Large Lithium-Ion Batteries – a Review

Dennis Doerffel[1], Suleiman Abu Sharkh[2]

[1]REAPsystems Ltd, 61A Ivy Road, Southampton SO17 2JP, UK.
dennis@reapsystems.co.uk , Tel/Fax: +44-2380-556516 (Corresponding Author)

[2]University of Southampton, SES, Highfield, Southampton SO17 1BJ, UK.
suleiman@soton.ac.uk , Tel: +44-2380-59-3397

Introduction

Lithium-ion batteries have been extremely successful in the portable equipment markets such as laptops and mobile phones. Currently, the lithium-ion battery technology is transitioning from small cells to large size batteries for a range of applications. Existing systems can be significantly enhanced using this lightweight battery technology and new innovative products can be launched. A better understanding of lithium-ion technology is key know-how for any forward-looking company that works or wants to work with large battery applications. Knowing more about these batteries and understanding how they work and what is required in order to operate them, will help designing safer, smaller, lighter, better performing, longer-lasting products with higher customer acceptance and at lower cost. It will help reducing the time and number of iterations during prototyping and design and hence reduce the time to market. Costly tests, time consuming “wrong” strategic / tactical decisions or even dangerous designs can be avoided by better understanding the lithium-ion battery technology.

This paper will provide a suitable “entry point”. It brings the reader up to speed with the most essential understanding and it will guide the way into the world of lithium-ion battery technology. The paper will touch the most relevant topics including performance comparisons with other battery technologies, the lithium-ion working principle, behaviour and specific characteristics, safety issues, ageing, electronic protection and management requirements as well as a short overview of different battery management implementations and options for cell equalisation. Advantages, disadvantages and issues will be discussed and linked to the fundamental working principles.

Background Information on Lithium-Ion Batteries

Lithium-ion batteries dominate the market for most portable products such as mobile phones, laptop computers, etc. The great success of the lithium-ion battery is mainly due to their significant advantages in terms of performance.

Performance Comparison

Performance is always relative to many other attributes. The most common way for comparing the performance of energy storage solutions is to use the Ragone plot. In such plots, one performance attribute on the first axis is always related to another important performance attribute on the second axis. The first illustration shows the specific energy in Wh/kg over the energy density in Wh/litre for several different energy storage technologies.

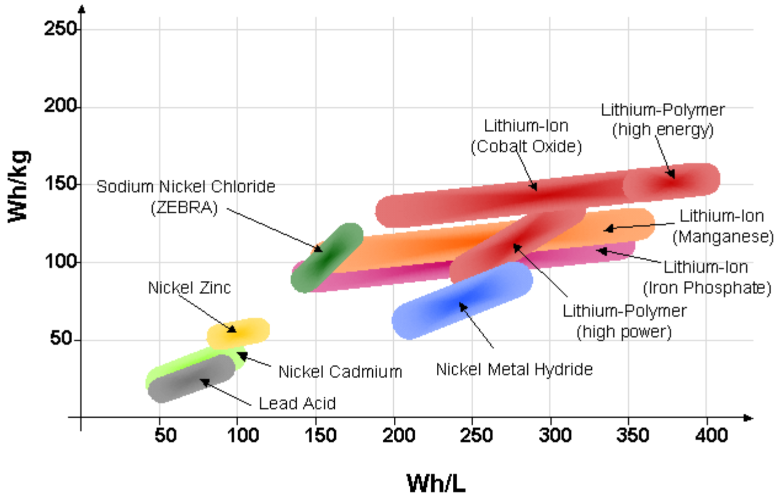

Illustration 1: Energy storage performance of different technologies

This illustration shows clearly, that the family of lithium-ion cells provides much smaller size and much lower weight for a given stored energy if compared with the other most common battery technologies. In particular, size and weight are up to 4 times reduced if compared with the most common battery type, the lead-acid battery.

Following, we will use the term lithium-ion cell in order to represent the whole family of lithium-ion cells. Terms such as lithium-iron, lithium-polymer, lithium-phosphate, etc. will only be used in order to specify a particular type of lithium-ion cells.

Many engineers are aware, that lithium-ion batteries are very good at storing energy. However, there is still a fair “knowledge-gap” regarding the power-capabilities of lithium-ion cells. Many people consider them as not very powerful. The second illustration is another very common Ragone plot, which shows the specific energy over specific power for several energy storage technologies including fuel-cells and combustion engines.

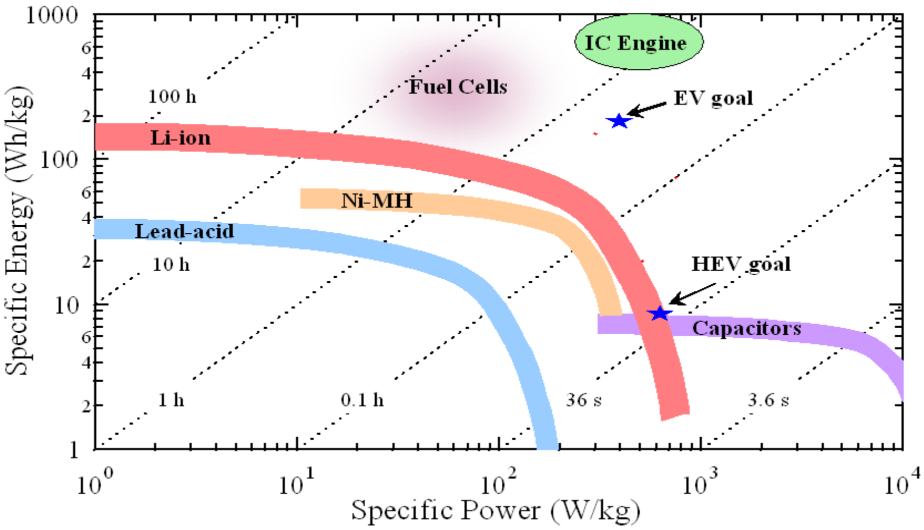

Illustration 2: Ragone plot for different energy storage solutions (Berkeley Electrochemical Research Council Ref: Venkat Srinivasan and John Newman: http://berc.lbl.gov/venkat/Ragone-construction.pps.)

Firstly, it is obvious, that the lithium-ion technology performs better than lead-acid or nickel-metal hydride (NiMH) cells in terms of both, energy and power for a given battery weight. This means, that lithium-ion cells exhibit very good power performance. This however depends on the internal construction. It can also clearly be seen, that for very high power requirement, capacitors make more sense than battery technology in terms of electrochemical energy storage technology – but the energy storage capabilities of capacitors are very limited. However, this graph only compares two attributes. Other attributes, such as volume, cost and “special attributes” have to be considered as well when making choices. We will discuss a few “special attributes” later.

The graph also shows the performance characteristics of fuel cells and combustion engines. However, both of them are energy converters and the energy storage has to be treated separately. In the above case, a typical amount of stored energy (fuel + fuel tank) has been considered for this particular application (e.g. 60 litres of petrol in a car) in order to derive the overall specific energy / specific power performance of the energy storage + converter device. The result will vary significantly for other applications and is also dependent on the type of power that is required on the output (e.g. mechanical or electrical). However, this estimate is sufficiently good for demonstrating that combustion engines are much better in this comparison. It also demonstrates that fuel cells perform well for storing energy, but may require battery backup or capacitor backup for providing short term power. Again, cost, size and other attributes cannot be displayed in such Ragone plots at the same time, but need to be considered.

The Ragone plot in illustration 2 shows a typical characteristic of all batteries, which is in contrast to the behaviour of other types of energy storage, e.g. in liquid fuels: The available energy decreases rapidly when drawing very high power. This is mainly due to the significant voltage drop and hence power loss when drawing very high currents.

The Construction and Working Principle

It is important to picture the construction and understand the fundamentals of the working principle in order to use battery technologies effectively and appropriately. The construction of a typical lithium-ion cell is illustrated in our third illustration:

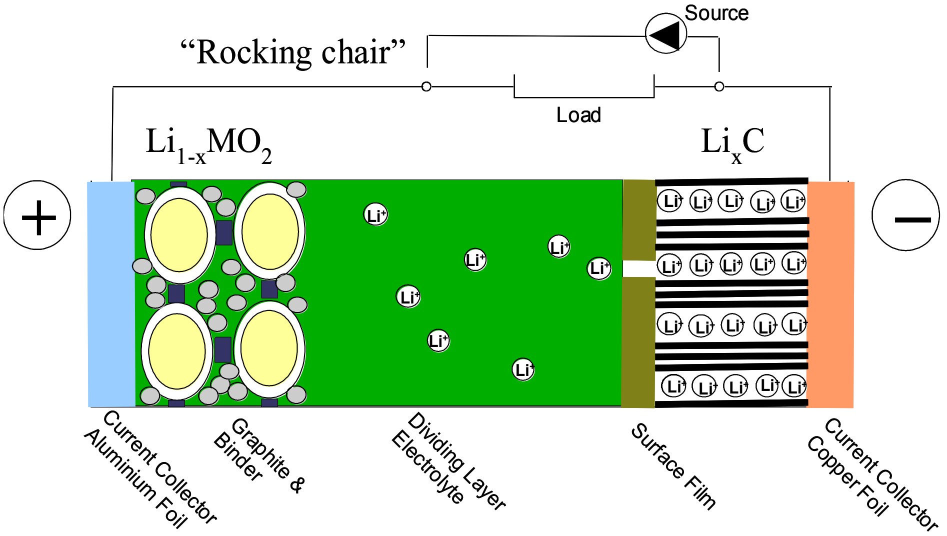

Illustration 3: Model of the construction of a lithium-ion cell

Illustration 3 shows a model of the most important structural features of a lithium-ion cell. From left to right, one can see the current collector and the active material of the positive electrode, then the electrolyte and dividing layer (separator) and on the right the active material and current collector of the negative electrode.

Due to the high voltage of a lithium-ion cell (nominal 3.6V), the choice of materials for the current collectors is very limited: The positive electrode consists of aluminium and the negative electrode is made of copper. Usually, the terminal material is the same as the electrode material in order to avoid potential differences and risk of corrosion inside the cells. In any case, making reliable and long-lasting connections, especially to the aluminium electrode / terminal can pose some challenges.

The electrolyte is an organic solvent with a lithium based salt in solution. The electrolyte is electronically non-conductive, but solves and transports lithium-ions. There is a range of different suitable solvents for lithium-ion cells. Frequently, two to four different solvents are mixed in certain proportions and additives may be added in order to “engineer” the desired characteristics. Currently, the formulation is optimised for a general broad use. However, the formulation could be optimised for certain applications (e.g. high temperatures in UPS systems).

During charging, the lithium-ions move through the electrolyte from the positive to the negative electrode. During discharging they move in the opposite direction. They do not form a solid phase of lithium-metal and go back in solution. No metal lithium is formed at any stage during the process. The ions just move back and forth – hence, amongst electro-chemists, lithium-ion cells are also called “rocking-chair”. The reaction kinetics in lithium-ion cells are much faster than in lead-acid batteries, but the moveability of the ions in the electrolyte is comparatively slow. This is why early lithium-ion cells were not particular powerful. However, nowadays, the paths through the electrolyte are kept very short and hence, high power is available. This is achieved by utilising a thin fleece in which the electrolyte is absorbed. Alternatively, the electrolyte is contained in a polymer. This separator allows the active materials to be very close together.

Both electrodes consists of many small particles as shown for the positive electrode in illustration 3. The particles here are a lithium-metal-oxide and are “glued” together and to the current collector using a binder. A conductive filler (e.g. Graphite) is used to increase the conductivity between the particles. The negative electrode looks very similar, except that the conductive filler is not required, because the particles consist of conductive material themselves (e.g. graphite, coke). Performance is increased by controlling the particle size and keeping them small in order to increase the surface area and reduce the travelling distances for the lithium-ions inside the particles. Nano-technology is the key-word for the ultimate control of this process.

The particles on both electrodes are covered with a surface film , which is called solid-electrolyte-interphase (SEI) as indicated on the right hand side of illustration 3. The left hand side in fact shows one of those particles with its SEI zoomed in. Again both electrodes look very similar. During charging / discharging, the lithium-ions travel through the electrolyte, then between the particles, through the SEI into the solid particles. Entering the solid particles is called intercalation. The active material (particles) may contain no or up to a certain saturation limit of lithium-ions, which can almost freely move inside the layers of the particles – just like in a liquid solution. This is why the active material containing intercalated lithium-ions is also called solid-solution.

Comparison of Specific Behaviour

We have already mentioned a few quantifiable battery attributes, such as energy, power, weight, size and cost. These are quite easily comparable. However, most energy storage solution exhibit a range of “special attributes”, which may be specific to a certain technology and which cannot always be quantified. Many of these attributes are very important for the day-to-day use of the energy storage solution and should hence be taken into account when selecting a certain technology solution. A few “special attributes” of the most common battery technologies shall be mentioned here and compared with the lithium-ion technology.

Most batteries are labelled with their nominal capacity in Ah. However, Peukert has studied an effect for lead acid batteries in 1899, which showed that the available capacity heavily depends on the discharge rate. Usually, the nominal capacity applies to a five hour discharge with a constant current. In many applications, the discharge rate is much higher, in which case the available capacity decreases heavily. We have further investigated this effect [1] and we found that this effect makes it very hard to predict the remaining capacity of a lead-acid battery during a discharge with varying currents. Also, we found that this effect does not exist for lithium-ion cells. The available capacity does not decrease significantly with higher discharge rates as shown in illustration 4.

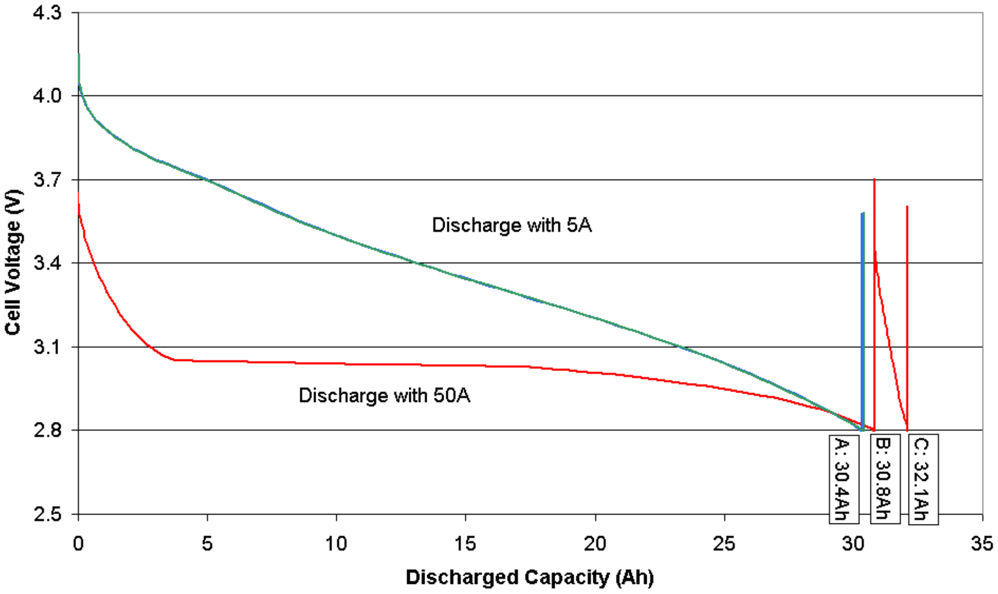

Illustration 4: Discharge curve of a ***lithium-ion cell*** *using two different discharge rates.*

Another well-known effect is the “memory-effect” of nickel-cadmium (NiCd) cells, which also slightly applies to NiMH cells. If a NiCd cell is not fully discharged from time to time, it appears to “remember” this lowest state of charge which it had during those cycles: after a while, it will not be able to provide sufficient power below this state of charge any more. NiCd cells therefore require a full discharge from time to time. This is very user-unfriendly for many applications (in particular power-tools).

Lead-acid batteries exhibit the opposite behaviour. They will start performing worse if kept in low-charge regions for too long times. In cyclic applications, undercharge is what kills the lead-acid battery and it is important to provide lead-acid batteries with a full charge as often as possible. Charging currents should be as high as practical, charging voltages should be high and opportunity charges should be applied wherever possible. However, in stand-by applications where the battery is kept fully charged all the time, such as in uninterruptible power supplies, the opposite problems becomes more evident: The cells will die due to corrosion or dry-out, which is a result of gassing. In these cases, the charging voltage should not be too high. Getting it “just right” becomes a challenge, especially, when trying to manage a high voltage pack with several cells in series connection.

Lithium-ion cells do not exhibit any of the above characteristics. Basically, they can be stored or used in any state of charge and they can be recharged whenever suitable. However, they should not be kept at very high state of charge and very high temperatures, as this will increase the thickness of the SEI (see illustration 3). The ionic conductivity of the SEI is not very good and the travelling through that SEI is one of the major rate limiting steps. Increasing it means loss of performance.

Some types of batteries suffer from a sudden death when reaching their end of llife. Flooded lead-acid batteries for example can suffer from internal short-circuit after a certain cycle life, which will cause them to stop working altogether and almost without warning. Lithium-ion cells are subject to a monotonous and predictable ageing: The capacity and the performance will decrease slowly over time and cycles without any surprises. The most important ageing processes will be explained later.

Compatibility with Existing and Well-known Battery Technologies

The 12V block lead-acid battery is a very common battery type. Many components are designed to work with the typical voltage range of those batteries. Lithium-ion cells however exhibit a nominal voltage of 3.6V and hence, it is not possible to obtain exactly the same voltage: Three lithium-ion cells in series provide 10.8V nominal and four cells provide 14.4V. There may be a problem finding a suitable matching voltage when trying to use lithium-ion cells. However, the nominal voltage should not be the only value under consideration. The following illustration compares the total voltage swing as well as the most important voltage levels for a lead-acid battery and three or four lithium-ion cells connected in series.

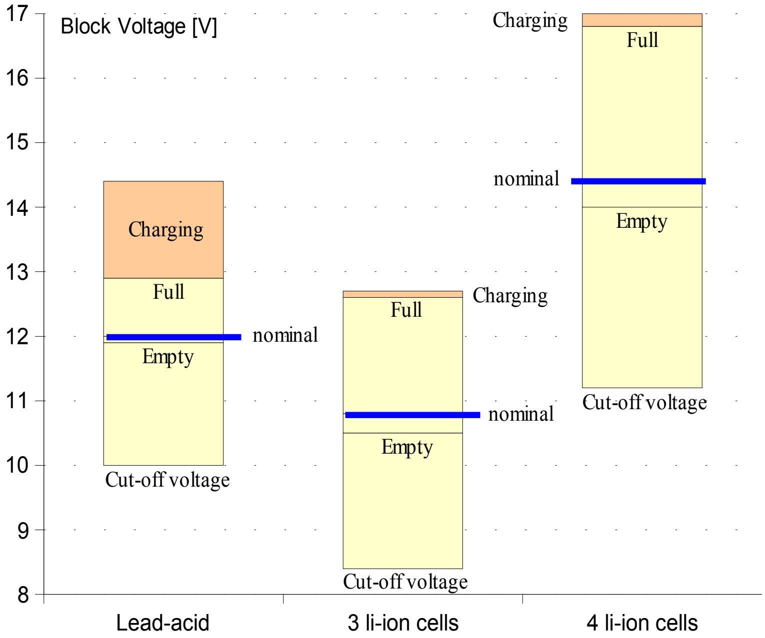

Illustration 5: Typical voltage ranges of a 12V lead-acid battery block compared with three or four lithium-ion cells that are connected in series.

The most important voltage levels to be considered are (from bottom to top): The cut-off voltage, which is the minimum permitted voltage level during discharging. The next voltage level is the "empty" voltage, which is the voltage of an empty battery in equilibrium. Equilibrium means that there is no charging or discharging current and that the cell voltage has reached a stable value. The next voltage level is the nominal voltage and then the "full" voltage, which is the voltage of a full battery in equilibrium. Finally, the top voltage is the maximum voltage at the end of charging.

It can be seen that the voltage levels very much differ between the three solutions. No exactly matching lithium-ion solution can be found for a 12V lead-acid battery block. Lithium-ions have a different voltage swing characteristic. The relative total voltage swing is about the same as for the lead-acid, but the voltage swing during discharging is much higher for the lithium-ion cell if compared with the lead-acid. This is because the lead-acid exhibits a high voltage swing just during charging, whereas the lithium ion doesn't. This can be of importance for applications, where the discharging components are not connected during charging.

However, the problem of matching voltages becomes less of an issue at higher battery voltages. E.g. a battery with 10 x 12V lead-acid blocks in series can be matched quite nicely with 33 lithium-ion cell in series.

Examples of Other Important Battery Characteristics

There are many more important characteristics, which should be considered when choosing the energy storage solution. Go through all of them in great detail would be out of scope for this paper. However, we will briefly mention a few more characteristics, where the lithium-ion technology performs differently:

- Many battery types exhibit some issues with heat. They degrade rapidly at elevated temperatures and some heat up significantly during discharging or charging, especially towards the end of charging - effective cooling may be required. Lithium-ion cells are very efficient and they do not heat-up as much. There are no side-reactions by design and hence they do not heat up at all towards the end of charging. In fact, the thermodynamics make them cool down slightly during charging.
- Batteries with water-based electrolytes may freeze and the case may crack at very low temperatures. This is a well-known problem for fully discharged lead-acid batteries with low acid concentration. The organic solvent in lithium-ion cells does not freeze at low temperatures.
- The performance of some batteries becomes very poor at low temperatures. It is difficult to make general statements about low-temperature performance of lithium-ion cells. However, it is possible to make and buy modern lithium-polymer cells with very good performance at low temperatures.
- Lead-acid batteries tend to produce hydrogen gas towards the end of charging. Hydrogen is explosive even in tiny concentrations and this is why there are several regulations and good practices about the ventilation and explosion protection when using lead-acid batteries in various applications. Lithium-ion cells are fully sealed and there is no gassing, hence no risk of explosions.
- Lead-acid batteries and NiCd batteries are quite robust towards over-charging and deep discharging (abuse tolerant). Depending on the level and duration of abuse, they may not suffer significantly. Lithium-ion cells are slightly more sensitive to abuse conditions. Heavy abuse may cause dangerous situations such as fire.

- For some battery types, it is fairly difficult to determine the remaining capacity during usage (fuel-gauge): lead-acid batteries suffer from the Peukert-effect and NiMH batteries exhibit a significant voltage hysteresis between charging and discharging. Further on, it is fairly difficult to determine the end of charge with NiMH cells. Lithium-ion cells have none of these problems and the coulomb efficiency is 100%. Hence, simpler and more robust state of charge algorithms can be used.
- Lithium-polymer cells are fully sealed and contain no compressible volume. They can be used under very high pressure without any pressure hull and without any loss of performance.

Of course, this is not an exhaustive list and explanation of all attributes and characteristics. Others are e.g. cost, which are currently much higher for the lithium-ion cells, but will come down with volume production. Also, lead-acid batteries are a well-known and mature technology, whereas the behaviour and issues with lithium-ion cells are not commonly known amongst system designers. However, the greatest issue with lithium-ion technology is the safety and this is why we have dedicated a separate section to this topic.

Safety

Lithium-metal provides a high voltage potential and this is why the lithium-ion cell exhibits such a high terminal voltage of 3.6V. This in return is the reason for the high energy density of the cells. The high terminal voltage prohibits the use of water-based electrolytes, because electrolysis would occur – an organic solvent is used instead. This organic solvent has advantages, because it does not freeze at low temperatures. However, all these advantages cause the main disadvantages regarding safety at the same time: Lithium metal is highly reactive and cannot be extinguished with water; high energy densities and high power densities usually equal higher safety risks; and the organic solvent is flammable. Fortunately, there are various working principles, making those cells intrinsically safer than it appears at a first glance.

Firstly, there is no metallic lithium inside lithium-ion batteries. Various lithium-metal batteries have been researched and tried, but for safety reasons, the lithium-ion cell has evolved from those early and sometimes dangerous trials. Since there is no highly reactive lithium-metal inside lithium-ion cells, they are intrinsically much safer than these early predecessors. Lithium metal may be plated on the negative electrode if the cells are being overcharged. However, usually this plated lithium-metal instantly reacts with the electrolyte and just increases harmlessly the SEI layer. However, this reaction may produce sufficient heat in order to start a thermal runaway in case the plating occurred at a high rate, e.g. when overcharging the cell with a high current.

Fortunately, the separator exhibits a shut-down behaviour, which means that it stops the lithium-ions from moving through it once the temperature inside the cell rises to a certain level. This will stop the overcharging and hence further reactions. Unfortunately, the separator will break down, if the process has sufficient thermal momentum and the temperature keeps rising despite the shut-down. When breaking down, the separator will loose its integrity and may allow the positive and the negative electrode to touch each other. This would cause a rapid and exothermic reaction, the solvent will ignite which will lead to more heat generation and even faster reactions. A safety vent will open and prevent the build-up of dangerous pressure inside the cell. The cell will not explode but catch fire. The heat of the fire will cause other cells next to the burning cell to catch fire as well. The positive side of things here is that unlike with burning liquids, the fire will be contained within the battery and not spill out. Reversing polarity with high currents can cause a similar scenario.

For those reasons it is important to prevent every single cell in a pack from entering any of the above abuse conditions. Electronic protection and management will be discussed in the following chapter. Dangerous abuse conditions may also arise from either mechanical impact, from faulty cells or due to growth of dendrites, which could penetrate the separator and cause local internal short-circuits. However, cell manufacturers and independent institutes perform various mechanical and electrical tests and subject the cells to abuse conditions in order to assess the safety of the cell design. Dendrite growth and separator penetration cannot normally generate sufficient local heat for starting a thermal runaway. Low cell voltages or 0V at the cell terminals are indications for internal short-circuits and should not be ignored. Rapid charging should be prohibited in such cases in order to prevent sufficient local heat generation inside the cell. This is usually a task for the battery protection or management electronics.

It is possible to safely use lithium-ion batteries. Good system design and electronic protection are essential in order to achieve this. Finally, the battery industry and research institutes are constantly working on higher intrinsic safety – just like engineers were working for decades, to make cars, engines, fuel tanks and petrol stations safer.

Ageing

So far, the longevity of the small lithium-ion batteries in most portable applications was not really an issue to the manufacturers or suppliers. However, for large expensive battery packs, ageing and lifetime become a real issue. Unlike lead-acid batteries, where it is fairly well known how long they last in certain applications, ageing of lithium-ion batteries is still fairly poorly researched, mainly due to the fact that large lithium-ion cells were not commonly available. Saft in France, AEA technology in the UK and Gaia in Germany can provide some information for certain usage conditions. However, these information are not based on a huge number of tests, cell designs are still changing faster than those tests could be performed and there is no general “formula” in sight, which puts all conditions into relation with the rate of ageing and also with the requirements of a particular application. For this reason, we cannot give a satisfactory answer on the life of lithium-ion batteries here, but we will explain the most important ageing mechanisms briefly.

The working principle of lead-acid batteries demands ageing, because material goes into solution, is transported and crystals are formed. However, in theory there is no such thing in lithium-ion batteries: lithium-ions just move back and forth, travel through the SEI and intercalate into the electrodes without significant volume change. However, in practice, there are three main ageing processes (not considering any abuse conditions):

1. The SEI grows and lithium is consumed, because the SEI may get damaged when lithium-ions travel through it. The SEI then instantly grows back, but increases its thickness around the original damage. A thicker SEI results in worse performance and the consumption of lithium may eventually result in reduced capacity.
2. Solvent molecules may “co-intercalate” together with the lithium-ions into the host structure and hence damage the surface structure and prevent further intercalation of lithium-ions. This will result in reduced capacity as well as performance loss due to decreased active surface area.
3. Finally, the electrolyte is not totally stable. It decomposes with time. The rate of decomposition depends on temperature, terminal voltage and the mixture of solvents. Generally, highly viscous solvent mixtures will decompose slower, but perform worse. High temperatures and high terminal voltages will accelerate the decomposition process.

The above ageing models are not very well researched yet as mentioned earlier. But it is rather obvious that low temperatures and lower terminal voltages during storage will prolong battery life.

Protection and Management Requirements for Lithium-Ion Batteries

Electronic protection circuitry is required in order to ensure a safe operation of lithium-ion cells. Firstly, we would like to discuss the essential protection requirements.

Essential Requirements for a Simple Electronic Protection

Exceedingly high currents can lead to high temperatures inside the cell and this may cause thermal runaway. A fuse is the simplest form of protection against high currents. Over-voltage or cell reversal (negative terminal voltage) can cause dangerous situations and need to be prevented for each cell. Hence, every cell voltage needs to be monitored and the protection circuitry needs to be able to disconnect the battery from the load or charging device. In the simplest form, this is achieved by employing two comparators per cell and letting each of them switch a relay off, which disconnects the pack from any connected load or charger in case any of the cells exceeds the maximum allowed cell voltage or if any of the cells goes below the minimum allowed cell voltage. Finally, high temperatures may cause dangerous situations especially during charging. Most manufacturers of lithium-ion cells do not allow charging in case of ambient temperatures exceeding 45 degC. The electronic protection circuitry in its simplest form needs to measure several cell temperatures and disconnect the battery pack from any load or charging circuitry in case any of the temperatures exceeds the maximum limit. The essential functionalities of an electronic protection device are summarised in illustration 6.

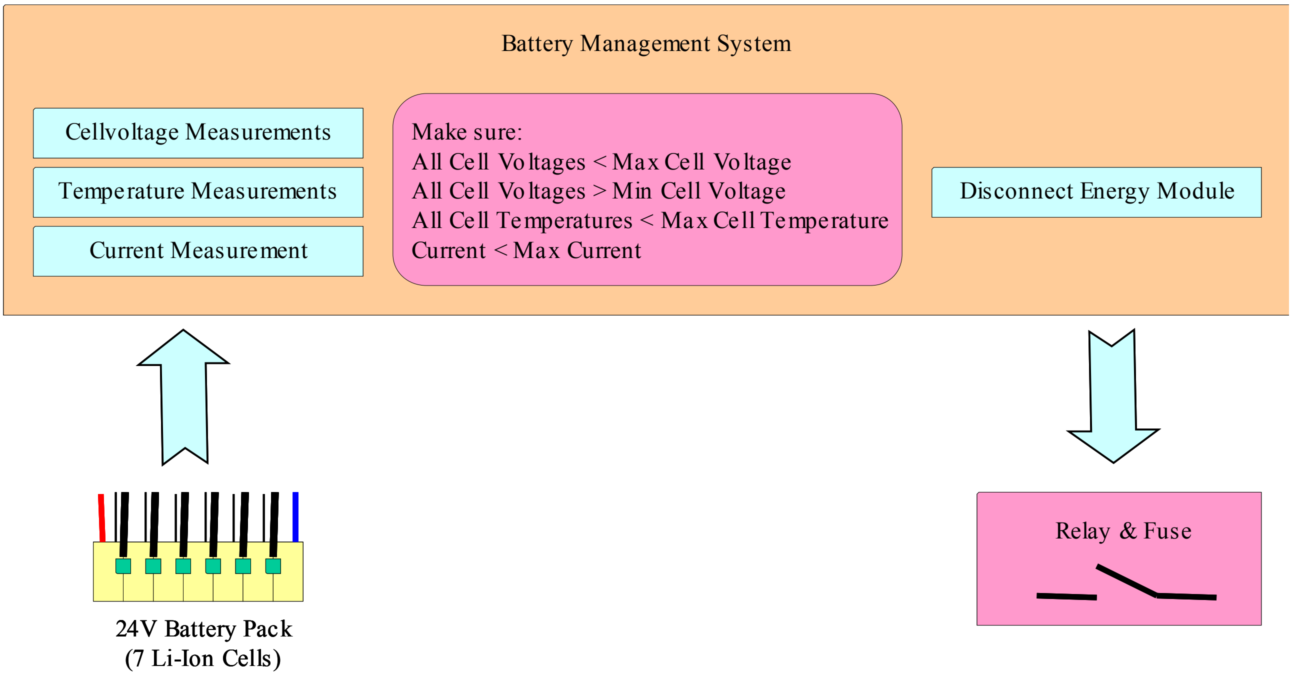

Illustration 6: Essential functionalities of any lithium-ion protection circuitry.

No intelligent control is required for such a simple protection device. However, the behaviour and performance of such a simple protection may not be suitable for all applications nor may this be satisfactory for many users. We will mention a few major disadvantages of such simple protection circuitry:

- The permitted current during discharging is usually higher than the permitted current during charging. Using only one fuse for charging as well as discharging limits the available discharge current to the maximum allowed charging current.

- The simple protection circuit will disconnect the pack immediately and without warning if any of the monitored values was outside its limit. This is undesirable or even dangerous for many applications. The expected behaviour as known from other battery types without protection electronics is that it should continue to work and the user should feel a decrease of power before it stops delivering energy.
- Some manufacturers provide more sophisticated specifications, such as charging or cut-off voltages that depend on temperature or current. Most of them specify different temperature limits for charging and discharging and usually, there are different current limits for different durations (peak current – continuous current).
- Most battery chemistries can be overcharged without harm. In fact, most batteries must be slightly overcharged in order to equalise several cells that are connected in series. The equalisation is required in order to fully charge all the cells and hence obtain the full capacity of the pack. Lithium-ion cells however must never be overcharged, because there are no side reactions that could absorb the excessive energy. This means, that lithium-ion cells require active equalisation circuitry in order to keep all cells within a pack in a similar state of charge.
- Lithium-ion cells are usually charged until they reach their maximum allowed charging voltage and then the charger should keep this voltage and taper down the current (constant voltage charging phase) until the current drops below a certain limit, at which point the cell is considered fully charged. If several cells are connected in series, it becomes very unlikely, that all cells reach this maximum charging voltage at the same time and since the external charging device has no inside knowledge about individual cell voltages, it would continue charging until the battery protection device disconnects the battery from the charger. However, in such a case, there would be no constant voltage phase and one would not be able to return the full battery capacity. This problem increases with higher charging currents, ageing cells, mismatched cells or if no equalisation was implemented.

Requirements for Simple Battery Management Suitable for a Range of Applications

The above disadvantages of the simple electronic protection translate into a list of requirements that are important for managing the battery in a range of applications to an acceptable standard. Namely, they are:

- Distinguish between charging and discharging current limits.
- Dynamically control discharging and charging based on single cell voltage and temperature measurements instead of just disconnecting the battery from the load or charger. Additionally, one should give an early warning before disconnecting the pack.
- More sophisticated and interdependent or time-dependent cut-off levels.
- Cell equalisation (balancing).

It is still possible to implement these additional functionalities with purely analogue circuitry. However, the circuit will become reasonably complex and difficult to tune for different applications or battery sizes and types. Systems based on micro controllers are not necessarily more expensive nowadays. They are more flexible and probably easier to design in first place. However, there are issues when relying on software for safety functionalities and this usually means that additional hardware protection has to be added, which increases the cost slightly.

Requirements for a Fully Featured Battery Management System

Since a micro controller is probably used anyway, several useful and important features can be added without greatly increasing the cost:

- User information such as raw battery values (temperature, current, voltages), status / problem information or information about state of charge, state of health, state of function, remaining time, etc. can be generated and made available on analogue or digital interfaces, which connect to displays, instruments or other computers.
- Service information can be stored or generated, such as internal cell resistance, problems during the last usage, etc. This is important in order to assess the usage history, e.g. in case of warranty claims.
- The usage can be logged, e.g. total accumulated capacity since the last service, which again is important in case of warranty claims. It also helps learning and understanding the ageing behaviour of the battery.
- Unique battery identification can be implemented, which would be important to prevent fraud.
- More sophisticated, more intelligent or self-learning algorithms can be implemented, e.g. for state of charge calculations, optimum performance or longer life.
- System management functionality can be integrated in some cases and hence save the cost for an additional system controller.
- Parameter spaces can be provided for the user, for service personal or for OEMs, so that they can parametrise the battery system to their requirements and taste.
- Systems in service can be upgraded or updated according to the latest battery knowledge and battery systems can be customised for specific requirements more easily.
- Battery know-how can be separated from electronics know-how. The software can be developed and kept confidential by the battery specialist, whereas the hardware can be developed by electronics design house.
- A range of interfaces or bus-systems can be implemented in order to allow interfacing with other external components using various standards (plug-and-play). E.g. overriding motor controllers or chargers in order to implement dynamical charge / discharge control based on single cell measurements as mentioned earlier.

Illustration 7 shows an example of a sophisticated battery management system using a master-slave architecture.

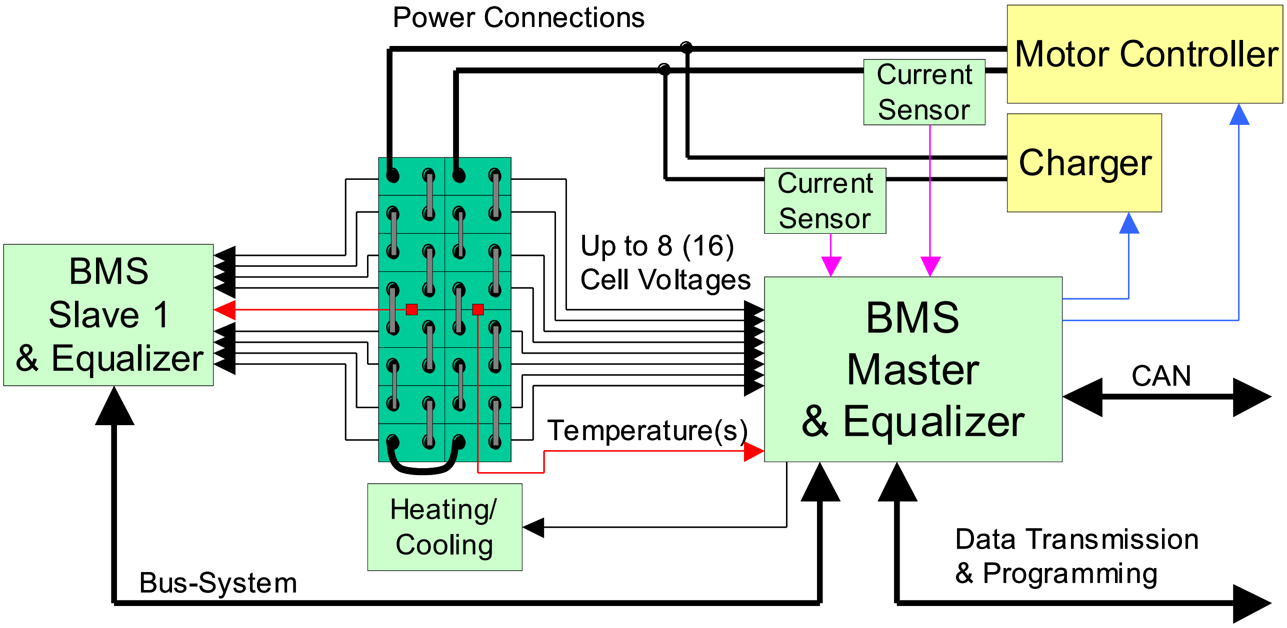

Illustration 7: Example of a sophisticated BMS in master-slave architecture.

Different Approaches for Managing Lithium-Ion Batteries

BMS Architecture

There are various possible BMS architectures in order to fulfil some or all of the aforementioned features and requirements.

- Probably the most obvious architecture is a central BMS module, which measures all the cell voltages, the temperatures and the currents and provides the above functionalities to whatever extent. However, this approach is not very modular, and either it requires one dedicated design for each possible number of managed cells or – if there was only one design – it would be oversized in case it had to manage fewer cells. This solution has even more significant disadvantages when it comes to managing batteries with high voltages or large or distributed batteries. Electrical isolation becomes an issue on the central BMS and would significantly increase the cost. In systems, where the battery is distributed over various locations, the wiring from the BMS to all the parts of the battery becomes an issue. However, for a small number of cells connected within one battery, the central solution can be a sensible option.
- Another possible architecture is one protecting or managing module per cell. The modules can be attached directly to the cell terminals and make each cell "intelligent". However, in high power and large battery systems, the current requirements usually do not allow having one disconnecting device per cell, because it would become too big, heavy and expensive. This means that all the cell management systems would still have to communicate with each other and with external devices. Each cell will require additional connections for communication and also for analogue safety. A central master module is probably required for sophisticated functionalities ad providing certain bus system standards such as CAN or RS485, making this solution less neat. Finally, due to many different cell shapes and designs, it will not be possible to have "one design for all". However, there may be specific applications and certain market volumes or cell designs, where this solution is a sensible option.

- The third option is a partly centralised solution, which tries to combine the advantages of the centralised and the decentralised solution. A partly centralised management system will consist of management modules which can independently manage a number of cells. Several of those management modules can be employed for managing higher number of cells. In that case, the independent modules will be communicating on a bus system in order to determine overall battery information and control outputs. One of the modules can act as a master, which connects to external components such as disconnecting relays, charger and motor controller, so that no additional master module would be required. Such a system is shown in the example above (illustration 7). A partly centralised BMS can be designed to suit a range of cell types, cell sizes and cell configurations. The partly centralised option also reduces the bus load for communication thanks to smaller message overheads and this means reduced EMC, power consumption or higher speed, which may be desirable when it comes to closed loop controls.

Different Methods for Cell Equalisation

Cell equalisation is an important and major task for any lithium-ion battery management system. Again, there are three major categories of solutions:

1. Full current shunting allows to shunt the maximum possible charging current “around” each cell, so that a fully charged cell will not receive any further charge whilst other cells that are connected in series with that cell can still receive full charging current. The advantage of this system is that any common charging equipment can be used without any need for communication between the BMS and the charger. However, communication between the cell modules is still required, because the current shunting cannot prevent any cell from exhibiting too low voltages. The shunted current is dissipated as heat and this will be a problem in systems with high-power charging capabilities: large and expensive shunt regulators (e.g. 1kW per cell !) will be required and they will produce significant heat. Finally, the regulation needs to be quite precise and this may be a cost issue if the maximum permitted charging voltage depends on certain factors such as temperature or current or if it was parametrisable.
2. Another type of equaliser can overcome the disadvantages of the above solution. We will call this type “energy distribution”, because rather than dissipating excessive energy. This type of equaliser can take excessive energy from one cell and redistribute it across the other cells where required. This has obvious theoretical advantages over the dissipative type: smaller and less expensive heat-sinks are required if any at all, because only the inefficiencies of the power distribution do contribute to heat generation. Additionally, this equaliser maximises the energy available from the whole pack. The pack would not be limited by the weakest cell. However, redistributing the full discharging currents in a high-power battery requires high power components and will probably not be cost-effective, small and lightweight. However, it finally depends on how the redistribution circuitry exactly works. There are three major implementations of this type of equaliser: one controlled isolating DC/DC per cell working on a common voltage bus; “flying capacitor(s)”; “switched reactor/inductance”. It is not within the scope of this paper to discuss their working principles and advantages / disadvantages. More information can be found in various publications.
3. The third option is to equalise the cells using low-power dissipation. This is the lowest cost option, because the equalisation circuitry can sit on the BMS board and the equalisation currents are small enough so that they can be shunted through the

measurement cables, which are required for single cell voltage measurement anyway. Considering that cell-imbalances in terms of state-of-charge mainly stem from differences in self-discharge rates, small equalisation currents will be sufficient for keeping all cells at the same state of charge. The obvious disadvantages are that the weakest cell determines the performance of the pack and that the BMS needs to be able to control the charger, so that the charging current can be reduced if one of the cells reaches the charging voltage before the others. However, cell variations will become smaller with higher cell production volumes and the advantages of the first two equaliser types will become smaller and will not justify their significantly higher cost.

Conclusions

Lithium-ion batteries can provide significant advantages over almost any other battery technology and they can be used for substituting combustion engines in some applications. They can be used in addition to or instead of fuel-cell technology with the advantage of being available and rechargeable through existing infrastructure right now.

The working principle is relatively simple and the behaviour is straight forward without any of the well-known complications such as sulphation, memory effect and without major pitfalls such as high self-discharge rates. The state of charge can be determined relatively easy and systems can be designed with high user-friendliness.

However, proper system design and electronic battery protection are required in order to assure safe operation. The ageing is not a sudden unexpected process, instead, it occurs at a fairly constant rate. However, there is only little knowledge on the exact ageing behaviour and life-time predictions are currently rarely possible.

A range of essential protection up to “nice-to-have” management requirements have been discussed. Various options and implementations for managing the cells have been pointed out and it has been indicated that some considerations and experience are required for determining an optimal solution for certain applications, cell types and market sizes.

Finally, we have mentioned the three main categories of equaliser solutions and their advantages and disadvantages. We have concluded that the lowest-cost low-power equalisation method is sufficient for keeping lithium-ion cells balanced.

About the Authors

Dipl.-Ing. Dennis Doerffel obtained his Dipl.-Ing. Degree from the University of the German Forces Hamburg (UniBWHH) in 1995. He was responsible for the purchase and maintenance of automated testing software in the German Army before he discovered his passion for electric vehicles and batteries. He started his PhD project on “Energy Management of Hybrid- and Electric Vehicles” with a focus on testing of large lithium-ion batteries at the University of Southampton in 2001. Since 2003, he is the founder and technical director of REAPsystems Ltd. REAPsystems specialises in designing and providing battery management solutions for large lithium-ion batteries.

Dr. Suleiman Abu-Shark obtained his BEng and PhD degrees from the University of Southampton in 1990 and 1994 respectively. He is a senior lecturer in Control Engineering, Electric Machines, Power Electronics and Electrical Systems. He has also been working on battery systems, battery testing, electric and hybrid electric vehicles and underwater equipment. His passion are integrated underwater thrusters.