Proceeding of the 2015 IEEE
International Conference on Information and Automation
Lijiang, China, August 2015

Design of a Battery Management System Based on Matrix Switching Network*

Xiangjiang Yang

China Electric Power Research Institute
Beijing, China
yangxj@epri.sgcc.com.cn

Huirong Jiang, Zhicheng Deng
School of Aeronautic Science and Engineering
Beihang University
Beijing, China
deng@buaa.edu.cn

Abstract **– Battery Management Systems are the key modules for Lithium-Polymer (LiPo) batteries. They control the charging /discharging parameters, measure the voltages and state of charge (SOC) of the battery cells, equalize the charge/discharge characterizes of individual battery cells and notify the main controller of the status of the battery pack. They are also the critical safeguards against potential damages to the batteries.**

Due to the fact that LiPo batteries have great energy density, low discharge rate, high cell voltage and lack of memory effect, they are widely used in applications such as electric vehicles and electric bicycles. However, because one battery pack needs a lot of battery cells connected in series, the battery pack is prone to fail than a single cell battery. Moreover, the battery cells are always different in the SOC and internal impedance. This means if the weak cell hits the protection limit while the other cells in the series are still sufficient to power the system, the battery pack cannot be used either. This will limit the capacity and efficiency of the battery pack.

To improve the reliability and capacity of Li-Po battery pack, this paper propose a novel battery management system, on which, individual battery cell can be dynamically connected to or disconnect from any position of the battery series via the matrix switching network. By appropriately controlling the matrix-switching network, the battery cells can be configured to different configurations to suit different application scenarios e.g. active cell balancing, multi-voltage output, and weak/fail cell replacement.

Index Terms – Battery Management System, Matrix Switching Network, Lithium-Polymer Cell, Redundant Battery.

I. INTRODUCTION

Compared with Lead Acid, NiMh and NiCd batteries, LiPo battery has many advantages, such as high energy density, low self-discharge rate, high cell voltage, long life, flexible form factor, lack of memory effect, and etc [1-4]. These advantages make LiPo batteries wildly used in electric vehicles, electrical bicycles, laptops and other consumer electrical products [5]. Batteries used in most of these applications mentioned above are made up of long strings of battery cells to achieve appropriate operational voltages. In this configuration, because there are a lot of cells in the series string, the batteries are prone to fail than single cell batteries. And the more battery cells used, the less reliability the batteries have.

Another problem to a LiPo battery with series cells is cell imbalance. Because no two cells are identical, they are always different in the state of charge (SOC), capacity, internal resistance and ageing characteristics, even for cells that are from the same production line [6]. The variations in an individual cells' characteristics in a series string could cause cell capacity degradation and safety problems. For example, during the charging cycle, the charger terminates the charging procedure while the voltage of the battery has reached the voltage limit. However, at full charge termination, the weak cells with low capacity will over charged, and the rest of the cells in the series will under charged. On the other hand, during the discharging cycle, the weakest cell with low capacity and high internal resistance will have the greatest depth of discharge and will tend to have lowest voltage. Through continuous charging and discharging cycles, these weak cells will be further weakened and the cells' inner pressure will rise with consequent explosion risk.

To improve the batteries' reliability and solve the problems caused by cell imbalance, battery management methods/systems for LiPo batteries were developed. In [7-9], several passive and active battery-balancing methods were introduced. These methods are commonly used in many battery systems. They are effective not only for increase the battery life but also for increase the safety of the battery system. However, no method could work under a situation where any one of the cells in a series chain is dead or severely damaged. H.Shibata, S. Taniguchi and etc. present a battery management system using multiple switches for serially connected batteries in [10,11]. This switch structure could bypass damaged cells and prevent potentially dangerous situations, but it will affect the battery's output voltage as well. A.Manenti, A. Abba and etc. developed a battery management system based on switching network architecture and cell redundancy [12]. This system utilizes a state-of-charge (SoC) balancing algorithm and a redundant cell to isolate the damaged cell and prevent battery voltage reduction. However, its' configurations are limited, and it is not suit for some battery failure situations.

This paper proposes a battery management system for multi-cell batteries. The aim is to improve the reliability of the battery pack, improve the efficiency of the cell balancing procedure. The reminder of the paper is organized as follows.

* This work is partially supported by China Electric Power Research Institute.

978-1-4673-9104-7/15/$31.00 ©2015 IEEE

First, the design requirements and system architecture are presented. Then, the balancing algorithm and hardware realization are discussed. Finally, the conclusion and future work are given.

II. Design Requirements

A traditional battery management system as illustrated in Fig. 1 consists of four main parts: the data acquisition block, the processor, the switches, and the communication unit. The system measures crucial information of cells, realizes cell balancing, protects the battery against damages/dangerous status and provides notifications on the status of the battery to the main controller.

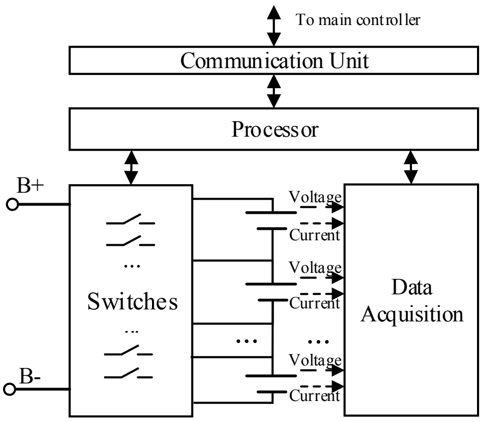

Fig. 1 A traditional battery management system.

For LiPo batteries, the battery management systems are the key modules for safety usage. The design requirements for them are mainly decided by two factors including cell balancing and fail management.

A. Cell Balancing

A LiPo battery usually includes several cells that work together in combination. Ideally, all the cells in a battery should have the same characteristics. However, no two cells are exactly the same. If the cells go out of balance, individual cells will be overcharged or over discharged, and lead to cell degradation or explosion. To prevent imbalance in individual cells from occurring, the battery management system should have cell-balancing capabilities. Hence, the capacity and lifetime of the battery could be extended.

The fundamental of cell balancing is to equalize the voltage and SOC among the cells when they are charging and discharging. A lot of techniques can be used to balance the LiPo batteries, e.g. dissipative shunting resistor, analog dissipative shunting, resonant converter, switched capacitor, step-up converter and etc. Considering energy cost, environmental cost and heat dissipation, a preferable method should be very efficient in charging and discharging procedures.

B. Fail Management

For multi-cell batteries, when the cells are connected in a series configuration, if any one of the cells fails, the entire battery fails. Given a battery consisting of n battery cells connected in series, the reliability of the battery can be written as:

$$R_b=R_{c1}\times R_{c2}\times R_{c3}\times\ldots\times R_{cn}$$

Where R_{c1}, R_{c2}, R_{cn} is the probability of successful operation of cell 1, cell 2 and cell 3 respectively.

Apparently, to increase the reliability of the battery, fail management need to bypass damaged cells in the chain to prevent potential dangerous situations, and reduce the voltage drop of the battery to give the loads a relatively stable power supply.

III. System Architecture

As previously indicated, many battery management systems have been developed. Most of them use shunting, shuttling and energy converter method to balance the battery cells and increase the balancing efficiency. The drawback of these solutions is that they utilize a lot of inductors, capacitors and diodes to transfer energy between cells. This will lower the transfer efficiency. Even if these systems could be built with low cost components and achieve high transfer efficiency, the control system is very complex since they have to deal with many pulse width modulation (PWM) signals to control the current in these components. Furthermore, they are unable to handle situations where one or more cells failed.

Our idea is to implement a system on which few components are used in the energy transfer process, and all the battery cells can be independently connected to or disconnected from the series via a matrix switching network.

A. Switching Network

Fig. 2 shows the block diagram of the proposed matrix switching network. As shown in the figure, it includes a configuration switching network (CSN) and a charging/discharging switching network (C/DSN). Battery cells BAT1 to BATn are connected to the row lines of the $2n\times 2n$ CWN. The row lines and the column lines with the same line numbers in the CSN are connected together. The switches in the CSN make it possible to change the connecting status of the n cells by simply changing the state of the switches ($K_{1,1}$,$K_{1,2}\ldots K_{1,2n}$, $K_{2,1}$,$K_{2,2}\ldots K_{2,2n}$, …, $K_{2n,1}$,$K_{2n,2}\ldots K_{2n,2n}$). ComLine1 and ComLine2 are used for charging and discharging. They can be configured to different voltage level with different charging/discharging rate via the CSN and C/DSN.

The two switching networks shown in Fig. 2 are the key section of the system, they has four main purposes.

1) Connect Cells in Series: When high voltage level is needed, the cells can be configured to be connected in series. For example, if $K_{3,2}$, $K_{5,4}$, $K_{7,6}\ldots K_{2n-1,2n-2}$ switches in CSN, $CK_{1,1}$, $CK_{2,n}$ switches in C/DSN are closed, and the rest of the switches are open, then all the cells are connected in series, and the highest voltage level is obtained via ComLine1 port.

2) Connect Cells in Parallel: Battery cells can be configured to be connected in parallel for high charging/discharging rate applications. For example, if $K_{3,1}$, $K_{4,2}$, $K_{5,1}\ldots K_{2n,2}$, $CK_{1,1}$, $CK_{2,2}$ in the CSN and C/DSN are closed, and the rest of the switches are open, the highest charging/discharging rate is obtained.

3) Bypass/Replace Damaged Cells Dynamically: An individual cell can be bypassed or replaced easily by just changing several switches in the CSN. Assuming, BAT1, BAT2 and BAT3 are connected one after another, and BAT2 is deteriorated. To replace BAT2 with BATi, the CSN opens the switches $K_{3,2}$, $K_{5,4}$, and closes the switches $K_{2i-1,2}$, $K_{5,2i}$ are closed.

4) Provide Multiple Outputs: Many electrical products need several different voltage levels. Usually, they use several regulators stages to get these voltage levels. This will lower the energy efficiency. The combination of the CSN and C/DSN enables the battery to supply different voltage and current rate by changing the connections between cells.

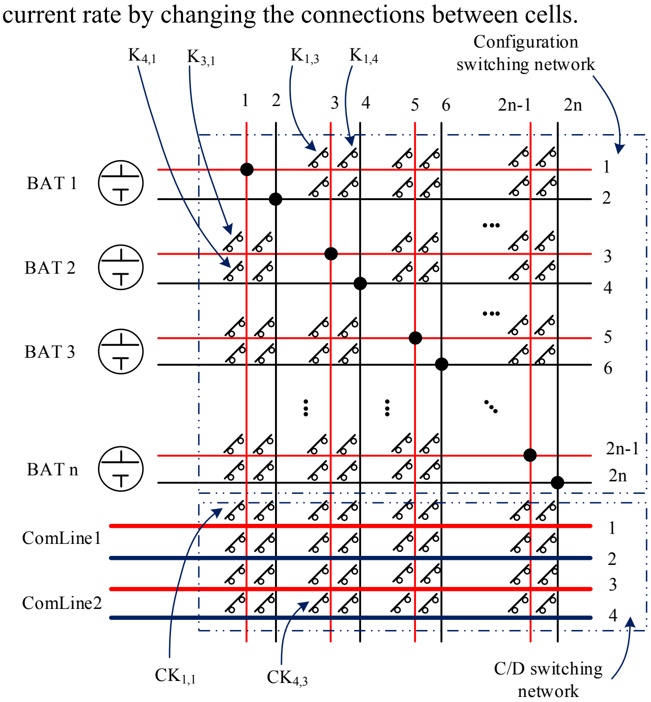

Fig. 2 Block diagram of the proposed matrix switching network.

B. *Proposed Battery Management System*

The proposed hardware framework for battery management systems is illustrated in Fig. 3. The system is a little similar to the common system except that it has a switch refreshing unit to control the switches in the CSN and C/DSN, and the switching network connect to the cells in a different way.

- Switch Refreshing Unit

Typically one port pin is required to control one switch. To control the 2n×2n CSN, it is not feasible to allocate one pin to each switch. Therefore, the system adopts a switch refreshing mechanism to reduce the port pins. The principle of the refreshing mechanism unit of controlling the switches is shown in Fig 4.

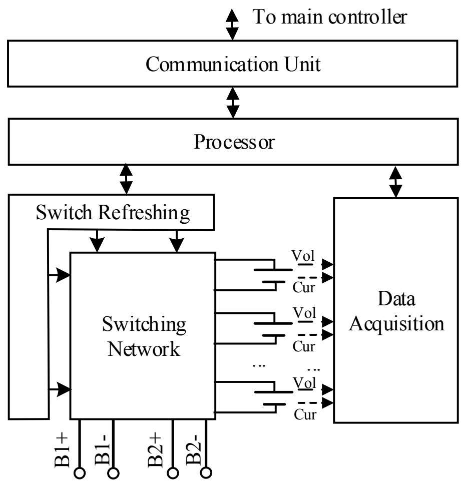

Fig. 3 Block diagram of the proposed battery management system.

The refreshing cell contains one transistor and one capacitor. The states of the switches are controlled by $K_{1,2}$, $K_{1,3}$,…, $K_{2n,2n-1}$ control signals. To change the state of a switch e.g. $K_{i,j}$, Rowi is raised high to turn on the transistors in the *ith* row, and Colj is set to high to open the switch or low to close the switch. Due to the cell capacitor, the state of this switch can be hold for a limited time. To maintain this state, the switch refreshing unit will charge the capacitor periodically.

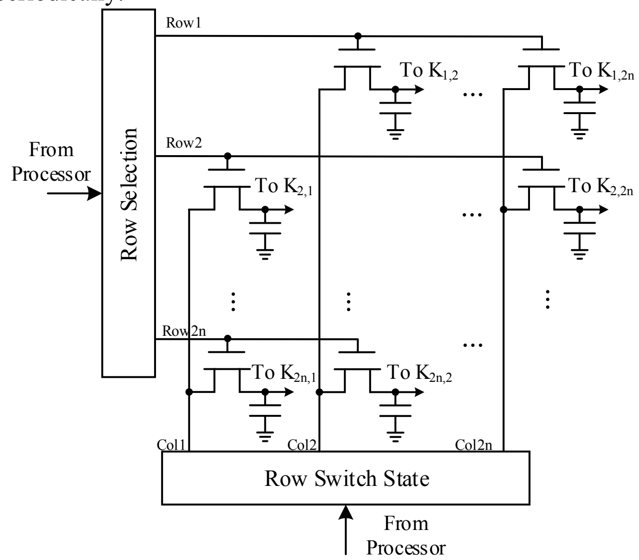

Fig. 4 Principal of the switch refreshing unit.

- Connection between Cells and Switching Network

Unlike a traditional battery management system, in the proposed battery management system, the cells connect to the switching network independently so that the cells can form many different configurations.

IV. Balancing Algorithm

Since all the cells are measured, and any one of the cells can be dynamically connected to the other cell in parallel, the balancing algorithm can be written as Fig. 5.

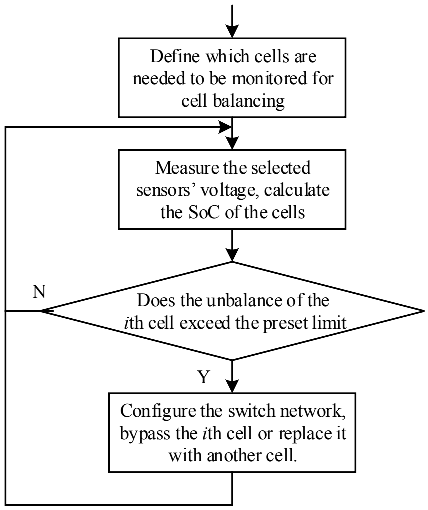

Fig. 5 Flow chart of the balancing algorithm.

V. HARDWARE REALIZATION

This section illustrates the implementation of the key components needed for the battery management system proposed in section III.

- Processor

A LPC2129 is utilized as the main processor. The LPC2129 is an ARM7TDMI-S based microcontroller together with 256kB of embedded memory. It offers 4 channel 10-bit ADC, 2 CAN cannels, 2 UART ports, PWM channels, and 46 GPIO lines. These characteristics make it suitable for the proposed system.

- Electrical Switch

Electrical switch is the essential component for the matrix switching network. Because electromechanical relays have many mechanical parts, they have limitations in package size, switching speed, mechanical lifetime and power consumption. Unlike electromechanical relays, MOSFET uses CMOS transistors to implement the circuit switching. There is no mechanical in a MOSFET switch. However, a single MOSFET switch can only allow one directional current flow. In order to provide bidirectional switches for the CSN and C/DSN, a switch as shown in the Fig. 6, consists of two MOSFET and two diodes is used. This switch has two states. When the control signal is HIGH, current can flow both direction through the switch. When the control signal is LOW, current cannot flow in either direction.

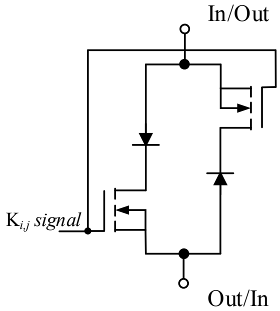

Fig. 6 Diagram of a bidirectional MOSFET switch.

VI. CONCLUSION

The main issues in the design of a battery management system for LiPo batteries are how to solve the cell imbalance problem to increase the battery life, and how to improve the battery's reliability. This paper proposed a battery management system based on matrix switching network. Firstly, the design requirements of the system are discussed. Then, the system architecture is explained. Finally, the balancing algorithm is explained.

The core of the proposed architecture is the technique of matrix switching network and the corresponding control algorithm. The main advantages of the architecture are the capabilities to dynamically balance the battery cells during charging and discharging procedures, and bypass/replace the deteriorated/damaged/failed cell during operation.

Moreover, the proposed architecture is very flexible and energy efficient. The cells can be configured to connect in series or in parallel, different voltage level with different charging/discharging rate can be obtained just by changing the states of switches in the matrix switching network.

ACKNOWLEDGMENT

The topic of research is support by. The authors would like to give their thanks to Baisong Zhai and Hui Lv for their help and assistance during the research.

REFERENCES

[1] J. Cao and A. Emadi "Batteries need electronics", IEEE Ind. Electron. Mag., vol. 5, no. 1, pp.27 -35 2011

[2] Vazquez, S.; Lukic, S.; Galvan, E.; Franquelo, L.G.; Carrasco, J.M.; Leon, J.I. "Recent advances on Energy Storage Systems", IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society, pp. 4636 – 4640

[3] Y. U. Jeong and H. V. Venkatasetty, "Recent advances in lithium-ion and lithium-polymer batteries," in *Proc. 17th Annu. Battery Conf. Appl. Adv.*, 2002, pp. 173–178. Y. U. Jeong and H. V. Venkatasetty, "Recent advances in lithium-ion and lithium-polymer batteries," in *Proc. 17th Annu. Battery Conf. Appl. Adv.*, 2002, pp. 173–178.

[4] D. Coastes and C. Fox, "Multiple advanced battery systems for electric vehicles", BCAA 1994 – 9th Annual Battery Conference on Applications and Advances.

[5] Y. J. Lee, K. Rajashekara, and A. Emadi, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2237–2245, Jun. 2008.

[6] S.H. Wen, "Cell balancing buys extra run time and battery life", Analog Application Journal, pp.14-18, 2009

[7] N. S. Jian Cao and A. Emadi, "Battery balancing methods: A comprehensive review", Proc. IEEE VPPC, pp.1 -6 2008

[8] J. Ewanchuk, D. Yague and J. Salmon, "A modular balancing bridge for series connected Li-ion batteries," in Proc. of IEEE Energy Conversion Congress and Exposition (ECCE11), pp. 2908-2915, 2011.

[9] B.L.Alvarez, S.V.Garcia, C. F. Ramis, "Developing an active balancing model and its Battery Management System platform for lithium ion batteries," Symposium on Industrial Electronics (ISIE), pp.1-5, 2013..

[10] H. Shibata , S. Taniguchi , and etc, "Management of serially-connected battery system using multiple switches", Proc. IEEE Int. Conf. Power Electron. Drive Syst., vol. 2, pp.508 -511 2001

[11] Harada K., Taniguchi S., Adachi K. and etc., "On the removing of less quality battery from series-connected system", 22nd International Telecommunications Energy Conference, pp.761-764.

[12] A. Manenti , A. Abba , A. Merati , S. M. Savaresi and A. Geraci "A new BMS architecture based on cell redundancy", IEEE Trans. Ind. Informat., vol. 58, no. 9, pp.4314 -4322 2011.