EVERLASTING

Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

D8.13 – White Paper 10

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DISCLAIMER

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The EVERLASTING project (http://everlasting-project.eu/) will develop innovative technologies to improve the reliability, lifetime and safety of lithium-ion batteries by developing more accurate and standardized battery monitoring and management systems. This allows predicting the battery behavior in all circumstances and over its full lifetime and enables pro-active and effective management of the battery. This leads to more reliability and safety by preventing issues rather than mitigating them. To raise the awareness of the vital and positive role of battery management systems, a three-monthly white paper will be written on different BMS topics, aimed at a general technical public. These white papers are a few pages long and will be distributed via the EVERLASTING website and through the partners.

The first white papers focused on typical battery topics, such as BMS functions, the definition of State-of-Charge and State-of-Health and how to evaluate them, with a strong focus on Li-ion batteries.

2 WHITE PAPER 10: BATTERY MANAGEMENT FOR DIFFERENT TYPES OF BATTERIES

In this white paper we will discuss the battery management for different types of batteries. Battery management systems are an accepted feature in Li-ion battery applications, but their use with other types of batteries is discussed much less. In this white paper we will discuss whether battery management systems can be useful for other types of batteries (lead-acid, nickel-based, flow batteries…), what features would be useful and how they should be adapted.

2.1 INTRODUCTION

To evaluate the use of a BMS for various types of batteries, it makes sense to revisit the first white paper [1]. In there, the functionality and requirements of a typical BMS were presented and discussed.

Five areas were identified:

1. **Sensing and control**: The BMS must measure cell voltages, temperatures, and battery-pack current. It must also detect isolation faults and control the contactors and the thermal-management system.
2. **Protection**: The BMS must include electronics and logic to warn for or protect the operator of the battery-powered system and the battery pack itself against over-charge, over-discharge, over-current, cell short circuits, and extreme temperatures through an attached cooling or heating system.
3. **Interfacing**: The BMS must communicate regularly with the application that the battery pack powers, reporting available energy and power and other indicators of battery-pack status. Further, it must record unusual error or abuse events in permanent memory for technician diagnostics via occasional on-demand download.
4. **Performance management**: The BMS must be able to estimate state-of-charge (SOC), preferably for all the cells of the battery pack, compute battery-pack available energy and power limits, and balance (equalize) cells in the battery pack.
5. **Diagnostics**: Finally, the BMS must be able to estimate state-of-health (SOH), including detecting abuse, and may be required to estimate the remaining useful lifetime of the battery cells and pack.

Since lithium-based cells are relatively volatile, protection and safety is the most compelling reason for their use in such battery packs. However, other types of batteries often also employ a form of BMS in one way or another, even if their use is not driven by safety concerns.

2.2 OTHER CELL TYPES

In this section, we discuss other commonly used battery technologies, in the wide sense, and their need for or the benefits gained combining them with a BMS.

2.2.1 LEAD-ACID

Figure 1: Large 2V lead-acid cells (Source: Victron Energy)

Lead-acid cells are still widely used in applications where energy density and efficiency are not critical, cost outweighs lifetime considerations, or in areas where lithium batteries still do not perform very well (e.g. subzero engine cranking). Especially modern VRLA and AGM-type lead batteries cells are robust and tolerate continued moderate overcharging by design. In fact, the overcharging behavior acts to balance individual cells in a lead-acid pack. This negates the need for protection and advanced balancing functions, of which the added cost would only bring limited benefits. Nevertheless, extended overcharging or overcharging at high currents will still damage a lead-acid battery.

A well-known field of application for lead-acid batteries is the supply of the 12 V electrical system of conventional vehicles. With the spread of start-stop systems, advanced BMS algorithms were introduced for these batteries[2]. As the start of a combustion engine is a relatively short event, the ability of the battery to deliver a certain power at a given time is more relevant than the overall energy content of the battery. Physically motivated equivalent circuit models can for example be used to predict the cold cranking capability of the battery in the current state. As the fundamental mechanics in lead-acid batteries include the dissolution of electrode material and the electrolyte takes part in the main reaction, the modelling of these processes is more complex than in lithium-ion batteries. Yet, other fundamental effects as for example diffusion and temperature dependencies are similar for both battery types.

The advanced battery management algorithms are usually implemented in a small, integrated sensor that measures pack voltage and current. Due to cost and space constraints, the used algorithms have to be simple and robust.

At the higher-end of the scale, we find large lead acid batteries for mobile (e.g. forklifts) applications, and very large (>1000Ah) 2V 'wet' lead-acid cells for stationary energy storage. Due to the high investment cost and connected system availability requirements (e.g. telecom), the life of the cells in the latter are more closely monitored. The liquid electrolyte in them is redistributed using air circulation pumps (producing bubbles that mix the acid) to prevent stratification and early degradation, and its level is measured to protect against excessive acid concentration (which leads to early sulfation) or dry plates. Furthermore, lead-acid batteries require a regular full-charge to maximize useful life, and cell internal resistance measurements are taken as ageing indicator. In these scenarios, the added functionality of a BMS could outweigh the added cost and complexity [3], [4].

BMS requirements summary:

- Pack-level sensing (e.g. 12V block) of voltage, temperature and current.
- Interfacing via e.g. LIN or CAN for automotive applications, or with auxiliaries (for stationary storage).
- Performance management via predictive models for start-stop automotive applications.
- Active impedance monitoring in UPS applications[5].

2.2.2 NIMH

Nickel-metal hydride batteries are common in portable consumer applications, where they have replaced the use of Nickel-Cadmium batteries. NiMH cell voltage ranges between 1.0-1.2V, and are usually charged at up to 1.6V. Energy density is limited, and as with lead-acid batteries, the charging process becomes inefficient at SOCs > 80-90% [6]. NiMH cells also often exhibit high self-discharge and charge/discharge rates are limited to 1C.

NiMH cells are considered robust and safe, and manufacturers often specify that NiMH cells are tolerant of (moderate) overcharging (up to C10) [7]. Produced hydrogen in this phase will be recombined inside the cell but in case of severe overcharging hydrogen pressure could build up. NiMH cells are therefore equipped with a safety valve, not unlike lithium-ion cells.

Figure 2: Panasonic large infrastructure type 12V NiMH block (Source: Panasonic)

Notable automotive applications of NiMH batteries include the GM EV1, the Vectrix VX1 scooter and Toyota Prius hybrid car.

Due to the inherent safety, consumer electronics manufacturers often use simple chargers that forego advanced protection features. The overcharging tolerance therefore helps to reduce the cost of the system. Due to the significant fall in cost of lithium-ion battery packs (with BMS), NiMH is falling out of favor for many applications.

BMS requirements summary:

- Fast charging of NiMH batteries comes with certain peculiarities: charging is considered finished when a certain temperature or voltage gradient occurs.
- While not strictly necessary in many applications, it is beneficial to guard NiMH cell voltages. This will avoid excessive overcharging and hydrogen build-up, which will negatively affect the battery life.

2.2.3 LTO BATTERIES

One specific variant of lithium-ion batteries is the Lithium-Titanate (LTO) chemistry [8], [9]. LTO cells use LiTi ($Li_4Ti_5O_{12}$) crystals on the anode instead of graphite as in other lithium-based chemistries. The cathode materials can vary, as is common in other lithium-ion cells.

LTO allows for very high charge/discharge rates and exhibits excellent cycle life compared to other lithium-based cell chemistries, at the expense of low energy density. This is due to the low voltage range in which LTO cells operate: typically between 1.5 and 2.85V. The lower operating voltage means that BMSs designed for the prevalent higher-voltage chemistries cannot always be used on LTO packs, even though this is still within range of many standard BMS ICs.

Figure 3: Toshiba Super Charge Ion Battery (Source: Toshiba)

BMS requirements summary:

- Protection requirements are similar to the other lithium-ion chemistries with graphite anodes, even though LTO is considered safer as no lithium plating can occur.
- Specific SOH estimation needed, as the main ageing process on the anode does not occur, in contrast to other lithium-ion chemistries.

2.2.4 SODIUM-ION BATTERIES

One battery type that has had increased interest in recent years is the sodium-ion technology [10], [11]. Due to their use of abundant materials, they have a lower cost than lithium-ion batteries and are considered safer. Gravimetric energy density is currently at 90-120Wh/kg, comparable to some lithium-ion chemistries, and volumetric energy density at 210-250Wh/L. Sodium-ion cells typically operate in a window of 1.5-3.5V.

Figure 4: Tiamat Sodium-Ion 18650 cells (Source: Tiamat)

The increased safety of this technology is due to their resistance to being undercharged (as no dendrites can form during the subsequent recharging) and the possibility to use less flammable electrolytes as compared to lithium-ion batteries. This negates the necessity of certain protection features, as demonstrated by the Aquion saltwater battery [12].

BMS requirements summary:

- Undervoltage protection requirements are not as strict as for lithium-ion cells, but overvoltage protection remains important.
- Otherwise, requirements are similar as for lithium-ion cells in automotive or stationary applications.

2.2.5 SUPERCAPACITOR PACKS

Supercapacitors are employed when bursts of power have to be supplied, and where a battery would have to prohibitively over-dimensioned to do so. Typical supercapacitors 'cells' are of the EDLC type (Electric Double Layer Capacitor) and store up to 3000F at 2.5 to 2.7V [13], [14]. The upper voltage is limited by the breakdown voltage of the electrolyte. They can withstand millions of cycles.

Alternatively, lithium-ion capacitors [15], [16] are a hybrid between lithium batteries and EDLCs, and can reach higher voltages (up to 4V), but as with lithium batteries, should not be discharged below 2.2V.

Figure 5: Supercapacitor pack with Maxwell Boostcaps (Source: Argonne National Laboratory)

In case batteries are built from a series-string of EDLCs, it is common to find top-balance circuits on each cell. These circuits start dissipating energy when the EDLC voltage exceeds its maximum, e.g. 2.7V. Since the energy content of capacitors is much lower, small balancing currents in the order of 10-50mA are considered sufficient. This type of basic overvoltage protection does not require a full-fledged BMS.

Figure 6: JSRMicro ULTIMO lithium capacitors (Source: JSRMicro)

Lithium-capacitors on the other hand are more critical, as they do not tolerate being (left) undercharged (<2.2V). Therefore a BMS is essential to protect Lithium-caps.

Furthermore, applications where capacitors are used as energy storage often integrate some energy management system. In this case a BMS provides an interface to base power and energy estimations on.

BMS requirements summary:
1. Banks of series-connected EDLC capacitors are very safe but may require balancing.
2. Lithium-capacitor banks need to be treated like lithium-ion batteries: over- and undervoltage must not occur.
3. Interfacing with energy management systems for SOC and SOF (operating window) information.

2.2.6 FLOW BATTERIES & FUEL CELLS

In a flow battery two separated liquid electrolytes are pumped past a membrane that sits between two electrodes. The electrolyte carries dissolved electroactive elements that react at the electrodes by exchanging ions through the membrane. The capacity of a flow battery is determined by the size of the electrolyte storage tanks and independent of the power, which is governed by the surface of the exchange membrane. Single cell voltages range from 0.9 to 2.2V. Currently, the Vanadium Redox flow battery is the most commercially available type of flow battery, but many different types are on the market [17]–[21].

Figure 7: Redflow's Zinc-Bromine ZBM2 flow battery (Source: Redflow)

A fuel cell is a type of flow battery where the used reactants are extracted from the system. Hydrogen fuel cells [22] are widely known, and combine oxygen and hydrogen at the membrane, and emit water vapor at the exhaust.

Due to the low voltages of the cells, practical applications of fuel cells employ a stack of series-connected cells to achieve high voltages. The gasses are supplied to the cells in parallel fashion.
A consequence of this setup is that the gas supply to the individual cells of a stack can differ while the current flowing through them is identical. This can result in large differences in cell voltages within one stack. When a cell produces current at a low voltage (compared to the other cells in the stack), this is a clear indication something is wrong in the operation of this cell. Since the efficiency of a fuel cell at a given load current is directly related to the cell voltages (usually plotted in an I-V curve), cells should always be operated at the highest possible voltage. Consequently, any deviation from this optimal situation, e.g., due to a failing component or control, will be translated into a reduction of cell voltages. Consequently, cell voltages indicate the correct and safe operation of a fuel cell stack. Thus a fuel cell BMS's (or rather FCMS) task is primarily related to the monitoring of the stack's internal voltages and interfacing with an application's control system [23].

BMS/FCMS requirements summary:

- Due to the completely different nature of flow batteries and fuel cells, and the need for exact control of flowrates (pumps), pressure (valves) and temperature, BMSs for these systems are tailored solutions.
- Ageing and degradation of these batteries are primarily linked with the state of the exchange membrane. SOH is thus dependent on temperature, operating hours, amount of starts, … and again very technology specific.
- For safety and lifetime management, the BMS has to keep the voltage of every cell or group of cell is in the expected range (depending on the operating state: start up; working phase; purging;…).

2.3 CONCLUSION

From the overview in the previous section we can see that not just lithium-ion batteries can benefit or require the features provided by a BMS system. However, safety and protection are often the biggest drivers that justify the added cost of a BMS, followed by the need to interface or follow-up the state of the storage device. Only relatively low-cost technologies such as lead-acid and NiMH batteries are often used without BMS, as they are inherently more tolerant against (moderate) overcharging or overdischarging. As a step-up, we also encounter independent balancing circuits in supercapacitor packs to protect against overcharging.

However in many applications where a battery represents a significant share of the system cost and where availability and lifetime are important considerations, a BMS is used to monitor and protect (e.g. by balancing at cell level or contactor override at pack level) and provide an interface to a ‘higher’ application (e.g. SoC/SoH/SoF and current information to an energy management system (EMS), contactor control, …) by means of a communication interface or simple signaling.

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