特集 New Battery Monitoring Unit for HEV/EV Li-ion battery*

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Lithium-ion (Li-ion) batteries have higher energy content and power density than Nickel-metal hydride (NiMH) batteries, but require careful management for durability and safety. Unlike NiMH batteries, which are controlled on a battery unit basis, each Li-ion cell generates a different voltage. Typically, the complex controllers required to equalize individual cell voltages are large and costly.

We have developed a fully functioning, low-cost, Li-ion battery monitoring unit (BMU) using an innovative new approach of embedding the cell-voltage equalizing and overcharge and overdischarge functions within an integrated circuit (IC). This new unit also performs fault diagnosis and measures the battery's internal resistance to monitor degradation.

Two key innovations facilitated the implementation of the IC to create this compact, low-cost, Li-ion BMU:

(1) A proprietary cell-voltage balancing system to equalise the voltage of each individual cell of a Li-ion battery:

This new cell-voltage balancing system eliminates much of the complex circuitry associated with conventional BMU systems. Conventional voltage control methods use a microcomputer to measure the voltage of all the battery's cells and discharges any above a target level. The new approach replaces the analogue-to-digital converters (ADC) and microcomputer with a simple circuit that discharges any cells with a voltage greater than the average cell voltage across the battery, significantly reducing the size and cost of the BMU.

(2) A new overcharge / overdischarge detection method utilising unique algorithms and a single comparator circuit:

This new approach combines both overcharge / overdischarge detection into a single comparator circuit embedded in the IC, eliminating the need for ADC and microprocessors.

Key words：EV and HEV systems; Lithium-ion battery; Nickel-metal hydride battery; BMU; Integrated Circuit.

1. INTRODUCTION

Interest in HEV/EV has grown rapidly in recent years, due to increasingly tighter CO2 emission regulations, and most car manufacturers are now planning to produce a number of EV or HEV models.

The demand for better performance and economies of scale are driving HEV/EV technological development. One such development is the shift away from Nickel-metal hydride (NiMH) batteries to Lithium-ion (Li-ion) based batteries (**Fig. 1**). However, Li-ion batteries require more sophisticated management than NiMH batteries to maximise service life and guarantee safe operation. This paper describes a new Li-ion BMU developed by us.

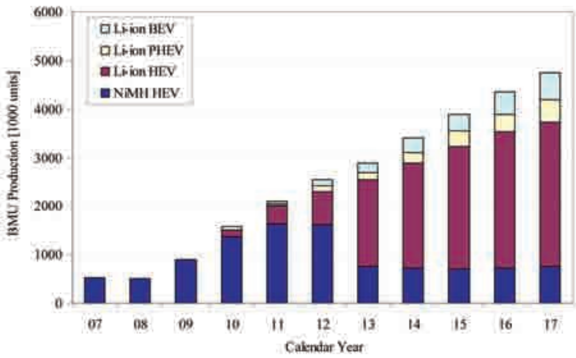

Fig. 1　Global BMU production forecast illustrating the growth of Li-ion batteries [1)]

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2. Design Philosophy

2.1 Double Flying Capacitor

One of the key NiMH BMU developments was the Double Flying Capacitor block voltage detection method.

In conventional voltage detection systems battery blocks are connected directly to an analogue-to-digital converter (ADC), which outputs the block voltage to a microprocessor via a series of opto-isolators (**Fig. 2**).

The DFC method on the other hand requires a fraction of the ADC and processing power and eliminates the opto-isolators and addition 5V power supply all together (**Fig. 3**).

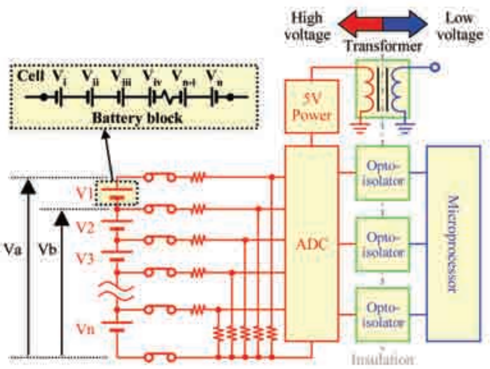

Fig. 2　Conventional voltage detection method

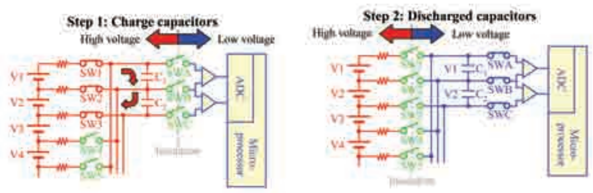

Fig. 3　New voltage detection method (Double Flying Capacitor)

The DFC configuration delivers performance and packaging benefits compared to conventional configurations, as shown in **Table 1** Furthermore, the elimination of the photo couplers and most of the ADC leads to a 72% cost reduction compared with conventional voltage detection system. (**Fig. 4**).

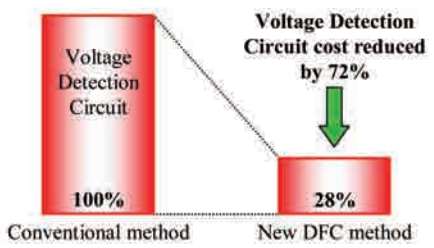

Fig. 4　Potential cost saving of the voltage detection circuit using the Double Flying Capacitor method

Table 1　Comparison of DFC BMU and conventional BMU specifications

	Our DFC BMU	Conventional BMU
Block voltage accuracy	0.6% Full Scale	2% Full Scale
Single block sampling time	4ms	10ms
BMU PCB area	211cm^2	477cm^2
BMU weight	400g	840g

3. Lithium-ion Batteries

Conventional motor vehicles use low-voltage lead-acid (Pb) batteries. Such batteries are not suited to the higher capacities required for vehicle electrification. Instead, NiMH batteries have typically been favoured for their balance of cost and performance.

However, Li-ion batteries, which have the highest cell oxidation reduction potential (typically 3.6V compared to 1.2V for NiMH batteries – **Fig. 5**), energy density and power density (**Fig. 6**) of all commercially available batteries, offer the potential for significantly improved performance and / or packaging.

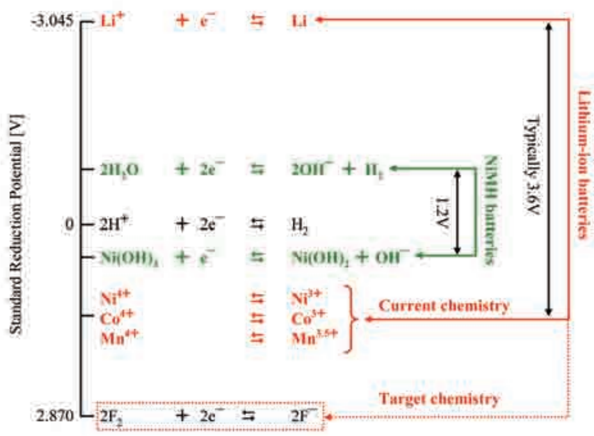

Fig. 5　Oxidation reduction potential of Li-ion and NiMH battery elements

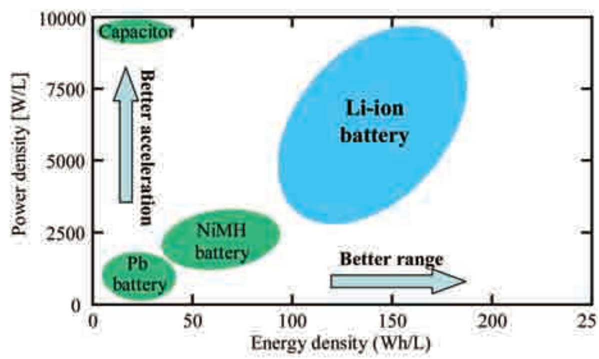

Fig. 6　Energy vs. power density characteristics of typical automotive batterie

In the past the high cost of Li-ion batteries has limited their market penetration. However, as costs have been reduced, Li-ion batteries have become a viable option for mainstream vehicles and are replacing NiMH in many applications.

Li-ion batteries require more sophisticated management to maximise their service life and guarantee safe operation. For example, NiMH batteries correct voltage differences between cells naturally during operation (due to reduced charging efficiency at high charge capacities) and, hence, can be controlled on a battery unit basis (**Fig. 7**). The voltage differences between cells in a Li-ion battery module are not naturally corrected. Indeed, due to variations in charge / discharge characteristics between cells, these differences may become even more pronounced during operation, reducing the usable capacity of the battery.

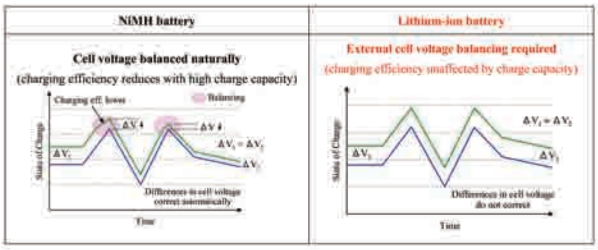

Fig. 7　Cell voltage behaviour of Li-ion and NiMH batteries

Li-ion cells typically use a negative electrode made of a copper foil coated with graphite and a positive electrode made of rolled aluminium foils. If the cell voltage is permitted to fall too low, overdischarging can occur. During overdischarging the negative electrode's copper foil starts to dissolve into the electrolyte and is deposited onto the positive electrode (**Fig. 8**), reducing the positive electrode's ability to accept lithium ions and limiting the capacity of the cell. With extreme discharging copper shunts may form between the electrodes, short circuiting the cell.

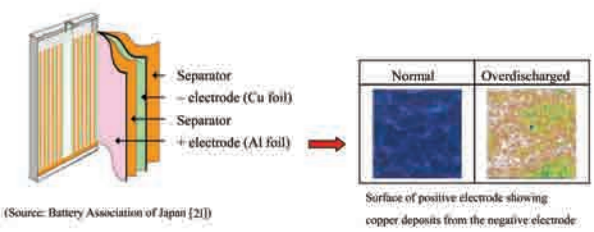

Fig. 8　Overdischarge situation of Li-ion Battery

During overcharging, lithium starts to build up on the negative electrode faster than it can dissipate, resulting in the creation of unstable metallic lithium plates. The positive electrode becomes an oxidising agent and loses stability. As the cell temperature increases with continued overcharging, the oxygen expands and the internal pressure rises. The cell starts to deform (**Fig. 9**) and, ultimately, will vent flammable gases and may even rupture.

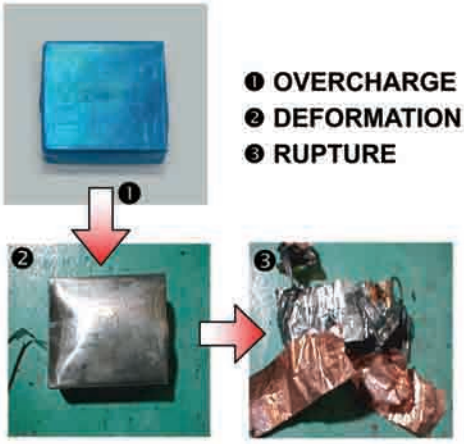

Fig. 9　Deformation (❷) and rupture (❸) of a Lithium-ion battery cell due to overcharging 3)

To prevent the damage from overcharging or overdischarging occurring Li-ion cell voltages must be limited to a safe operating range. **Fig. 10** shows a Li-ion battery with variations in cell voltage. To ensure the safe operation of the battery the BMU must carefully control the state of charge to ensure the cells with the highest voltage do not overcharge and the cells with lowest voltage do not overdischarge. As a result the operating capacity of the battery can be significantly reduced.

At the end of the journey, the BMU balances the cell voltages and the full operating capacity of the battery can be restored.

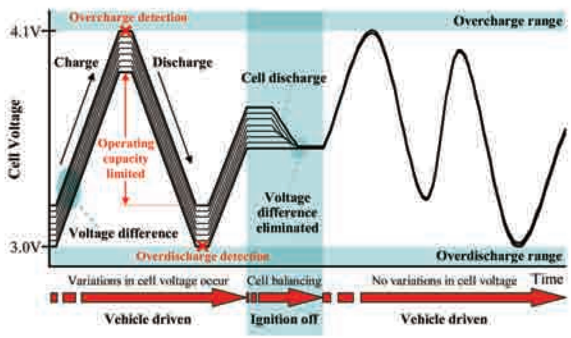

Fig. 10　Effect of voltage difference

In order to use a Li-ion battery effectively without failure, the voltage of each individual cell must be monitored and controlled individually. Controlling Li-ion batteries at an individual cell level, instead of a battery block level requires larger, more costly and complex systems compared to those previously used on NiMH batteries. Hence, reducing the costs of Li-ion BMU is a key development target.

4. New Lithium-ion Battery Monitoring Unit

4.1 Overview

We have developed a new, compact and low-cost Li-ion BMU (**Fig. 11**), based on the following technical developments:

1. An innovative new circuit architecture that combines many of the functions of the BMU onto a single microchip
2. A proprietary cell-voltage balancing system to equalise the voltage of each individual cell of a Li-ion battery.
3. A new overcharge / overdischarge detection method utilising unique algorithms and a single comparator circuit.

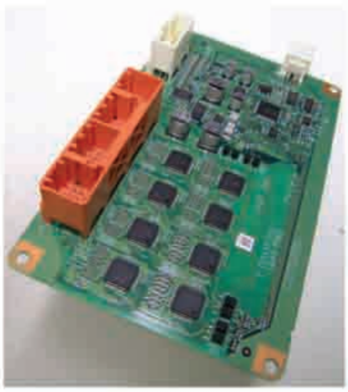

Fig. 11　New Li-ion Battery Monitoring Unit

4.2 Integrated Circuit (IC)

A conventional Li-ion BMU have tended to be large and costly as they require numerous high voltage circuits to be routed around the PCB to perform the functions required of a Li-ion BMU (such as cell-voltage balancing). The design philosophy behind this new development was to achieve a significant reduction in both the physical size and cost of the new BMU by developing an Integrated Circuit (IC) that combines many of these functions onto a single microchip and eliminates much of the high voltage circuitry.

This new IC (**Fig. 12**) has been designed and manufactured in-house and contains unique algorithms that perform the key Li-ion cell monitoring functions.

Fig. 12　Picture of the Integrated Circuit (left) and microchip contained within (right) that has been developed for the new Li-ion Battery Monitoring Unit

4.3 Cell voltage balancing system

The requirement to balance the voltage of Li-ion batteries at an individual cell level, combined with the high number of cells required for many applications (over 100 in some applications) leads to large, complex circuitry for conventional Li-ion BMU systems.

We have developed a new, proprietary cell-voltage balancing system that uses a specialised IC to eliminate much of the complex circuitry associated with conventional BMU systems, significantly reducing the cost of the Li-ion BMU.

Conventional voltage control methods use a microcomputer to measure the voltage of all the battery's cells and discharges any above the target level. The new approach replaces the ADC and microcomputer with 2 simple circuits that discharge any cells with a voltage greater than the average cell voltage across the battery (**Fig. 13**).

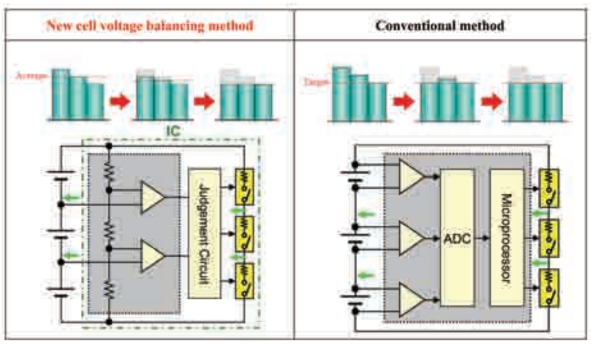

Fig. 13　The new cell voltage balancing method (l) and the conventional method (r)

Fig. 14 illustrates this process. In this example the battery block contains 6 cells. During the balancing process all cells above the average voltage (initially 3.995V) are discharged. As these cells discharge the average voltage is gradually reduced.

Additional cells discharge as the average voltage drops below the voltage of each cell. This process continues until the difference in voltage between the cell with the lowest voltage and the average cell voltage is below a threshold value.

This process typically takes about one hour.

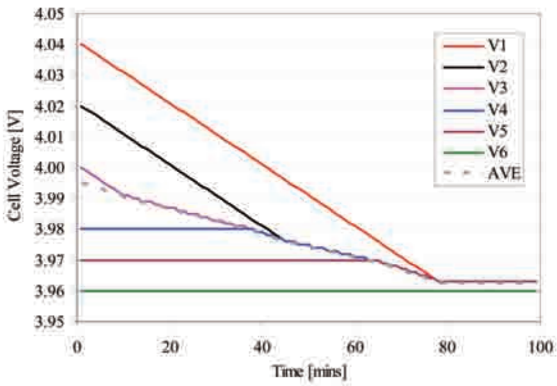

Fig. 14　Waveform of Cell-voltage balancing

4.4　Overcharge and overdischarge detection technology

A new overcharge / overdischarge detection system has been developed for the new Li-ion BMU. Both functions are performed at an individual cell level by a single comparator circuit (**Fig. 15**) imbedded in the IC.

Fig. 16 shows the behaviour of the comparator circuit. When switch SW1 is closed (SW2 is open), overdischarge judgements are performed. If the cell is overdischarged, the comparator output shows “low”. Likewise, when switch SW2 is closed (SW1 is open), overcharge judgements are performed. If the cell is overcharged, the comparator output shows “high”. This design eliminates the need for an ADC or microprocessor in the overcharge / overdischarge circuit.

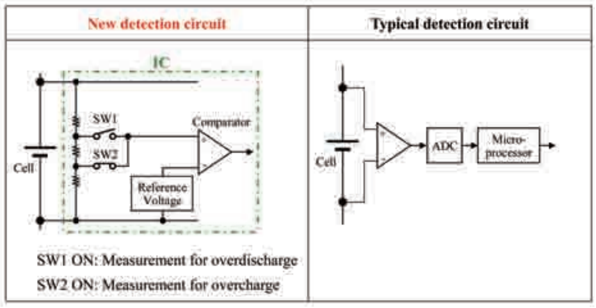

Fig. 15　Circuit embedded in the IC

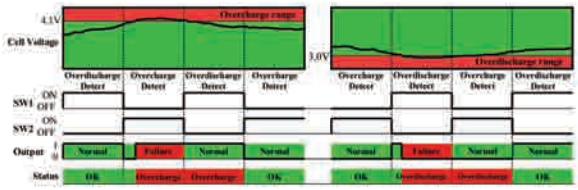

Fig. 16　New overcharge and overdischarge measurement method

5.　Functional safety

System redundancy was a key consideration throughout the design and development process of the new Li-ion BMU. As a result, the new IC design delivers a high level of functional safety. For example, the overcharge / overdischarge detection circuits embedded in the IC have been duplicated (**Fig. 17**) enabling this system to remain functional in the event of a malfunction.

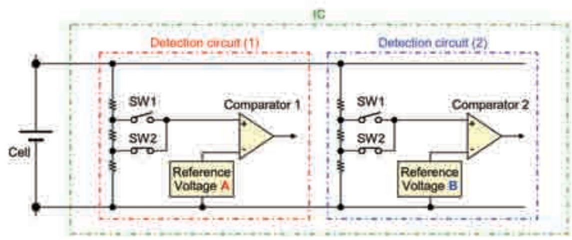

Fig. 17　Architecture of double detection circuits

6. Future issues

The BMU is directly connected to high-voltage source, hence electrical noise is encountered. Such electrical noise must be eliminated to ensure the effective management of Li-ion batteries, as the individual cells must be controlled at the millivolt scale. However, due to the unique nature of the noise it cannot be simulated under laboratory conditions and the noise filtering specifications for the BMU can only be established following tests on a representative vehicle. This can cause delays in fixing the final specification of the BMU. Further development is ongoing to mitigate this issue.

7. Conclusion

We have developed a new BMU for Lithium-ion battery applications that offers a significant cost reduction compared to conventional units

- In-house IC design and manufacturing capability used to embed discharge control and overcharge / overdischarge detection circuits in a single chip
- Analogue-to-digital converters and microprocessors eliminated from these processes
- BMU size significantly reduced

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