出國報告（出國類別：國際會議）

參加 2014ISIE 國際研討會發表論文

服務機關：國立虎尾科技大學

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出國期間：5/30－6/8

報告日期：103/7/17

摘要

本研討會目的是針對工業電子(Industrial Electronics)之研究開發，提供一個會議平台，讓相關學者進行交流討論，促使此研究領域能更為蓬勃發展，本次會議涵蓋『電動機驅動器』、『轉換式電源』、『工業電子應用』、『再生能源電源轉換技術』、『儲能設備充放電技術』與『LED 應用技術』。本人參與部分偏向電力電子技術，其技術廣泛應用於生活層面，它們被應用於電池充電器、LED 光源驅動器、電源供應器等設備，這些都是與我們生活密不可分的。ISIE2014 國際研討會提供了關於電力電子研究領域的交流場合，相信經由此次研討會的所投稿的眾多論文與各國學者交流後，能更了解電力電子最新研究發展動態，並帶回大會論文得之最新研究資料，並仔細鑽研，相信能有效提升本研究群的研究能力。

目次

本文

一、 目的

本研討會目的是針對工業電子(Industrial Electronics)之研究開發，提供一個會議平台，讓相關學者進行交流討論，促使此研究領域能更為蓬勃發展。本研討會歷史悠久，從初次舉辦目前已舉辦有 20 多年之久，本次會議涵蓋『電動機驅動器』、『轉換式電源』、『工業電子應用』、『再生能源電源轉換技術』、『儲能設備充放電技術』與『LED 應用技術』，亦符合本人之電力電子應用研究領域。

二、 過程

本研討會由土耳其海峽大學(Boağziçi University)負責聯繫協調主辦，所有研討議程均在 Grand Cevahir hotel 舉行。此次會議議程從 6 月 1 日至 6 月 4 日共四天，除了論文發表外，也安排了專題演講與學術教學課程。我和其他教授都積極把握四天議程，聆聽專題演講、參觀展示攤位與參與論文發表與討論。論文發表分成『口頭報告』和『海報展示』兩部分。在議程期間依據自己研發的領域與興趣，參與了多個場次的論文成果發表，都是有關電力電子(Power Electronics)領域的論文，內容涵蓋『電動機驅動器』，『轉換式電源』，『工業電子應用』、『再生能源電能轉換技術』、『儲能設備充放電技術』與『LED 應用技術』等。除了在論文發表議場內，在中場休息期間也和國內外學者寒暄討論。他們對於台灣近年來在電力電子相關領域的蓬勃發展，均深表敬佩與欽羨。特別是台北科技大學電機系賴炎生教授榮獲 IEEE 院士，為台灣電力電子爭光，也讓我們與有榮焉。

我的論文（The Optimized Capacity for Lithium Battery Balance Charging/Discharging Strategy）發表安排在第三天 6 月 3 日下午，是研究鋰電池最佳化充放電技術，針對電池容量與電路效率，提出平衡充電技術電路與控制策略，發表的過程很順利，也能引起聽眾高度興趣。針對本篇論文的提問甚多，能與國外學者，針對自己研究領域進一步做深入討論，提供不少意見交流與指教，對本人後續研究有不少助益

三、 心得

工業電子與電力電子廣泛應用於人類生活上，如：電池充電器、LED 光源驅動器、電源供應器等設備上，都是與人類密不可分的設備。ISIE2014 國際研討會除了工業電子外，亦提供了關於電力電子研究領域的交流場合，相信經由此次研討會的所投稿的眾多論文與各國學者交流後，能更了解電力電子最新研究發展動態，並帶回最新研究資料，並供學生仔細鑽研，相信能有效提升研究群的研究能力。

四、 建議事項

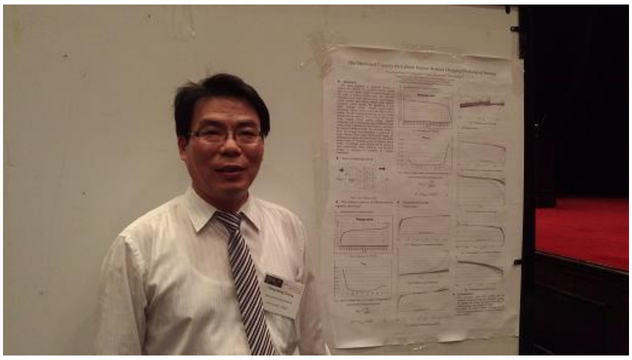
1.台灣學者參與在歐洲舉辦之國際研討會並不是很熱衷，相對於在亞洲舉辦之國際研討會，因路途遙遠及經費的限制，參與的比例較少。但歐洲研討會相對能與多國國際學者交流的機會較多，由其是鼓勵學生們的參與國際研討會，應在經費及核定時程上給予較方便的規劃，以本次研討會為例，原本有一名學生有意前往，但於出發前仍未見經費核定，學生礙於經費問題不敢預購機票及預訂旅館，而未能成行，相當可惜錯失一次國際交流機會。

2.國際研討會與舉辦亦可促進觀光，台灣應可鼓勵學術單位大量舉辦，除可讓國內學者免舟車勞頓即可與國際學者交流外，亦可促進國內旅遊觀光。

附錄

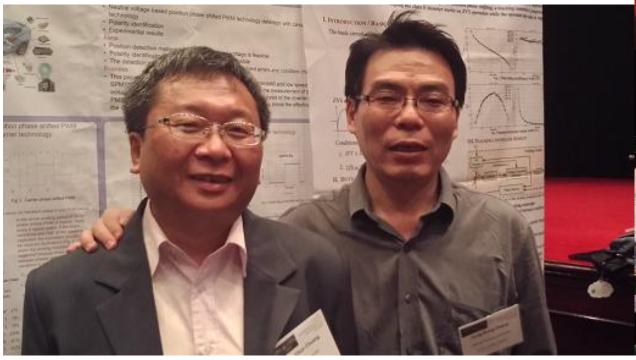
於 ISIE2014 國際會議報到處

於 ISIE2014 國際會議海報處



於論文發表處

於各國學者晚宴交流



與國內學者合照

與國內外學者合照

The Optimized Capacity for Lithium Battery Balance Charging/Discharging Strategy

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***Abstract*—This paper proposed an optimized strategy to enhance the capacity of a cascaded Lithium battery pack. An active balance system is used to elongate the life cycle of Lithium battery pack. The proposed techniques cover active balance circuit, digital balance control module and Lithium battery pack capacity optimized control strategy. By integrating E-class series resonant circuit, shunted multi-winding transformer, balance control switch and digital control module, the cell charging/discharging process will be divided into ten intervals. Every interval has its own linear voltage versus surplus charge capacity relationship with corresponding slope. Different proper balance factor is defined for each interval to determine the action of balance switch. The cell with voltage is below the average. The experiment is performed by using Lithium battery pack 16S1P to investigate the charging/discharging behavior of each cell and define balance factor to switching action of balance control switch. The battery pack function will be measured when experiencing charge imbalance and optimized strategy is employed to complete the balance requirement.**

Keywords—Lithium battery; active balance circuit; optimal strategy; balance factor; corresponding slope

I. INTRODUCTION

Due to predominance of environmental consciousness accompanied with the modern technology, Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) are playing the major role in automobile industry. The electric vehicles require DC voltage ranging from tens to hundreds volts, even with thousands watt of power backup. Therefore, one single cell can no more meet voltage, current and power requirements for a modern electric vehicle. In general, the high power applications of cell are accomplished by connecting many single ones in series to obtain higher voltage. The discrepancy among every single cell would lead to significant influence. There exists minor difference among every single cell when produced, let alone after long-time usage. The single cell with poorer performance will create vicious cycles and cut down the life cycle. Before the standard life time, the whole cell is damaged. Therefore, battery management [1] becomes an important issue in practical application. The battery management includes balanced charging technique and balanced discharging technique. It aims at equalizing the charging amount and discharging amount on every single cell to ensure the identical surplus charge and further storage efficiency of battery pack.

A comprehensive battery management system includes measurement, balancing, and protection [2]. Wherein, precise measurement is the principal function. In the charging process of Lithium battery, the voltage variation is very minor. It is only in the end of charging and discharging process, the cell voltage would appear abrupt change. Hence, it is important to measure the voltage on every single cell precisely. A battery management system is composed of software and hardware. Its management is somewhat different from the type of battery and can be accomplished through investigating the battery characteristics, constructing battery module and measuring battery electric charge within. In a battery pack connected in series form, Cells with identical capacity initially suffer from different capacity reduction on every single cell after long time use as demonstrated in Fig.1. In Fig. 1, Cell_1~Cell_3 are all originally healthy battery with capacity 10AH. After being used a period, Cell_1 still preserves its original capacity 10AH, Cell_2 keeps 9AH capacity while Cell_3 upholds only 7AH capacity. The unbalanced capacity will lead to unbalanced charging and discharging effect. The unhealthier Cell_3 can only be charged to charging voltage limit 3.6V for preventing from overcharging. At this point, Cell_1 and Cell_2 possess only 3.4V and 3.5V respectively, leaving 15% and 10% correspondingly idle capacity. On the other hand, the unhealthier Cell_3 can only be discharged to discharging voltage limit 2.1V for preventing from under charging while Cell_1 and Cell_2 reach 3V and 2.8V respectively with 15% and 10% capacity unused. After long-time usage, Cell_1 and Cell_2 in the cascaded battery pack merely utilize 70% and 80% of their capacity with 30% and 20% idle capacity. The overall capacity of battery pack will, inevitably, be drastically reduced. Therefore, charge balance is an essential condition in a cascaded battery pack.

The authors would like to acknowledge the financial support of the National Science Council of Taiwan, R. O. C.

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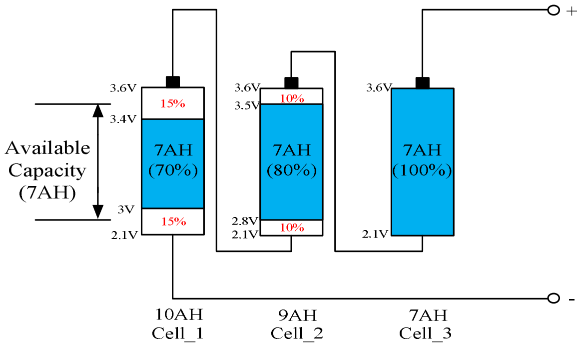

Fig. 1. Unbalance among cells in the battery set

With regard to battery management, to select a proper balancing strategy is very important. Battery balancing circuit is the prerequisite of battery management. In recent years, many researches on battery balancing have been proposed. It can be categorized into passive balance structure [3] and active balance structure [4-5]. In the passive balance structure, energy cannot be regenerated but only be dissipated. It is commonly used in hybrid vehicle with less patent trouble and high frequency interference. In another respect, active balance structure possesses the merits of determining charging proportion of the individual battery according to its surplus charge amount. More, by using energy storage devices such as inductor and capacitor, the energy conversion can efficiently be accomplished. Thus, active balance structure is more popular in the electric vehicle applications.

Despite that the balanced battery can be fulfilled by both passive balance circuit structure and active balance circuit structure, great diversity among batteries still leads to limited balancing effect. Therefore, a proper balancing strategy plays the key role in the battery pack balancing. In general, balancing strategy can be classified into voltage balance method and charge balance method [6-7]. Voltage balance method is to equalize the voltages on every single cell after charging or discharging. Whereas, it exists the drawbacks of unequal internal resistances among each cell, thus rendering cell voltage unequal even for cells with identical capacity. Charge balance method is a balance scheme based on capacity of the individual cell. It merits to subsidize single cell with lower charge and precisely equalize the charge on every single cell. Whereas, it also undergoes disadvantage of be constrained on the structure of balance circuit. In the balancing process, only one single cell can execute energy subsidization with simultaneous charging multi-cells being not allowable. Also, as the balancing current is too small, single cell of battery pack with more charge might reach the charging voltage limit or discharging voltage limit earlier, thus leading to full charge on single cell with fewer charge being unattainable.

To summarize the above mentioned battery charging and discharging methods, the active balancing circuit method is used in this research to complete the battery balance optimization. According to the literatures, Lithium Lithium battery experiences drastic voltage change during the end of charging and discharging periods. Therefore, this research presents a balancing strategy according to the derived slopes of voltage versus SOC to regulate the voltage on individual cells and balance the cell with insufficient charge thereon.

II. ACTIVE BALANCING CIRCUIT OF LITHIUM BATTERY PACK

To achieve highly efficient balance charging and discharging of Lithium battery pack, the high frequency series resonant converter is used as the main frame of circuit structure. The series resonant circuit is designed to operate as inductive load to feature power switch with zero-voltage-switching(ZVS) function. Through the high frequency energy conversion of transformer along with series resonant converter, the EMI effect can be reduced and energy conversion efficiency can be increased.

In this research, a high-frequency series resonant converter along with multi-winding transformer is used as illustrated in Fig. 2. In Fig. 2, resonant circuit is operated with high frequency sinusoidal wave energy conversion and power switch is controlled to work in ZVS to reduce the switching loss. Through the conduction and cut-off of power switches S_{chg} and S_{dchg}, the amount of balance current can be controlled by the calculation results from LabVIEW which receives data from voltage and current detection module. The balance control switches are connected in series with primary windings of transformers. If control switch is cut off, no energy will transfer to secondary winding. The multi-winding transformer makes the individual conduction and isolation of transformer possible. Hence, balance action can be carried out with respect to single cell or any combination of cells.

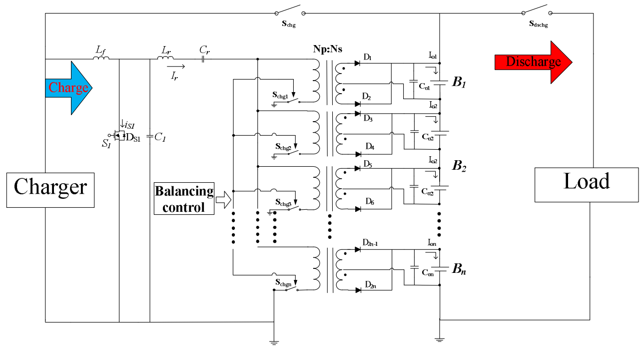

Fig. 2. Active balancing circuit

III. THE STRATEGIC ANALYSIS OF LITHIUM BATTERY CAPACITY OPTIMIZED

A. Charging balance strategic analysis:

In this research, Lithium battery characteristics are measured by assigning 1C charging rate. As shown in Fig. 3, the whole charging process is divided into early, medium, and end three stages. The linear section within each stage can further be divided into several intervals. The early stage is divided into three intervals; medium stage is divided into four intervals; end stage is divided into three intervals. The relationships between voltage change and surplus of charge are approximated by different slopes of lines as expressed in (1). The complete charging period will be divided into ten intervals, they are: interval I with battery voltage under 3.1V; interval II between 3.1V and 3.3V; interval III between 3.3 and 3.35V; interval IV between 3.35V and 3.37V; interval V between3.37V and 3.4V; interval VI between 3.4V and 3.43V; interval VII between 3.43V and 3.45V; interval VIII between 3.45V and 3.49V; interval IX between 3.49V and 3.53V; interval X between 3.53V to 3.58V. According (1), the line slopes of voltage change versus surplus of charge in each interval are listed in Table I.

$$m = \frac{\Delta V}{\Delta SOC} \tag{1}$$

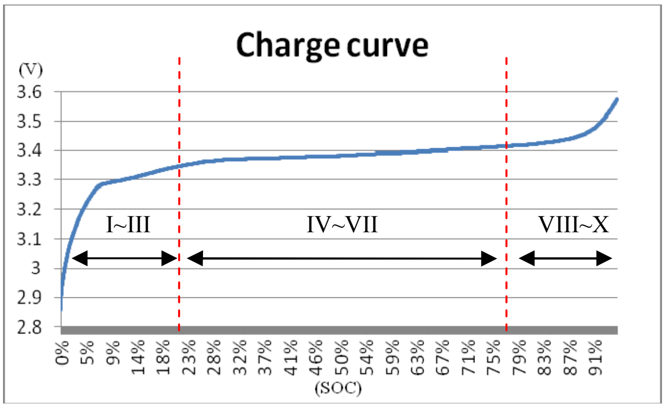

Fig. 3. Charging curve of battery

TABLE I. SLOPES OF VOLTAGE CHANGE VERSUS SURPLUS OF CHARGE CHANGE OF VARIOUS INTERVALS DURING CHARGING PERIOD

Interval	ΔV	ΔSOC	m(ΔV/ΔSOC)
I	0.239V	1.90%	0.126
II	0.2V	9.30%	0.0215
III	0.05V	11.00%	0.00454
IV	0.02V	7.90%	0.00253
V	0.03V	35.40%	0.0008
VI	0.03V	19.10%	0.00157
VII	0.02V	3.80%	0.0052
VIII	0.02V	2.70%	0.0148
IX	0.04V	1.20%	0.03
X	0.05V	1.30%	0.03

By inspecting Table I, it reveals that intervals I~II and intervals VIII~X are the pre- and post- charging periods respectively. The voltage changes are more noticeable during these intervals. Instead, the voltage fluctuation is smooth in intervals IV~VII which dominate the most period of charging. It can be observed that the slope of voltage change versus surplus charge significantly affects the voltage fluctuation as shown in Fig. 4. Fig. 4 displays the charging curve of Lithium battery with 4% maximum difference in surplus charge. Before the end of charging, the maximum and minimum voltage difference is 0.12V. In the end of charging period, voltage undergoes more magnitude change. The cell with more surplus charge will reach charging voltage limit earlier, thus, resulting in incomplete charging on cells with smaller surplus charge. It is overcome by assigning different balance factor X_n according to different slope in each interval. With the difference of surplus charge of all cells being kept under 1%, the voltage discrepancy among cells would be smaller than 0.1V. During the charging process, the Lithium battery pack is being charged while being measured at the same time. The average voltage is calculated and used to determine the corresponding interval and its associated balance factor for achieving balanced charging.

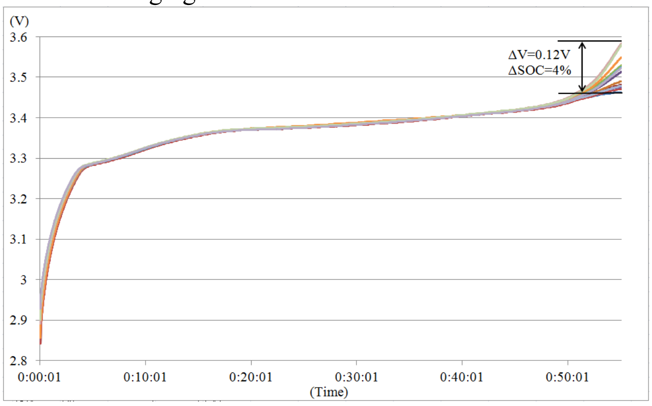

Fig. 4. Battery surplus charge with 4% maximum difference

B. Discharging balance strategic analysis

In this research, Lithium battery characteristics are measured by assigning 1C discharging rate. As shown in Fig. 5, the whole discharging process is divided into early, medium, end three stages. The linear section within each stage can further be divided into several intervals. The early stage is bisected into two intervals; medium stage is divided into five intervals; end stage is divided into three intervals. The relationships between voltage change and surplus of charge are approximated by different slopes of lines. The complete discharging period will be divided into ten intervals, they are: interval I with battery voltage over 3.31V; interval II between 3.31V and 3.29V; interval III between 3.29 and 3.25V; interval IV between 3.25V and 3.2V; interval V between 3.2V and 3.15V; interval VI between 3.15V and 3.12V; interval VII between 3.12V and 3.09V; interval VIII between 3.09V and 3.05V; interval IX According (1), the line slopes of voltage change versus surplus of charge in each interval are listed in Table II.

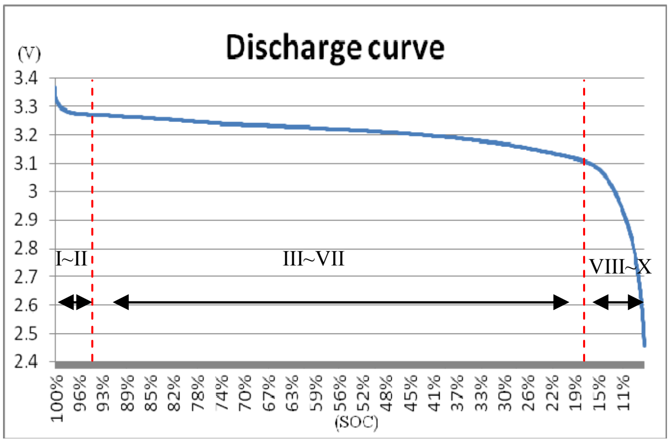

Fig. 5. Discharging curve of battery

TABLE II. SLOPES OF VOLTAGE CHANGE VERSUS SURPLUS OF CHARGE CHANGE OF VARIOUS INTERVALS DURING DISCHARGING PERIOD

Interval	ΔV	ΔSOC	m(ΔV/ΔSOC)
I	0.058V	0.5%	0.1160
II	0.02V	0.8%	0.0250
III	0.04V	18.6%	0.0022
IV	0.05V	37.7%	0.0013
V	0.05V	16.9%	0.0029
VI	0.03V	6.3%	0.0047
VII	0.03V	3.6%	0.0083
VIII	0.04V	1.9%	0.0200
IX	0.15V	3%	0.0500
X	1.5V	2.7%	0.5550

Intervals I~II and intervals VIII~X represent earlier and end stage of discharging period respectively. In these intervals, the voltage change is evident. Conversely, the voltage in intervals IV~VII, which dominates most of the discharging period, alters smoothly. By observing the different line slopes of voltage change with respect to surplus of charge within different intervals, it can be roughly recognized that the amount of voltage change is significantly affected by the surplus of voltage as displayed in Fig. 6. Fig. 6 shows the discharging curve of a Lithium battery pack with 16 cells connected in series, in which, the maximum surplus of charge being 2%. Just prior to the end of discharging, the difference between maximum battery voltage and minimum battery voltage is 0.3V. In the end of discharging period, great voltage change would happen. Cells with lower surplus of charge will reach discharging voltage limit earlier and lead to capacity reduction of battery pack. In the process of discharging balance, the power consumption of balance circuit comes from Lithium itself. If too strict balance factor is assigned, increased balance actions would result in extra waste of energy. The available capacity might, therefore, be curtailed. According to the slopes of each interval, different balance factor X_n is designated to keep the difference among all cells under 2%. During the discharging process, the Lithium battery pack is being charged while being measured at the same time. The average voltage is calculated and used to determine the corresponding interval and its associated balance factor for achieving balanced charging.

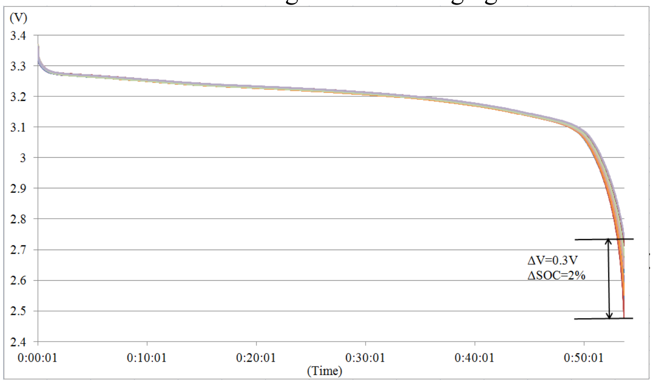

Fig. 6. Discharging curve in case of 2% difference in battery surplus charge

IV. Experimental Results

In the experiment, a Lithium battery pack with 16cells connected in series is used to test the performance of charge balance. Balance charging/discharging is based on terminal voltage to determine the balance factor. Before experiment, one cell with minor different charge is placed within the Lithium battery pack. The experiments are operated in 1C charging and discharging rate to execute the balance charging and discharging test.

A. Charging balance :

Fig. 7 is the charging curve of Lithium battery pack without charging balance. Cell_1 is the one with minor different charge. Fig. 7 shows that the voltage of Cell_1 rises abruptly in the end stage and reaches the charging voltage limit quickly. This leads to the incomplete charging of Cell_2~Cell_16 to avoid overcharging of Lithium battery pack. Merely 85% of battery capacity is charged.

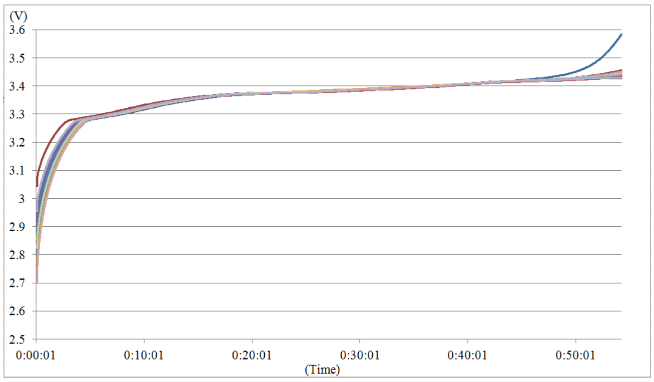

Fig. 7. Charging curve without balance charging

Fig. 8 is the charging curve of Lithium battery pack with charging balance. In Fig. 8, it can be observed that there exists voltage discrepancy among cells before charging. Through the application of charging balance strategy, the balance is achieved quickly and all cells exhibit the same trace in the end. For thoroughly investigating the balance process, the charging period is divided into three stages. Fig. 9 reveals the apparent charge discrepancy at the early stage. The charging balance is performed while voltage detecting is repeated until $V_{avg}-V_n < X_n$.

Fig. 10 displays the medium stage of charging period. It dominates most the charging period and possesses smooth voltage profile. As mentioned above, it is divided into four intervals IV~VII. According to Table I, intervals IV~VII, the voltage change rates are smaller than 0.01. Despite that the voltage discrepancy is minor during this stage, the voltage difference must be kept within 1% to avoid the possible increasing voltage difference in the final stage. The balance mechanism is initiated when $V_{avg}-V_n > X_n$.

Fig. 11 displays the final stage of charging period. The cell voltage difference becomes more and more apparent. As the difference between V_{avg} and V_n is greater than X_n, balanced charging keeps going until difference between V_{avg} and V_n is smaller than X_n. The balance charging mechanism is terminated with charging continuing to the end. The final battery voltage difference is 0.03V and 95% battery capacity is completed. The validity of balance management is effectively proved.

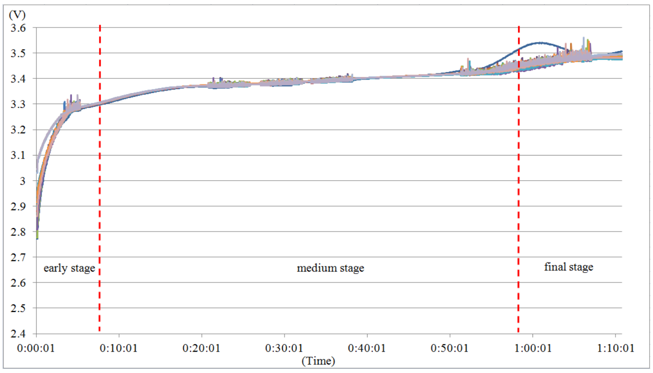

Fig. 8. Charging curve after balance charging

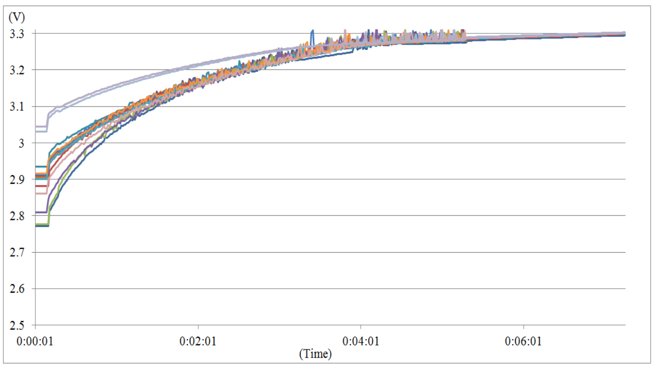

Fig. 9. Charging curves in the early stage

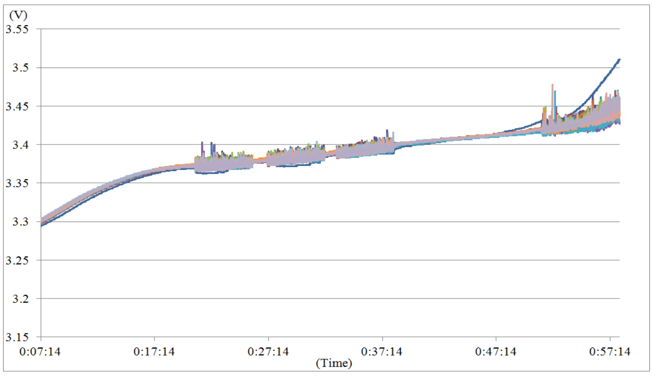

Fig. 10. Charging curves of medium stage

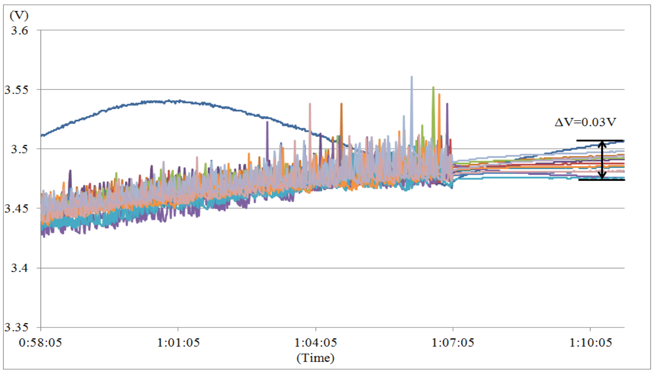

Fig. 11. Charging curves of final stage

B. Discharging balance :

Fig. 12 is the discharging curve of Lithium battery pack with charging balance. Cell_1 is the one with minor different charge. Fig. 12 shows that the voltage of Cell_1 drops abruptly in the end stage and reaches the discharging voltage limit quickly. This leads to the incomplete discharging of Cell_2~Cell_16 for avoiding over-discharging of Lithium battery pack. Merely 85% of battery capacity is preserved.

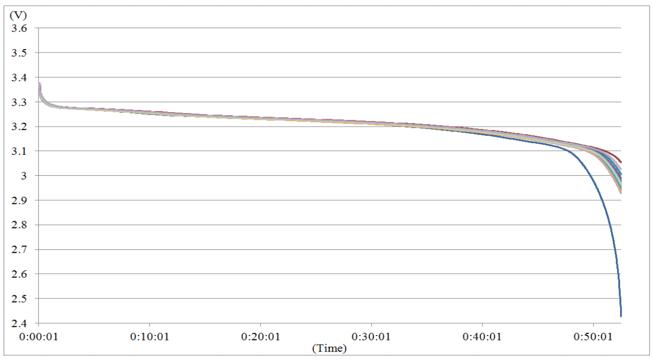

Fig. 12. Discharging curves without balance discharging

Fig. 13 is the discharging curve of Lithium battery pack with charging balance. Through the application of discharging balance strategy, the balance is achieved quickly and all cells exhibit the same trace in the end. For thoroughly investigating the balance process, the discharging period is divided into three stages. Fig. 14 reveals the apparent charge discrepancy at the early stage. The discharging balance is performed while voltage detecting is repeated until V_{avg}-V_n< X_n.

Fig. 15 displays the medium stage of discharging period. Voltage on each cell has arrive at smooth region, with voltage 3.2V. The voltage of worsened cell gradually falls below the average voltage. The balance mechanism is initiated when V_{avg}-V_n> X_n.

Fig. 16 displays the final stage of discharging period. In this stage, the declined slope of cell voltage becomes greater. As the difference between V_{avg} and V_n is greater than X_n, balanced charging keeps going until difference between V_{avg} and V_n is smaller than X_n. The balance discharging mechanism is terminated with discharging continuing to the end. The final battery voltage difference is 0.3V and 91% battery capacity is completed. The validity of balance management is effectively proved.

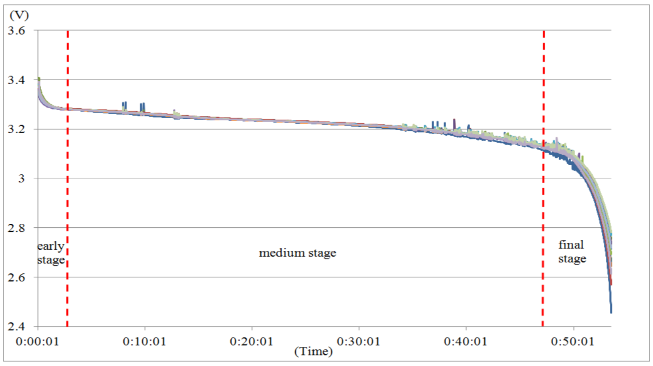

Fig. 13. Discharging curves with balance discharging

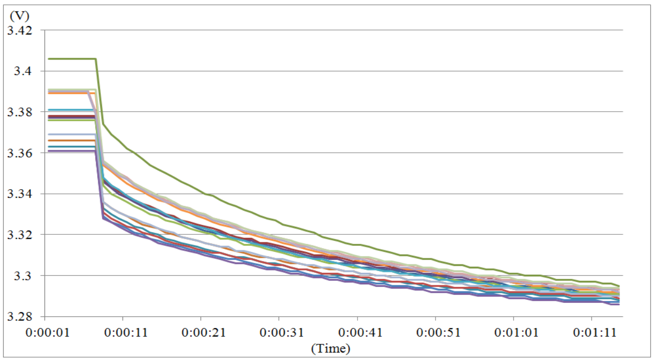

Fig. 14. Discharging curves in the early stage

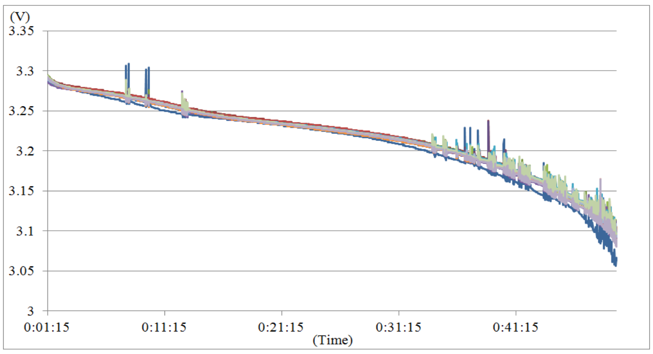

Fig. 15. Discharging curves of medium stage

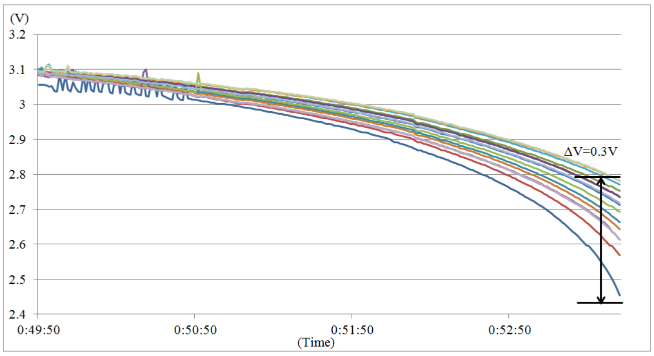

Fig. 16. Discharging curves of final stage

CONCLUSIONS

This research proposed a battery capacity optimized strategy to enhance the storage capacity of a battery system with cells being connected in series with a Lithium battery pack. By dividing the linear region during the charging/discharging process into ten intervals, the corresponding slopes of battery voltages versus surplus of charge are measured. Different balance factors are defined based on slope changes within each interval. Active balancing circuit is used to realize the proposed balancing strategy. The experiment results have verified that the proposed charging/discharging balancing strategy can regulate the voltages according to the slopes of voltage change versus surplus of charge. Eventually, the battery balance charging can be carried out and the optimized utilization of battery is accomplished.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the National Science Council of Taiwan, R. O. C. through grant number NSC 103-2623-E-150-001-ET.

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