. The algorithm to increase the operation speed and the precision is analyzed. By dynamically redistributing the current, the equalization procedure can be more quickly and efficiently. This approach has been verified by experiments.

Key words: Super-capacitor, Battery Management, Dynamic Equalization.

1. INTRODUCTION

Because of the environmental and energy problems, the investigation and development of electric vehicles have become more and more important for most countries in the world. In the research field of electric vehicles, it is well known that the battery technique is the bottleneck. In current stage, it is feasible and an effective way to develop pure electric bus with super-capacitors as unique energy storage applied to urban bus for determinate route in which the distance is limited. In comparison with electrochemical batteries, super-capacitor has the features of high power density, low resistance, wide temperature range, perfect characteristic in low temperature and suitability for quick charge and discharge. These features make the super-capacitor bus more suitable for urban drive cycle, such as frequent start/stop, acceleration and regenerative brake. Furthermore, super-capacitor has long cycle life (more than 100 thousand times) and capability of deep discharge, this will make the bus more cost effective. The disadvantage of super-capacitor is its low energy density, and this leads to the short driving distance of the bus. But this can be compensated by quick charge because in general the distance between two bus stations is no more than ten kilometers. In a word, so many satisfied features make super-capacitor a good choice for pure electric urban bus [2-4, 6, 10].

In order to meet the power requirement of drive motor, there must be a super-capacitor stacks with many cells in series and then in parallel as energy storage [7, 8, 11]. Similar to electrochemical batteries, because of the capacitance difference between the capacitor cells, after a number of deep discharging/charging cycles, the voltage difference between cells will be increased. This will accelerate the aging of the weak cells. In addition, the voltage difference will affect the output power of the super-capacitor stacks. So a management system with equalization function is essential when super-capacitor stacks are used in electric bus as unique energy storage [1, 5]. In this paper a practical super-capacitor stacks management system with dynamic equalization techniques is proposed.

1.1 Super-capacitor stacks

The super-capacitor stacks are composed of six hundred super-capacitor cells with three strings in parallel and each string composed of two hundred super-capacitor cells in series as shown in Fig.1. Ten capacitor cells with uniformity of capacity are in series and packaged as one stack. The voltage range of each cell is 0.8V~1.6V, the cell capacitance is 80000 farad. The voltage range of the whole energy storage is from 160V to 320V. The photo of a developed super-capacitor urban bus is shown in Fig.2. The box contains super-capacitor stacks in the bus is shown in Fig.3.

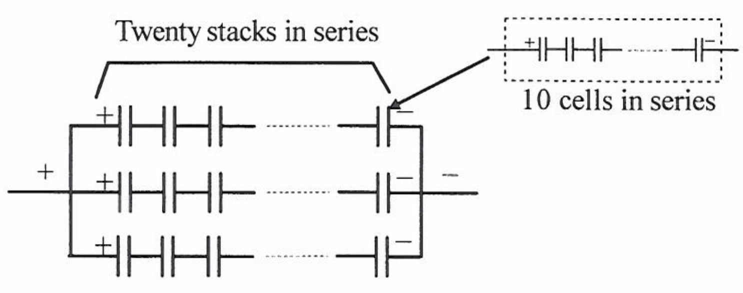


Fig. 1 The super-capacitor stacks in series-parallel.

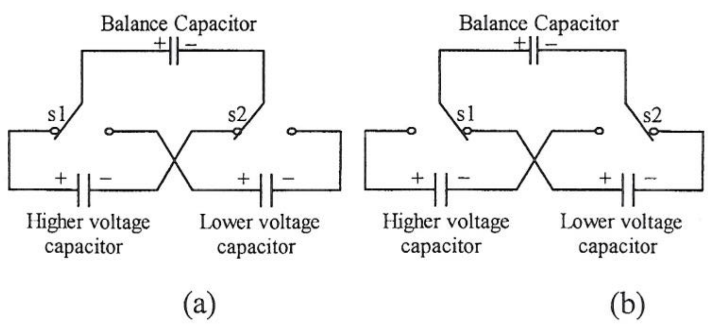
Fig. 2 The super-capacitor urban bus.

Fig. 3 The box containing super-capacitors.

1.2 Super-capacitor stacks management system

The management system includes two main functions. Firstly, many parameters are measured and monitored, including the individual voltage of sixty stacks, the total voltage of the stacks, the total charging and discharging current, and the internal temperature of the box. The other function is equalization on line. The state of charge (SOC) of super-capacitor is the main parameter that reflects the capacitance difference between different cells. The SOC and terminal voltage of super-capacitor cell has approximate proportional relationship. So it is feasible to achieve SOC balance through equalizing the terminal voltage. As described above, each stack is composed of ten cells in series and the cells were selected strictly so as to achieve approximate capacitance in a stack. Within a stack it is not necessary to equalize and this had been proven by experiments. So the equalization function is performed in the sixty stacks.

The principle of equalization operation is shown in Fig. 4. The main idea is to use another super-capacitor stack as balance capacitor (BC) to transfer energy from the highest voltage stack to the lowest one by switching S1 and S2 simultaneously. After many cycles of equalization, the voltage of individual stack will be closed to one another.



(a) Higher voltage capacitor charges BC (b) BC charges lower voltage capacitor

Fig. 4 Principle of the equalization.

The diagram of the super-capacitor management system is shown in Fig. 5. A data acquisition board was developed to periodically measure the total voltage, total current, temperature and twenty one stacks' voltage. A microcontroller and some extension units are used to control the switch network and realize the management functions. Fig. 6

shows the photo of the super-capacitor stacks management system.

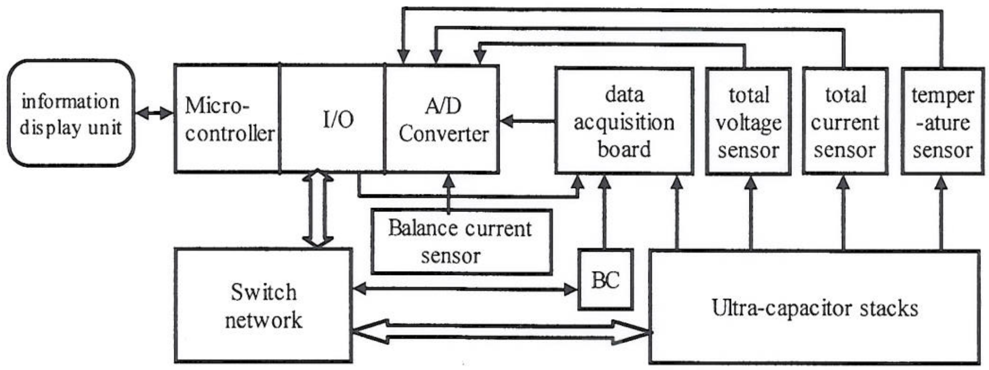


Fig. 5 Diagram of the super-capacitor management system.

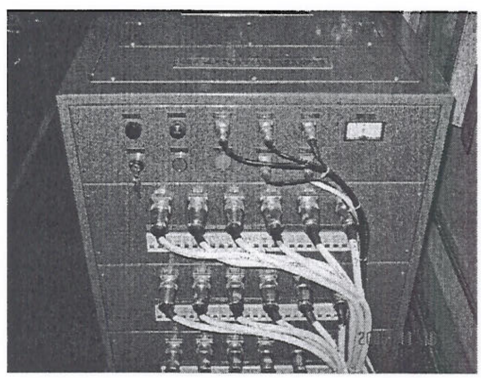


Fig. 6 Photo of the super-capacitor stacks management system.

2. CONTROL ALGORITHM OF EQUALIZATION

2.1 The selection of BC

The equalization operation is to connect BC to a certain super-capacitor stack in parallel by switching. The equivalent circuit is shown in Fig.7.

C_1 is the capacitance of BC. R_1 is its equivalent internal resistance in series. C_2 is the capacitance of the super-capacitor stack to be charged or discharged. R_2 is its equivalent internal resistance in series. S_1 and S_2 are the contactors of the switch. u_1 and u_2 are the voltages of C_1 and C_2 before the switch is turned on. If $u_1 > u_2$, then C_1 will charge C_2 when the switch is turned on. The function of voltage u_1 and u_2 versus time t is as follows,

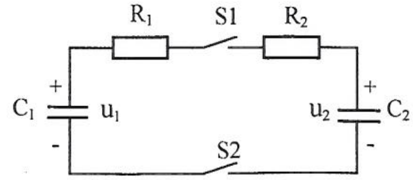


Fig. 7 Equivalent circuit of two capacitors in parallel.

$$u_1(t) = \frac{C_1U_1+C_2U_2}{C_1+C_2} + \frac{C_2}{C_1+C_2}\left(U_1 - U_2\right)e^{\frac{-(C_1+C_2)\,t}{(R_1+R_2)C_1C_2}} \quad (1)$$

$$u_2(t) = \frac{C_1U_1+C_2U_2}{C_1+C_2} - \frac{C_2}{C_1+C_2}(U_1 - U_2)e^{\frac{-(C_1+C_2)\ t}{(R_1+R_2)C_1C_2}} \tag{2}$$

The charging current is,

$$i(t) = \frac{U_1-U_2}{(R_1+R_2)}e^{\frac{-(C_1+C_2)\ t}{(R_1+R_2)C_1C_2}} \tag{3}$$

The decreasing speed of voltage u_1 and the increasing speed of voltage u_2 are $\frac{du_1}{dt}$ and $\frac{du_2}{dt}$ respectively.

$$\frac{du_1}{dt} = -\frac{U_1-U_2}{(R_1+R_2)C_1}e^{\frac{-(C_1+C_2)\ t}{(R_1+R_2)C_1C_2}} \tag{4}$$

$$\frac{du_2}{dt} = \frac{U_1-U_2}{(R_1+R_2)C_2}e^{\frac{-(C_1+C_2)\ t}{(R_1+R_2)C_1C_2}} \tag{5}$$

When the two super-capacitors are connected in parallel, the equalization speed is a function of the capacitance and the equivalent internal resistance of the two super-capacitors. So the correct selection of BC is very important to increase the speed of equalization.

From equation (4) and (5), the internal resistance of BC not only affects the time constant of charging or discharging, but also affects the initial varying speed of voltage u_1 and u_2. The less the internal resistance is, the higher the initial varying speed is, the less the decreasing time constant is.

From the above analysis, we should select BC with a small internal resistance so as to increase the initial equalization speed. But a small internal resistance will lead to a small time constant and then decrease the balance speed. To solve this problem, a control algorithm was adopted to change the frequency of the switch.

The capacitance of BC should be a suitable value. Too small capacitance of BC will lead to frequent switching and low energy efficiency. Too large capacitance of BC will decrease the equalization speed. In this project, it was selected as 3/4 of the capacitance of one stack. The rating voltage should be the same to other stacks.

2.2 Control algorithm

The control software includes four functions: data acquisition (voltage, current and temperature), equalization control, management and communication with Vehicle Management Unit (VMU). The most important function is the control algorithm of equalization.

In order to increase the equalization speed, three BCs were adopted in the three strings of stacks respectively. There are three states in the operation of the super-capacitor energy management system. They are charging, discharging and static state. The equalization control software estimates the state through the direction and value of the total current. Then different control algorithm is adopted for the corresponding state.

2.2.1 Equalization in the state of charging

Since super-capacitor has the feature of quick charge, it will be charged full within 20 minutes with a large current. BC is always controlled to parallel the stack with the highest voltage among the string in series. At that time, the capacitance of the stack is equal to the sum capacitance of BC and the stack. Larger capacitance results in slowing down the voltage increase while the voltage of other stacks is increasing quickly.

Following is the description of the procedure of switching BC from one stack to a new stack with the highest voltage among the string in the charging state. U_{full} is the rating voltage of a fully charged super-capacitor stack. C_{new} is the new highest voltage stack in the charging procedure. u_{new} is the voltage of C_{new}. C_{old} is the stack in parallel with BC before switching to C_{new}. u_{old} is the voltage of C_{old}.

Assuming $\Delta u = U_{full} - u_{new}$ and $\delta u = u_{new} - u_{old}$, when $\delta u \geq f(\Delta u)$, BC is disconnected from C_{old} and then connected to C_{new}. $f(\Delta u)$ is a composite function represented as:

$$f(\Delta u)=\begin{cases}\frac{1}{4}\Delta u & \Delta u \geq 6\text{V} \\ \frac{1}{3}\Delta u & 6\text{V} > \Delta u \geq 2\text{V} \\ \frac{1}{2}\Delta u & 2\text{V} > \Delta u \geq 1\text{V} \\ 0.5 & \Delta u < 1\text{V}\end{cases} \tag{6}$$

In this way all the stacks are protected from overcharge. By the end of charging, BC will be charged to nearly full and be ready for the discharge procedure.

2.2.2 Equalization in the state of discharging

Super-capacitor is capable of discharge with large current. Similar to the charging situation, BC is always controlled to parallel the stack with the lowest voltage among the string in series. At that time, the capacitance of the stack is equal to the sum capacitance of BC and the stack. In discharge, larger capacitance results in slowing down the voltage decrease while the voltage of other stacks is decreasing quickly.

2.2.3 Equalization in the static state

In the static state, there is no charging or discharging current flowing into or out from the stacks. The SOC of the whole stacks will be not changed. In this state the main task of equalization is to transfer energy from high voltage stacks to low voltage ones.

It is assumed that C_{max} and C_{min} are the super-capacitor stacks with the highest voltage and the lowest voltage respectively. U_{max} and U_{min} are the voltage of C_{max} and C_{min} respectively. U_{ave} is the average voltage of the whole stacks. U_{BC} is the voltage of BC. I_{BC} is the balance current flowing into or out from BC. I_g is the minimal balance current limit value. U_g is the minimal voltage difference limit value. Following is the procedure of equalization,

(a) Firstly find C_{max} and C_{min}

(b) Calculate U_{ave}, if C_{max} - U_{ave} $\leq U_g$, or U_{ave} - C_{min} $\leq U_g$, then go to step (f), otherwise continue to the next step.

(c) Compare U_{BC} with U_{ave}, if $U_{BC} \geq U_{ave}$, then BC is in parallel with C_{min}, C_{min} will be charged by BC. Otherwise if $U_{BC} \leq U_{ave}$, then BC is in parallel with C_{max}, BC will be charged by C_{max}.

(d) Check the current I_{BC}, if $I_{BC} \leq I_g$, then disconnect BC from C_{min} or C_{max}, and return to step (a). Otherwise if $I_{BC} \geq I_g$, continue to next step.

(e) Check the voltage difference U_{BC} - U_{min} (or U_{max} - U_{BC}), if it is higher than U_g, then go to step (d). Otherwise continue to next step.

(f) Stop equalization function.

3. EXPERIMENTAL RESULT

The equalization experiments were performed on a string of twenty super-capacitor stacks in series as described in section 1.1. The experiments were carried out in three operation states, including charging, discharging and static status. In order to investigate the validity of equalization, the experiments with equalization and without equalization were performed in the same condition. Fig.8 ~ Fig.13 shows the results.

3.1 Charging experiment

The initial voltage of the stacks is 168.8v corresponding to average voltage of 8.44v. The maximum voltage difference between stack voltage and the average voltage is 0.25v. The charging method is constant current and then constant voltage. In the constant current stage, the stacks were charged as a constant current of 50A for 12 minutes. When the total voltage reached 325V, the charging method changed to constant voltage.

The charging experiments were carried out in two cases, one is without equalization and the other one is with equalization function. Fig.8 shows the individual cell voltage after the super-capacitor stacks were charged and deeply discharged for ten cycles without equalization and then fully charged. In the figure, V_{ave} is the average voltage of twenty stacks. Δ_{max} is the maximal voltage difference between V_{ave} and individual stack voltage. Obviously the maximal voltage difference Δ_{max} was enlarged from 0.25v to 1.21v after ten cycles without equalization. Some of the stacks had been overcharged and some others were not yet fully charged. This is very harmful to the cycle lives of the overcharged super-capacitors.

Fig. 9 shows the charging result with equalization function. The voltage difference Δ_{max} is 0.32v by the end of full charge. It is still larger then 0.25v. This is because the equalization speed is a little bit low relative to the high charging current (200 ampere). But this result is good enough to prevent the stacks from overcharge.

3.2 Discharging experiment

The stacks were fully charged and then equalized in static state until the maximal voltage difference Δ_{max} equal to 0.25v. Based on this condition, the discharging experiment was performed through drive motor at a current of 30A~35A. The cut-off voltage is 160v. Fig. 10 shows the results of discharging without equalization. Similar to the charging experiments, by the end of discharging Δ_{max} were enlarged to 0.59v. Some stacks had been overdischarged. Fig. 11 is the results of discharging with equalization. The stacks were protected well from overdischarge and the online equalization precision is good enough.

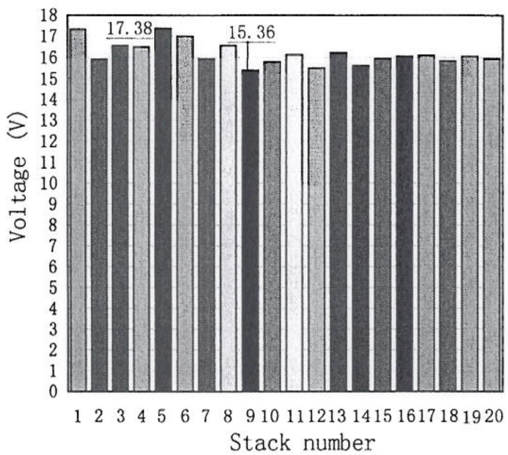


Fig .8 Individual cell voltage when fully charged without equalization
Vave=16.17v Δmax =1.21v

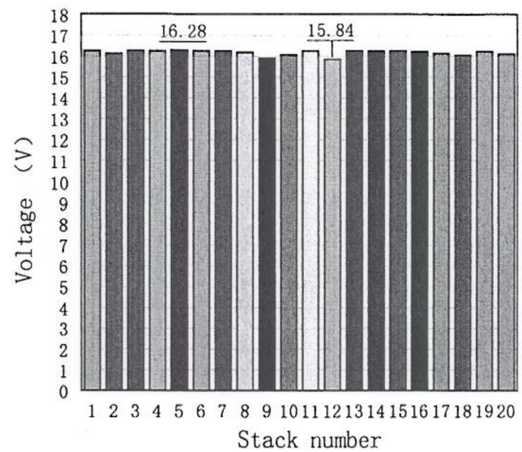


Fig. 9 Individual cell voltage when fully charged with equalization online
Vave=16.16v Δmax =0.32v

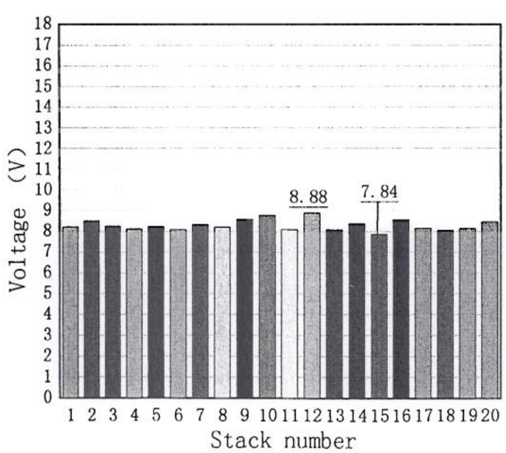


Fig. 10 Individual cell voltage when fully discharged with no equalization
Vave=8.29v Δmax =0.59v

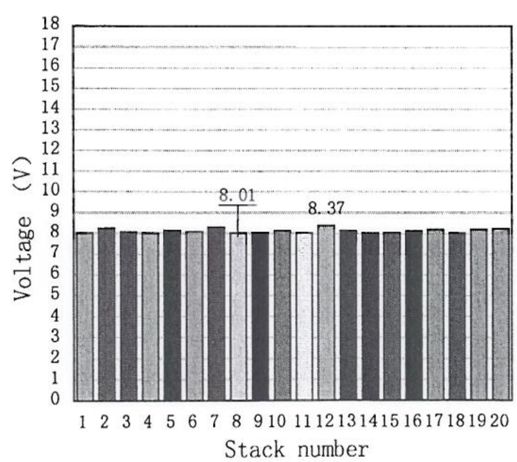


Fig. 11 Individual cell voltage when fully discharged with equalization online
Vave=8.11v Δmax =0.26v

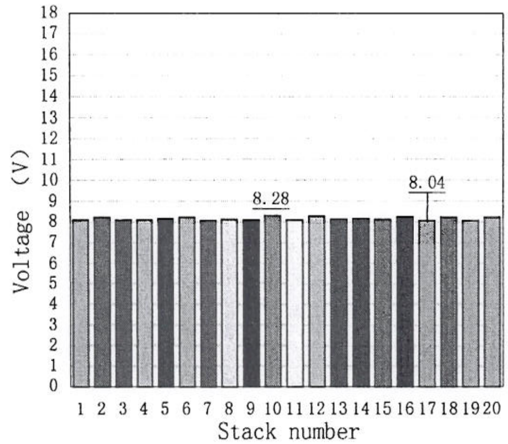


Fig. 12 Individual cell voltage after equalized in static state Vave=8.14v Δmax =0.14v

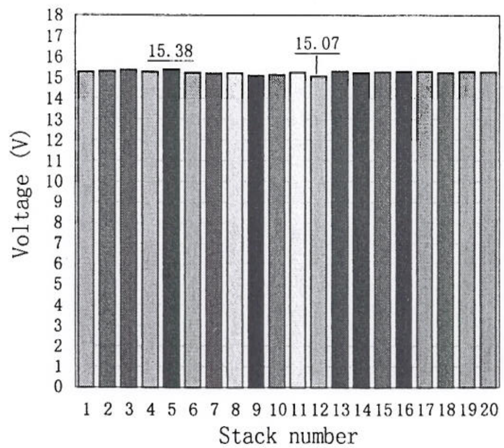


Fig. 13 Individual cell voltage after equalized in static state Vave=15.24v Δmax =0.17v

3.3 Equalization in static state

Equalization experiment in static state was carried out in the case of the stacks were nearly empty and full respectively. The equalization results are shown in Fig.12 and Fig.13 respectively. The initial maximum voltage differences Δ_{max} are 0.63v and 1.23v respectively. The equalization procedure lasted for several hours and stopped until the balance current was less than 0.5A. By the end of equalization the maximum voltage differences Δ_{max} are 0.14v and 0.17v respectively. This means the equalization precision in static state is very high.

4. CONCLUSION

The efficiency of the proposed super-capacitor stacks management system has been verified in experiments. All the necessary information for energy management such as voltage, current and temperature is measured and monitored. All the individual super-capacitor stacks are effectively protected from overcharge and over discharge through the equalization function. There is no doubt that this protection will extend the cycle life of the whole super-capacitor system and thus reduce the cost of the bus. The shortage is the relatively low online equalization speed compared to the quick charge and discharge ability of super-capacitor. But in fact the equalization operation needs not to be performed very frequently since the voltage difference between individual stacks becomes large only after many charge and discharge cycles. So the equalization is often performed in static status and results in very high equalization precision. On the other hand, the online equalization speed will be fast enough if the system was used for some electrochemical battery management systems.

5. ACKNOWLEDGMENTS

The authors of this paper would like to thank the Science and Technology Committee of Heilongjiang Province of China for the financial support to the project "Super-capacitor Stacks Management System".

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