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System protection for Lithium-ion batteries management system: a review

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ABSTRACT

Robustness of a battery management system (BMS) is a crucial issue especially in critical application such as medical or military. Failure of BMS will lead to more serious safety issues such as overheating, overcharging, over discharging, cell unbalance or even fire and explosion. BMS consists of plenty sensitive electronic components and connected directly to battery cell terminal. Consequently, BMS exposed to high voltage potential across the BMS terminal if a faulty cell occurs in a pack of Li-ion battery. Thus, many protection techniques have been proposed since last three decades to protect the BMS from fault such as open cell voltage fault, faulty cell, internal short circuit etc. This paper presents a review of a BMS focuses on the protection technique proposed by previous researcher. The comparison has been carried out based on circuit topology and fault detection technique.

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1. INTRODUCTION

Lithium-ion battery (LIB) has been launched into the market place by SONY in June 1991[1]. Today, Li-ion battery can be found in many applications such as electric vehicle (EV), smart gadgets, solar photovoltaic industries etc. LIB is a rechargeable electrical energy storage which has a lot of advantages such as fast charging, higher energy density, longer battery life and able to fit into a small and lighter package. Table 1 shows the comparison between LIB and other type of batteries. Despite having those advantages, LIB has a limitation such as memory effect [2]-[4], subject to aging [5] and contains very sensitive chemical [6]. Battery management system (BMS) has been proposed since 90's in order to ensure its reliability and the ability to operate under safe operating limit [7]. Basically, BMS protect the LIB by monitoring the parameter such as current, temperature, voltage and states of cell including state of energy (SOE)[8], state of health (SOH)[9]-[11], state of charge (SOC) [12], [13] and remaining useful lifetime [5], [14].

BMS can be classified into three categories namely centralized, distributed and modular BMS [15]. In centralized BMS, each battery cell is connected and controlled by a single micro-processing unit [16]. Meanwhile, a distributed BMS consists of one master controller and many slave modules [16]. In this topology, only slave modules have a direct contact to a single battery cell to perform cell monitoring. Combination of both centralized and distributed BMS is called modular BMS [17]. This topology consists of multiple modules connected to one another. Each module connects directly to more than one battery cell.

Table 1. Comparison between LIB and Other Type of Batteries [18]

Type of battery	Energy Density (Wh/Kg)	Advantages	Disadvantages
Li-Ion	110-160	High energy density, low maintenance	Sensitive chemistry, need protection, memory effect
Li-Polymer	100-130	more resistant to overcharge, more safe than Li-Ion	Less energy density compare to Li-Ion
Lead Acid	30-50	Safer than Lithium, no memory effect, low maintenance	Low energy density, environmentally unfriendly
NiCd	45-80	Safer than Lithium, fast and simple charge	Low energy density, memory effect
NiMH	60-120	Higher energy density than NiCd, safe, less memory effect	Limited service life, limited discharge rate, high self-discharge rate

Regardless the categories of the BMS, they have a direct contact to the battery cell and exposed to high risk of high voltage potential across the BMS if one or more battery cells are failed. A conventional BMS does not have the capability to detect a battery fault which leads to more serious issue such as fire or explosions [19]-[22]. This paper describes the protection techniques and categories based on fault detection methods. There are four categories of battery fault detection that normally used in BMS.

2. LITHIUM-ION CELL FAULT

Since LIB introduced by SONY in 1991, there is a huge number of recalls has been made for LIB. Recently, in 2017 Samsung experienced significant safety issues as the LIB inside Galaxy Note 7 facing overheating problem. This incident is a disaster for Samsung as they were forced to recall all Galaxy Note 7 and eventually cancelled the entire line.

By nature, LIB is hazardous. It contains a flammable liquid organic electrolytes [23] in contact with highly energetic material [4]. Inside LIB, there are anode and cathode layers separated by separator and filled by flammable electrolyte. This separator is very thin and tend to cause a premature failure if there is an abnormal abuse condition [24]. The abuse condition can be categorized into three categories; mechanical abuse, electrochemical abuse and thermal abuse [25]. Among these three categories, electrochemical abuse has drawn much attention as most of LIB incident is caused by electromechanical abuse such as over-discharge, over-charge, internal short circuit, external short circuit, gas generation etc. Table 2 shows the summary of incident related to LIB.

Table 2. Summary of Incident Related to LIB [21], [26]

Date/Source of incident	Type of application	Abuse condition	Incident description
8 Feb 2018/Airline	Notebook	Mechanical abuse	Smoke emitting out from shipment package.
28 Jul 2018/Media Report	Smart Bag	Short circuit	Arc and smoke begin when passenger try to remove battery from smart bag.
21 May 2018/News	Scooter	Over-discharge	A package containing a lithium-ion battery powered scooter caught fire at the UPS facility.
9 May 2018/Airline	e-cigarette	Short circuit	The bag was burned as well as the carpet of the aircraft after a passenger carry-on bag caught fire.
13 Feb 2018/Airline	Li-Ion Power bank	cell internal short circuit	Power bank got overheating, hot and started to smoke. The item was placed in a thermal containment bag.
3 Jan 2018/Airline	Solar bank charger	Short circuit	Solar bank chargers with lithium ion batteries, UN 3480, installed were discovered on fire during the loading process.

Nowadays, most of LIB available on the market is integrated with internal protection circuit such as current interrupt device (CID) and positive temperature coefficient (PTC). CID is a method to manage cell overcharge by disconnecting the circuit if overpressure event is occurred [1]. Inside the CID, there is a fusible link that connecting the cell's terminal and the electrode [27]. This fusible link acted as a fuse and melted if there is over current flow through it [28]. Another internal protection is PTC. PTC is a thermal fuse which used to prevent the thermal runaways. PTC will shutdown the batteries if the battery temperature is overheated [4], [29].

Regardless the type of internal protection, the aim of a BMS is to separate the faulty cell from the circuit and keep the cell in open state. Table 3 shows the comparison between LIB fault, types of abuse and how the fault will be managed.

Table 3. Comparison between LIB Faults

Fault	Abuse type	Causes	Is the fault manageable?
Internal short-circuit	Electrochemical abuse	Manufacturing defect	No
External short-circuit	Electrochemical abuse	Defective connection, wiring fault	Yes. By high speed fuse
Overcharge	Electrochemical abuse	Failure of charging unit, failure of BMS	Yes. By BMS
Overheating from external	Thermal abuse	Battery place near heat source	Yes. By open the cell internal pressure
Crush	Mechanical abuse	Physical abuse of battery pack	Yes by design enclosure with more vibration tolerance
Thermal run away	Thermal abuse	Faulty cell heating surrounding cells	Yes. PTC and CID

3. FAULT PROTECTION FOR BMS

LIB pack is used in numerous high voltage applications such as EV, unmanned aerial vehicle, photovoltaic energy storage due to its characteristic that has high energy density and high life cycle. LIB battery pack which composed of LIB cells which are connected either in series or parallel or both depend on requirement of the application. For large format of LIB application, BMS is crucial to ensure the safety and it reliability including protecting the BMS itself from any potential of high voltage fault. Since the BMS consist of plenty sensitive electronic components, protecting the BMS itself is quite challenging. Based on the previous studies, there are several fault detection techniques used to detect the battery cell failure.

3.1. Fault Detection using CVM Method

Cell voltage measurement (CVM) is a method used to detect faulty cell especially in a battery pack. Figure 1 shows the CVM topology. In this topology, CVM modules are used to measure the cell voltage V_{cell} on each battery cell. If V_{cell} is higher than 4.9V then open wire fault signal is triggered [7]. Meanwhile, if V_{cell} drop below 0.1V the cell internal short circuit fault is triggered. This method is widely used to detect the open wire fault [7]. However, according to [30], the major challenge of CVM method is higher number of sensors are needed to measure every cell voltage as LIB battery pack composed of huge number of cells connected in series.

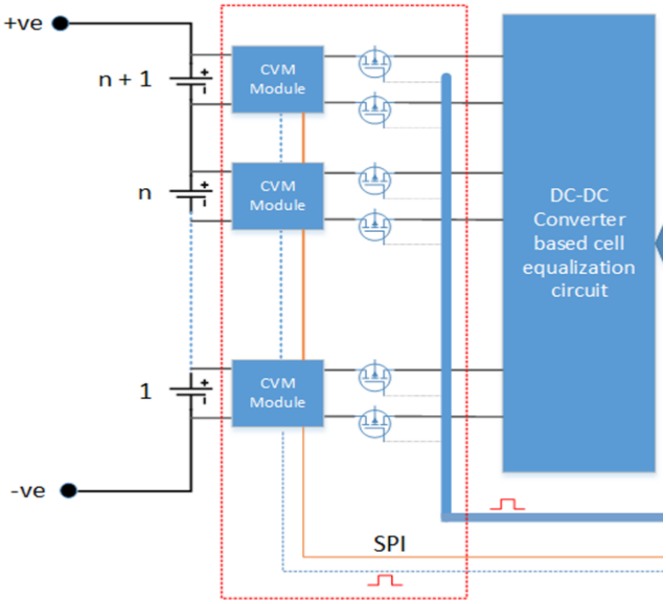

Figure 1. Cell voltage measurement topology

3.2. Fault Detection using Comparator

Comparator circuit is a device used to compare between two voltage signals and determines which signal is greater. In BMS protection circuitry, comparator is normally used to determine the under voltage and over voltage condition for each cell in a battery pack [31]. Based on Sumukha V Udupa [31], the comparator is used to compare between the input voltage (Vin) and the threshold voltage (Vth). The comparator input voltage is applied to the inverting input, so the output will have an inverted polarity.

If Vin is greater than Vth, the output will be drive to logic low and vice versa. This method can be used to determine the over-voltage and under-voltage fault. For Li-ion battery, upper threshold voltage is 4.25V and lower threshold is 2.5V [32]. Figure 2 shows the protection circuit using comparator. Vth is a voltage measure across zener diode Z1 and V_{R4} is a voltage measure across resistor R4. The operation of over-voltage and under-voltage is summarized in Table 4.

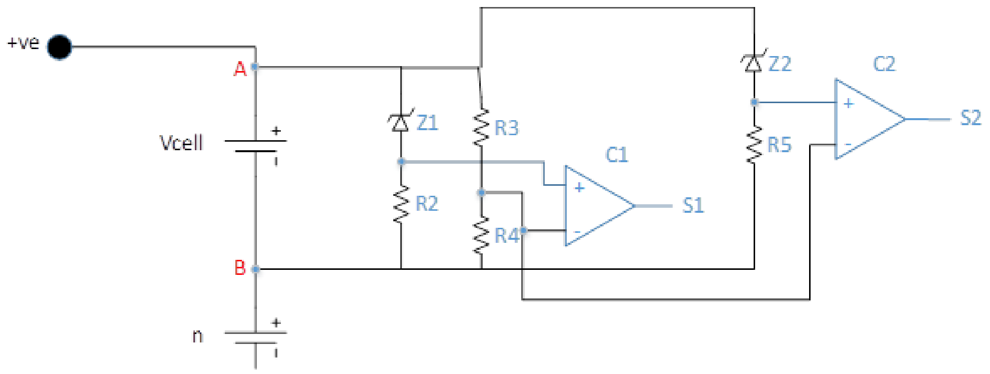

Figure 2. Protection circuitry using comparator

Table 4. Summary of Comparator Protection Circuitry Operation

Input Voltage	Comparator C1 Status (S1)	Comparator C1 Status (S2)	Condition
Vcell > 4.25V	High	Low	Over-voltage
Vcell = 3.0V	Low	Low	Normal
Vcell = 2.8V	Low	Low	Normal
Vcell < 2.5V	Low	High	Under-Voltage

The advantage of this topology is no microcontroller is required to measure the voltage. Thus measurement speed is no more the issue. However, noise on the input signal may cause the input to transit above and below the threshold voltage causing an erratic output [33]. Furthermore, the complexity of circuitry is one of the main issue as large format of LIB battery pack requires huge number of comparator.

3.3. Protection using Zener Diode Method

Combination of zener diode and fuse is the simple protection method introduced by [34]. Figure 3 shows the configuration of zener diode and fuse used as a fault protection device. In this topology, zener diode, Z1 acting as a voltage limiter. In normal condition, is not conducted and no significant current is flowing through the BMS. Thus, all fuses remain in closed state. When an over-voltage or reverse-voltage condition occurs, the zener diodes will begin to conduct, resulting the current to flow through the fuse and consequently blow the fuse to protect the voltage measurement electronics from damage. There are many situations that may lead to over-voltage and reverse-voltage occurrence, where some is unexpected.

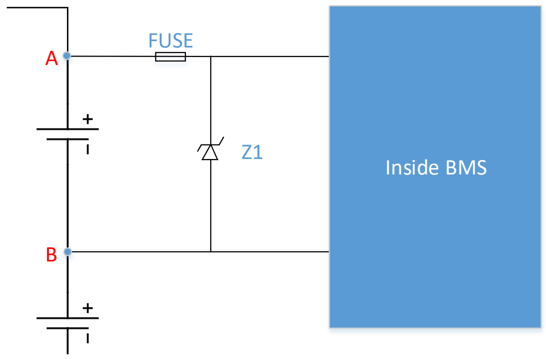

Figure 3. Combination of zener diode and fuse protection topology

This technique offers low cost protection circuitry and less component involvement. However, fuse need to replace every time its blown. Thus it is not economical in term of maintenance. Besides that, if high voltage applied to the zener diode Z1, it will break the Z1 before the fuse blown. Meaning that this topology is not efficient when applied to high voltage application.

3.4. Fault Detection using Drain-Source Voltage Monitoring Method

In BMS unit, MOSFET widely used as a switching component to distributes an excessive charge from one cell to another cell. However, Guangyuan Liu [35] has proposed a new technique using MOSFET to detect a failure of a battery cell by measuring its drain-source voltage. In this technique, MOSFET is connected in series between each cell in battery pack. In order to determine whether the battery is faulty or not, the status of the cell state is detected by sensing the voltage drop across the MOSFET. When the MOSFET is turned on, the current will flow through the MOSFET. Thus, voltage drop across the MOSFET can be derived by in (1).

$$V_{dsi} = i_i \, x \, R_{don} \quad (1)$$

Since the value of R_{don} is usually very low, the voltage drop across MOSFET, V_{dsi} is very small. Therefore, differential op amp is used to amplify the on-state voltage across MOSFET.

When $i_1=i_L$ and $i_2=0$, it tells that there is open cell battery fault is occurred in cell C2 as shown in Figure 4 [35]. During this condition, MOSFET S2 is turned off to isolate the faulty battery from the rest of battery pack. Figure 4 also shows a short circuit of battery cell. In short circuit fault detection algorithm, if i_2 is greater than a threshold value, I_{SCth}, means that cell C2 is short circuit. Since current i_2, flow in opposite direction, the body diode of MOSFET is blocked. Consequently, battery cell C2 will be separated from the rest of battery pack.

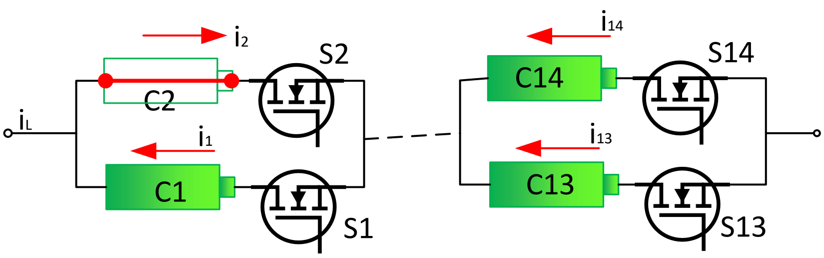

Figure 4. Battery cell short circuit

For large size of battery pack, a plenty number of MOSFET required on each cell. Beside, battery total current is limited to maximum current subjected to the MOSFET current rating.

4. FUTURE DEVELOPMENT

Robustness of BMS plays an important role to ensure its continuous operation especially when it use in medical or military application. Advanced control of battery cells and fault tolerance of battery pack are critical in future battery applications, especially in frequently recycling applications. Further studies need to be conducted to improve the speed of protection circuitry taken place when fault event occurs. Real time voltage sensing is may need to be considered replacing the zener diode. High speed MOSFET or IGBT switching capability can be explored to replace the function of the fuse.

5. CONCLUSSION

This review covers a difference type of cell fault detection technique and its control algorithm. Most of previous studies more focused on protecting the battery cell instead of protecting the BMS itself. Protection the BMS from fault stills a relevant field for future study, which include on less-complex of voltage sensing, high speed processing and compact design. Therefore, these fault detection technique discussed above should be considered for future development of high reliability and more robust BMS.

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