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On Adaptive SOH Equalization for $LiFePO_4$ Battery Packs

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Abstract:
Equalizing SOH between Li-ion batteries is critical for Battery Energy Storage Systems (BESS). It cannot only decrease the SOH deviation between batteries, but also increase total available charge until the end of life. To address this issue, an adaptive SOH equalization algorithm for $LiFePO_4$ batteries is proposed in this study. In situation of temperature difference distribution within the range 5℃ from module to module, the SOH equalizer by controlled depth of discharge (DoD) is applied to slow the rate of capacity fading. By realizing adaptive control loop, the exact cycle-life model is not necessary to determine the DoD value. The appropriate proportion control parameter K is determined by the adaptive control algorithm. The battery pack with the adaptive controller can increase 14.0% available charge in simulation cases with different temperature. Moreover, it can also increase 13.3% available charge in simulation case with both different temperature and capacity. The implementation includes the SOH equalizer and the battery management system. The platform provides both complete SOH equalization and the protection for battery energy storage systems. Experimental results that cycled an aged module and three fresh modules indicated that SOH gap between each module didn't reduce. Other controlled experiment cycled 4 fresh modules, and result showed the SOH gap between each module is reduced.

Keywords:
$LiFePO_4$ batteries, State of Health (SOH), Battery Energy Storage System (BESS), Depth of discharge (DoD), adaptive equalization

1. Introduction

Lithium iron phosphate ($LiFePO_4$) batteries are increasingly being used to match the demand of both the power density and safety consideration in prevalent electric vehicle designs. There are thousands of batteries in EV. For example, a Tesla EV includes more than 7000 18650 cells in battery packs. When batteries are discharging, each cell core acts like a heat source. The cells placed in middle are under the higher temperature environment, and their capacity fading rates are higher than other batteries. Many researches have been conducted in the topic of battery pack thermal management. The research results can reduce the modules temperature difference of battery modules by about 8^{o}C[1]. In the situation of temperature distribution smaller than 5℃ between modules, the simulation result shows that maximum difference of nominal capacity is 9.46% when average full charge capacity (FCC) reaches 80% rated capacity.

A complete battery management system includes the battery equalizer which balances either the battery SOC or the voltage. Typically, the temperature and the voltage are different slightly between each battery cell. Those differences make batteries stop discharging when the worst one reaches the termination conditions. Traditional researches focus on that cell balancing can obtain maximum usable capacity from the battery pack[2]. The most popular equalization is to apply active balancing algorithm in series connected lithium-ion batteries. An external circuit is designed to actively transport energy among cells, thereby extending the pack's operation time at the present cycle[3]. The same method is also used in the researches which study about parallel-connected batteries [4]. In this study, the focus is to extend the operation time for series connected battery pack and increase total available charge for parallel battery packs.

An adaptive SOH equalizer with controlled DoDvalues is applied to reduce the rate of capacity fading and increase total available charge capacity when the batteries reach the end of life (EOL). First, the utilization ratio of new batteries is enhanced by slowing won the capacity fading of the worst module, thereby increasing the total available capacity. Second, the exact cycle-life battery model is not necessary to determine the controlled DoD value. The value is adjusted adaptively by the control algorithm. Last, the SOH of battery is being equalized until the end of life. Therefore, the cost is reduced to identify each module SOH in re-purposing retired battery packs. This study is organized as follows. In section II, the adaptive control algorithm which equalizes the SOH gap is explained. Section III describes the implementation about the BMS and the experimental results. Section IV concludes this paper and discusses the related works

2. Adaptive SOH Equalization

2.1. Adaptive Control Algorithm

In order to equalize the SOH of each cell, we develop a proportion control system and select a control variable adaptively to slow the rate of capacity fading. The variable should not affect the fading of othermodules which are not controlled. The battery variables about C-rate and different charge/discharge process are not chosen. And depth of discharge (DoD) is suitable for our demands. The less DoD that is used, the more cycle-life the battery pack can provide[5,6]. But the DoD cannot always be reduced to zero for each cell in pack. They would lose the meaning of existing about providing power to system requirement. So we equilize SOHs by controling the DoD of worst battery module. It is assumedthat other modules will be discharged until batteries reach $\mathrm{DoD}_{\mathrm{Max}}$ designed by system. Those DoDs will be used in next ten cycles and affect FCC fading rates. The maxium difference between each battery is chosen to be our contorl loop feedback.The minum difference is set to be the command input in (2). The puepose it to make the max difference to equal the min difference and use their difference to be system error. The error will multiply by a control factor K to calculate $\mathrm{DoD}_{\mathrm{ctrl}}$.

$$\delta_{ij} = \mathrm{FCC_i} - \mathrm{FCC_j}, \delta_{ij} \geq 0 \quad (1)$$

$$\begin{cases} \triangle\, \mathrm{FCC}_{min} = \mathrm{Min}\left[\delta_{ij}\right] \\ \triangle\, \mathrm{FCC_{Max}} = \mathrm{Max}\left[\delta_{ij}\right] \end{cases} \mathrm{i, j} \in \{1,2,3,4\} \text{ and } \mathrm{i} \neq \mathrm{j} \quad (2)$$

Unfortunately, the proportion control system also need exact cycle-life model to find out which is the appropriate proportion. Each different proportion has different effect to battery pack. For example, large proportion has good performances in setting time. But it's not so good in the all life available charge. We have no idea to get the key proportion in the proportion control without models. By the way, there is no accurate model which fitting all battery. So we develop an adaptive control system.

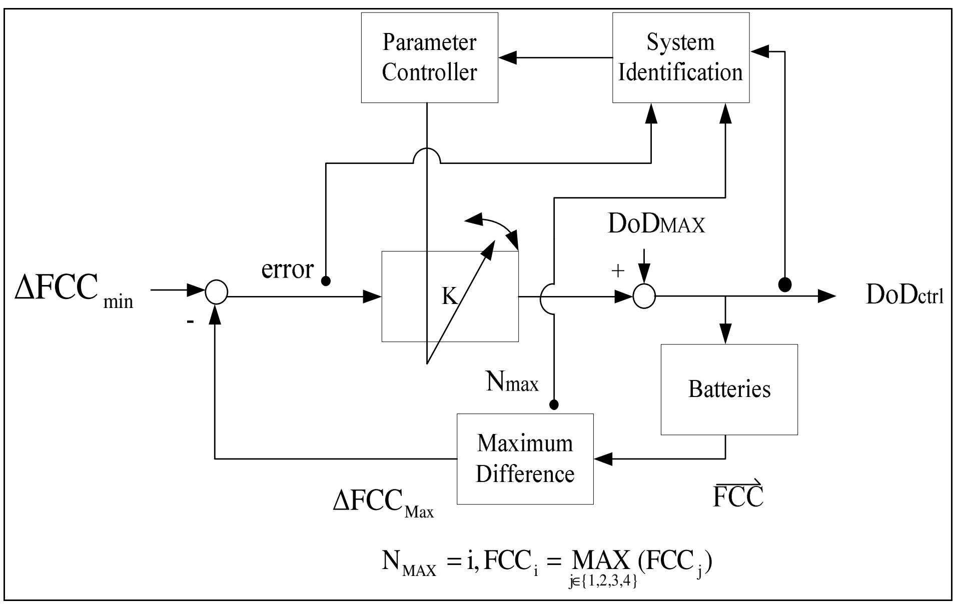
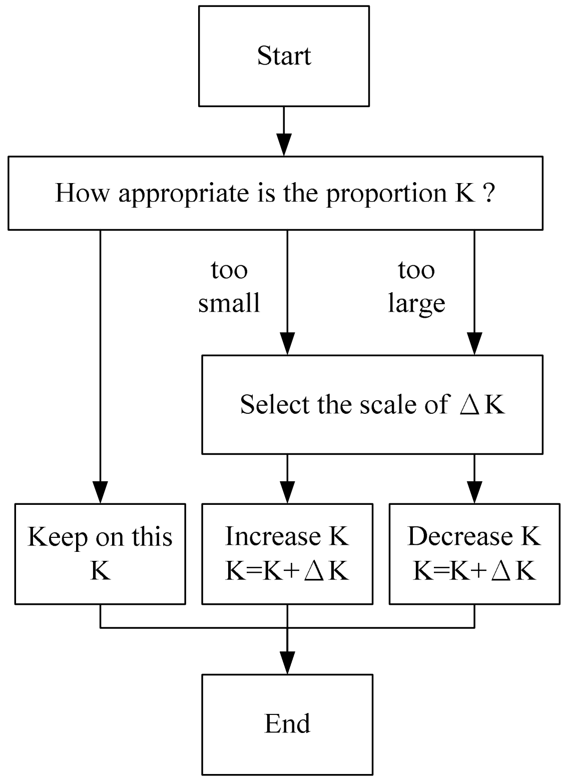


Figure 1:Adaptive control system.

As depicted in figure 1, we add other functions in the proportion control loop to avoid the requirement of the exact model for aged batteries. The system identification finds some trails to identify that $\mathrm{DoD}_{\mathrm{ctrl}}$ is worked or not. According to those trails, the parameter controller adjusts the value of K.Their operation flow is shown in figure 2.



Scale	ΔK
1	0.01
2	0.02
3	0.04
4	0.08
5	0.16

Figure 2:System identification and parameter controller flow chart.

In the beginning, the most important thing is that only poor battery should be controlled. Therefore, the DoD_{ctrl} should not let controlled battery's FCC be the newest one after ten cycles. Based on this opinion, we judge the proportion K from some rules. The value of K is increased under the following conditions: (i) if the system error is greater than or equal to the previous error, (ii) if the pervious DoD_{ctrl} is not 0, and (iii) if the current newest battery is the same as the previous freshest one. If the system error is less than the previous error or the current newest battery is different to the previous newest one, the value of K is reduced. It is hoped that if K is not close to the desired value, we can approximate it within one hundred cycles. So the biggest ΔK is 0.16, and the least one is 0.01. If ΔKis increased or decreased three times continuously, the scale will increase in the next step. If the direction of the control value is charged, the scale will be decreased. But we make an exception when the error is constant. In this case, the scale is decreased when the value of K is increased.

2.2. Battery Aging Model

An A123 System APR18650m1 $LiFePO_4$ cell with a nominal capacity of 1.1 Ah is modeled by the temperature, incremental DoD (Δ DoD), initial SOC, and charge process [6]. The Δ DoD is the difference in SOC from the initial stage to the final stage. It concludes that the different low discharge C-rates don't contribute to additional capacity fading [6]. The total capacity fade is calculated by

$$\xi(T, SOC_{avg}, SOC_{dev}, Ah) = \sum_i^E \left(\left(K_{s1} SOC_{dev,i} \cdot e^{K_{s2} \cdot SOC_{avg,i}} + K_{s3} e^{K_{s4} SOC_{dev,i}}\right) e^{-\frac{E_a}{R}\left(\frac{1}{T_i} - \frac{1}{T_{ref}}\right)} \right) Ah_i \tag{3}$$

$$SOC_{avg} = \frac{1}{\Delta Ah_m} \int_{Ah_{m-1}}^{Ah_m} SOC(Ah) dAh \tag{4}$$

$$SOC_{dev} = \sqrt{\frac{3}{\Delta Ah_m} \int_{Ah_{m-1}}^{Ah_m} \left(SOC(Ah) - SoC_{avg}\right)^2 dAh} \tag{5}$$

Here ξ is the total capacity fade, i is an event, which is an arbitrary determined period that the stress factors are assumed to be constant, T_{ref} is the reference temperature in Kelvin. Where K_{s1}=-4.092E-4, K_{s2}=-2.167, K_{s3}=1.408E-5, and K_{s4}=6.130 [6]. And usable capacity is

$$C_{use} = (Q_{nom} - \xi) \cdot e^{K_1\left(\frac{1}{T-K_2} - \frac{1}{T_{ref}-K_2}\right)} \tag{6}$$

Where K_1=-5.738 and K_2=2.099E2 [7]. Q_{nom} is the nominal capacity at reference temperature.

2.3. Simulation Results

We simulated our adaptive control system in the conditions as table I:

Module	1	2	3	4
Capacity (mAh)	1100	1100	1100	1100
Temperature (℃)	25	26	28	30

Table1: Simulation conditions

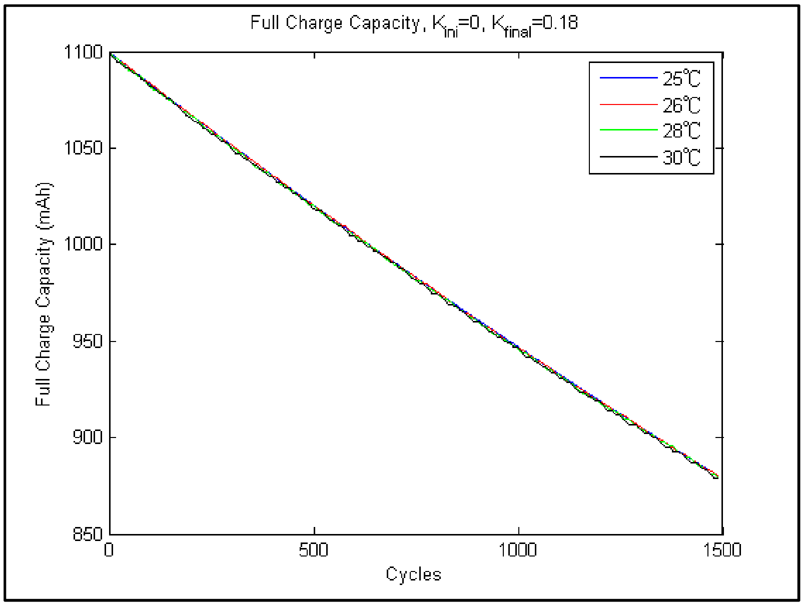


Figure 3: The FCC of cells cycled at different temperatures with adaptive control versus cycles.

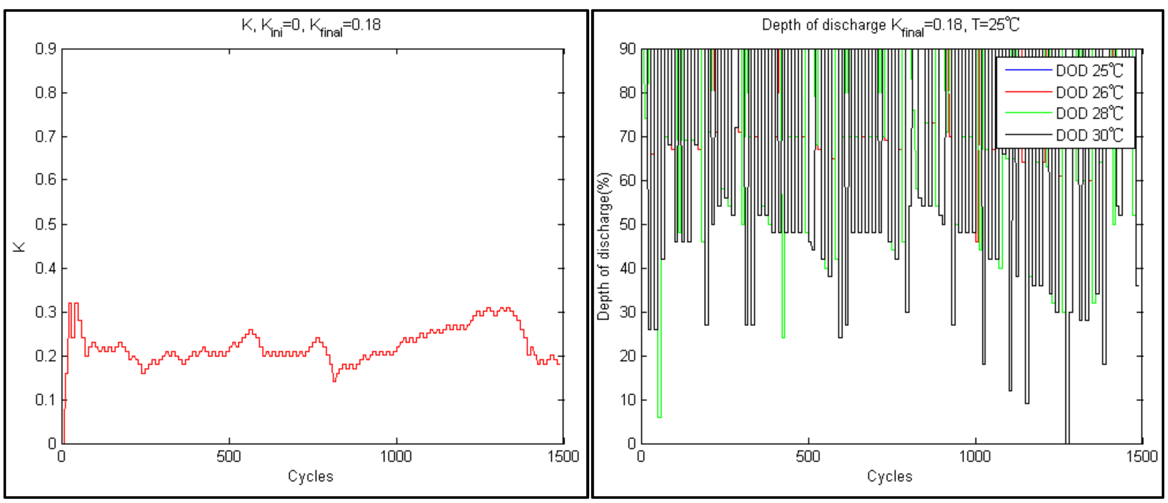


Figure 4: The parameter of system versus cycles (a) K and (b) DoD_{ctrl}.

Figure3 shows that the FCC of cells was close to each other, and the different capacity fading affected by temperature was controlled by our adaptive control system. The system proportion K variation and depth of discharge of cells are shown in figure4. The value K follows those adaptive rules and is changed every ten cycles. According to the K value and the system error, the controlled DoD is determined to compensate the temperature effect. By using this adaptive algorithm, the available charge capacity is rise from 4.13 kAh to 4.74 kAh, and the average available charge capacity with different initial K values is 4.71kAh. There is 14.0% additional charge improvement. If we set 0.5% of capacity in the end of life which is 5 mAh to be steady state error, the settle time is 0 cycle in temperature around 25℃ to 30℃ and 30℃ to 35℃.The settle time is about 300 cycles in 35℃ to 40℃. Furthermore, we simulated both different temperature and capacity with ±0.5% capacity error. The algorithm also reduces the FCC as shown in figure5, and increased 13.3% in available capacity.

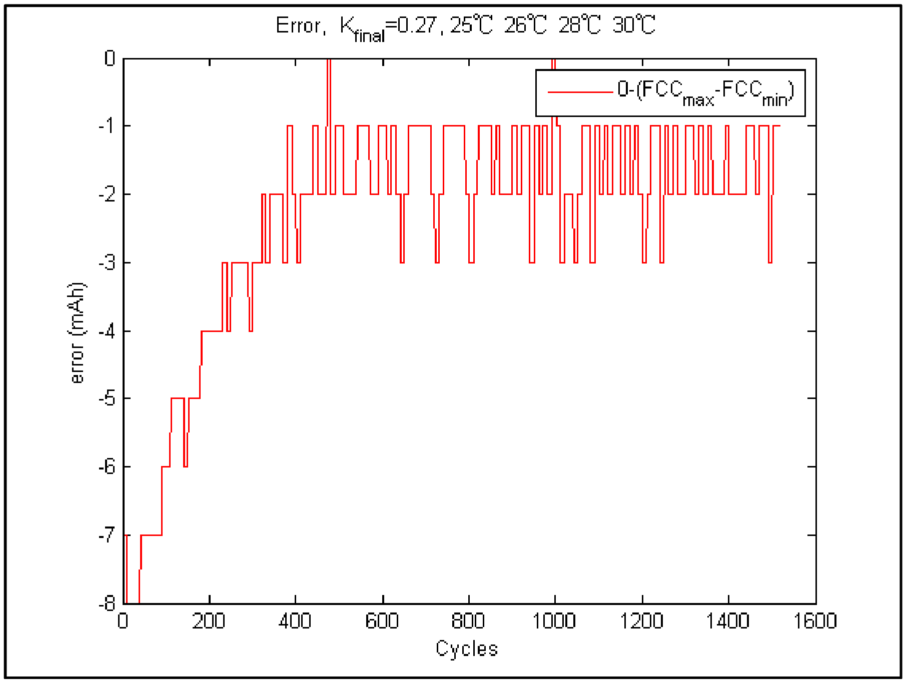


Figure 5. The error versus cycles with both different temperature and capacity.

3. Hardware Implementation and Experiment Results

The design of a PHEV or EV is made by considering an average current of around C/2 in a normal driving cycle and a peak current in the measure of C to 2C during high speed or accelerations [8]. So we design a system include gauging functions and adaptive control algorithm. And the discharging current is 1C and charging method is CC-CV.

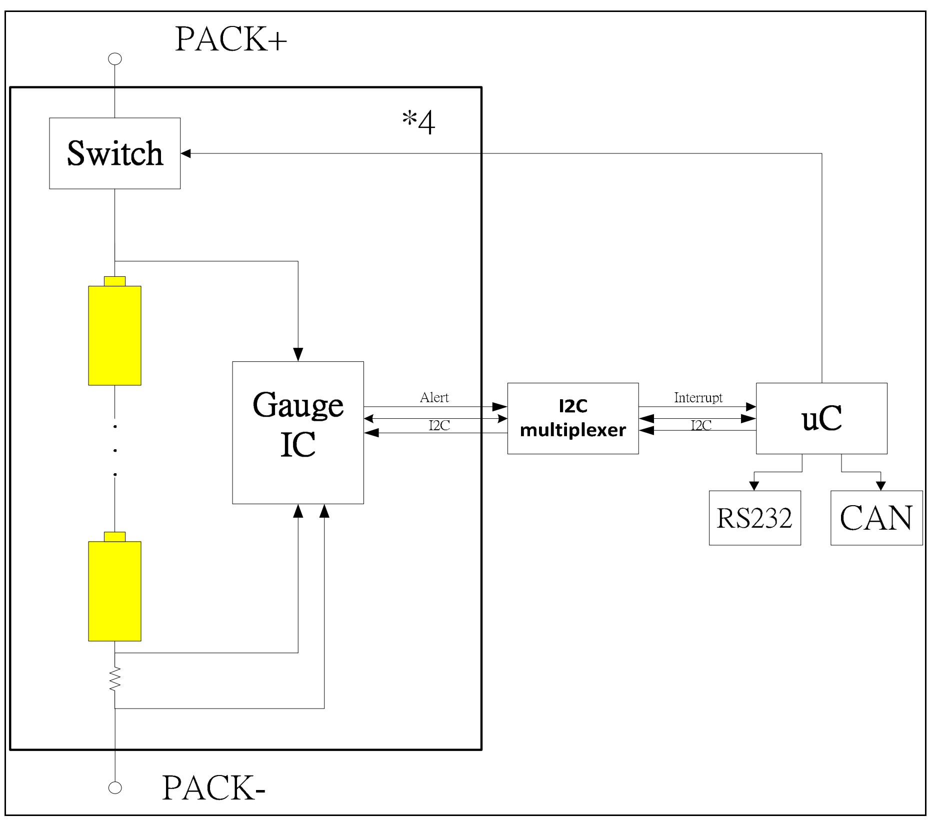


Figure 6: The system schema.

As depicted in figure 6, a series-connected battery is gauged by TI's gauge IC, bq34z100. And the pack connects each module's + and – to be pack + and -. The I^2Cmultiplexer collects data from gauge IC and send to micro-controller. The micro-controller checks battery status every one minute, and records data to PC. It calculates that information to control the worst battery's DoD. The system switches control flow is shown in figure7. When battery is in the full charge status, the system calculates the control SOC for next ten cycles. If the worst cell reaches the SOC low limit, and the system turns off its switch. Others continuously discharge to cut-off voltage, and then the system turns off switches. When the current is charging into some cell, the system turns on switches which are not under controlled at this moment. When other modules SOC are equal to the controlled cell, the controlled switch is turned on. After all, SOC values reach 100%, the next control cycle starts.

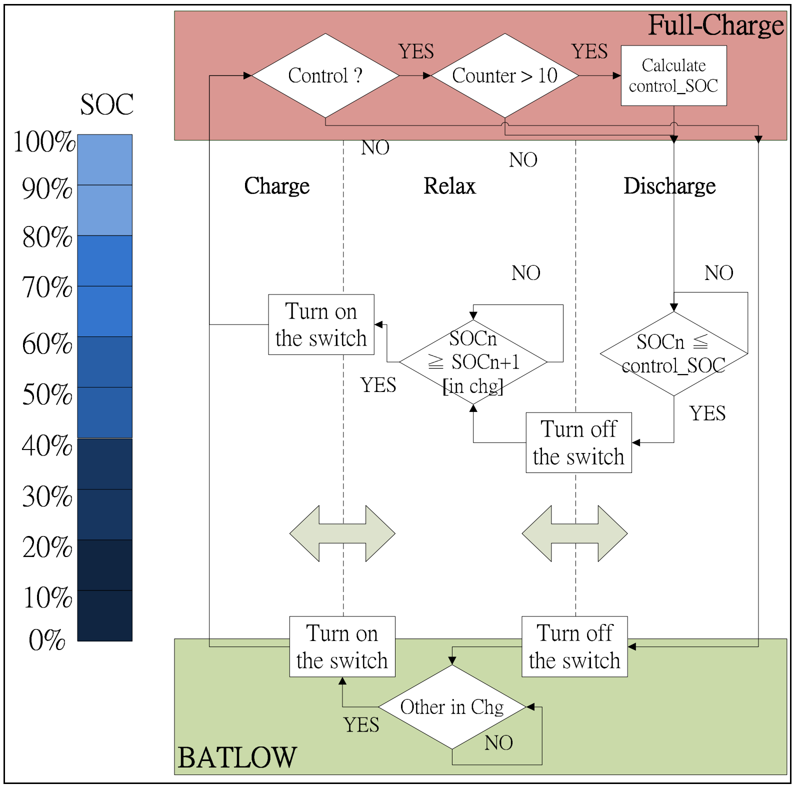


Figure 7: The switches control flow chart.

First, we implement an aged module and three fresh new modules, and all of them are cycled in room temperature. The FCC versus cycles chart is as figure 8. The experiment is intended to find out that if different SOH parallel batteries could approach each other automatically. Experimental results indicate that SOH gap between each module does not reduce. The worst one is not necessarily with the highest rate of capacity fading, and their FCC gap might expand as well.

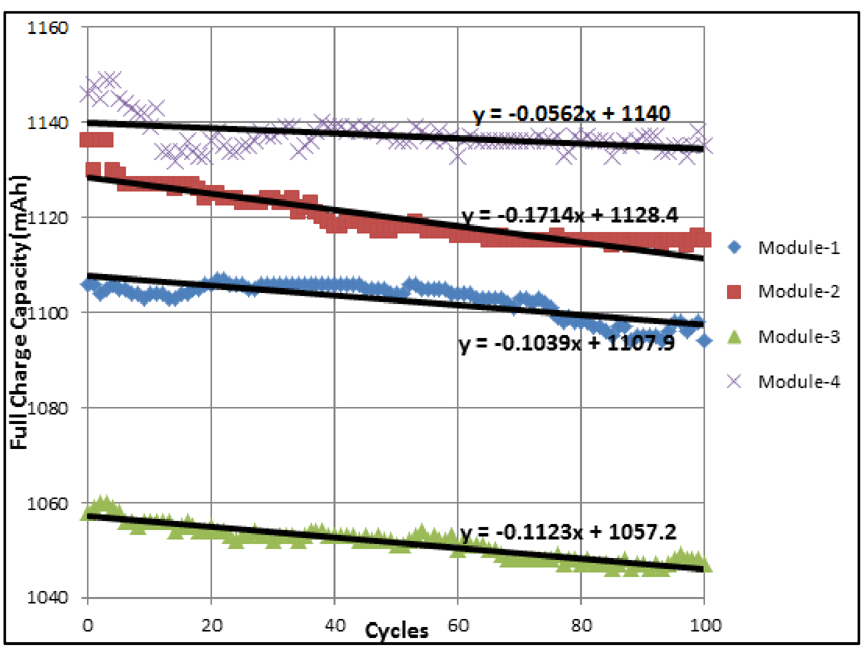


Figure 8: The capacity of modules without control versus cylces.

Then, 16 new cells are constructed intoa 4S4P module. The different initial capacities between the modules is unexpected. All the experiments of the modules are conducted in room temperature, and the results are shown in figure9. In this experiment, the controlled module is Module-2. By the controlled depth of discharge, we slowed the rate of capacity fading as predicted. But the Module-1 was not smoothly in 20 to 50 cycles. We guessed that SEI was formed in new cells, and its unstable state makes it vary drastically. Module-1 FCC is recovered after few cycles, so linear fitting line is decided by the interval of 50 to 100 cycles. By the way the Module-4 data missed in figure 9 from 20 to 40 cycles and around 80 cycles, because we choose the recording data in the figure basing on that FCC measured in SOC=100%. The controlled DoDseemingly causes the gauge IC not working for few cycles. Finally, the result shows the SOH gap between each module is reduced.

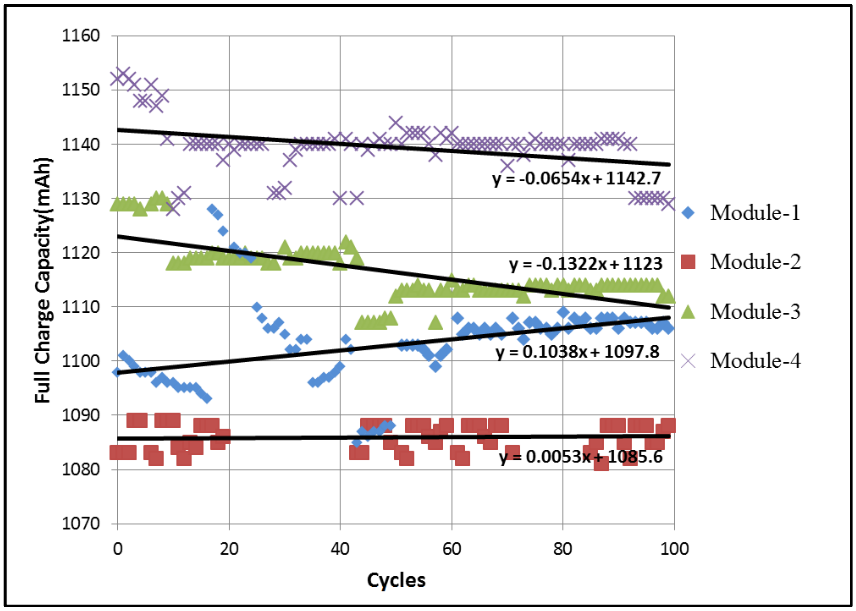


Figure 9: The capacity of modules using adaptive control versus cylces.

4. Conclusion

This paper proposes an adaptive SOH equalization control system for $LiFePO_4$ battery pack. Typical BMS focus on balancing the difference of batteries connected in series. They extend operation time in one cycle, and improve the safety of battery power system. But some parallel-connected battery BMS do the same job. We think BMS should extend operation time in series connected battery pack and increase total available charge in parallel pack. The control system should not need accurate modeling of $LiFePO_4$, and it balances batteries by the adaptive rules. Form simulation conditions and results in table II, we always could get over +10% increasing rate by using adaptive control. Even if the temperature is between 35℃ to 40℃, we also gain 12.6% average available capacity. The implementation includes safety protection and switch control by gauging and monitoring data. Experimental results that cycled aged and fresh modules indicated that SOH gap between each module didn't reduce. It should be controlled like experiment cycled 4 fresh modules, and result shows the SOH gap between each module was narrowed.

Methods/Conditions	Adaptive control	Without control	Increasing rate
25℃~30℃, rated capacity	4.71 kAh	4.13 kAh	+14.0%
35℃~40℃, rated capacity	1.70 kAh	1.51 kAh	+12.6%
25℃~30℃, ±0.5% rated capacity	4.68 kAh	4.13 kAh	+13.3%

Table 2: The increasing rate of different conditions

The future works should exam other kinds of $LiFePO_4$ battery model, and add some disturbance like implementation gauge IC measuring. Or we should use better accurate FCC gauge IC to make condition as simulation. Finally, we could compose series and parallel BMS to build high level BMS. It supervises and regulates itself. Then we could easily plus or reduce the level of battery power systems.

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