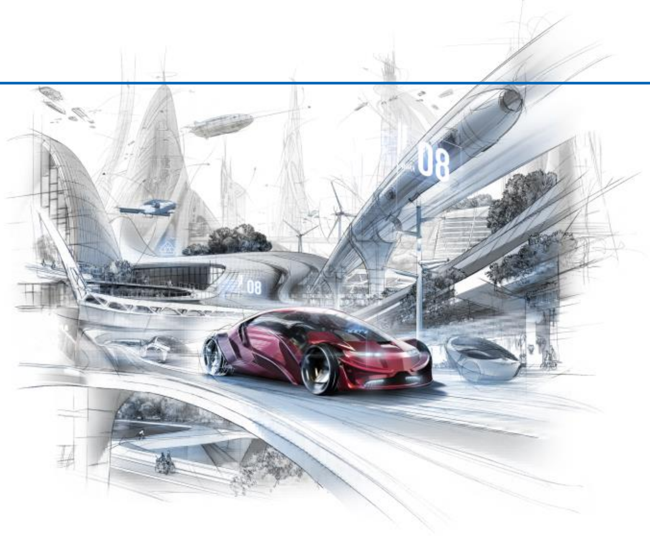

Battery-Management-Systems

With an increasing share of fluctuating renewable energies, the need for storage technologies is growing and the demand for reliable and safe energy storage systems is ever more increasing. In parallel, driven by the set global climate goals, the transformation of the mobility sector away from combustion engines to battery electric solutions such as the Battery-Electric-Vehicle is the key driver for the rapidly rising battery demand. The field of application for batteries is wide-ranging and the demands on them are constantly increasing. In order to meet the necessary requirements and to ensure a safe operation, battery management systems are an indispensable part of the application. The primary task of the battery management system (BMS) is to protect the individual cells of a battery and to increase the lifespan as well as the number of cycles. This is especially important for lithium-ion technology, where the batteries must be protected against overcharging and over-temperature to prevent the destruction of the cell. Necessary performance characteristics of new accumulators can only be achieved by intelligent battery management systems.

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Batteries are the key technology for the energy transition

The energy storage market

Energy and environmental issues have long been a challenge for the global industry. In recent years, the grim energy and environmental situation around the world have accelerated the strategic shift in transport and energy technology, triggering a global upsurge in the development of alternative propulsion- and energy storage.

Batteries are one of the most important key technologies for a wide range of applications from consumer electronics to electric vehicles and stationary power storage for the energy transition e.g., decentralized energy systems. This is also shown by the exponential growth of the market for lithium-ion batteries (LIBs), from less than 2 GWh in 2000 to more than 200 GWh in 2020. The outlook for 2030 is between 1,500 and 6,000 GWh (optimistic) and for 2040 up to 10,000 GWh, of which the e-mobility sector accounts for around 80%. Clearly, e-mobility already is and will be the key driver of the battery market.

Since its market introduction in 1991, the rechargeable LIB has been able to increase its performance characteristics in several development cycles and, within a decade, has displaced the nickel-metal hybrid technology (Ni-Mh) that dominated until then. LIBs are currently sharing almost a 50% market split with lead-acid-batteries (LABs).

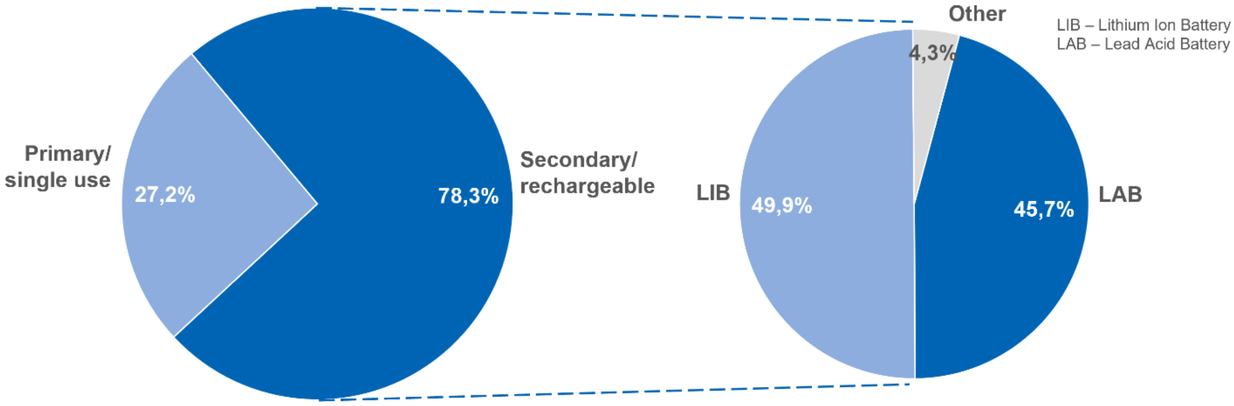

Figure 1: Global Battery Market-Share (2019)
[Technavio: London, UK, 2020, Global Secondary Battery Market 2020–2024]

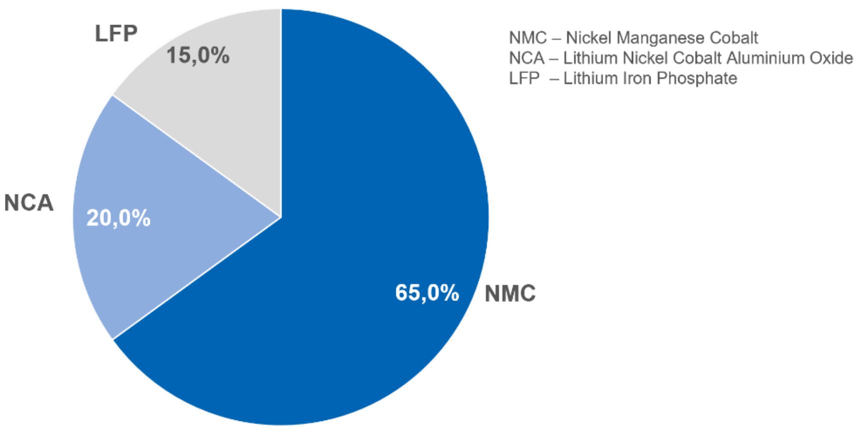

Figure 2: Market-Share of LIB in Battery Electric Vehicle (BEV) by cathode chemistry (2020), [BloombergNEF, 2021]

To improve the performance of future LIBs, researchers in the field of electrochemistry have further explored LIBs in terms of the electrochemical mechanism, including the effects of temperature, voltage, current, and aging on battery performance, the influence of overcharging, over-discharging, over-current, and overheating, and so forth.

The current generation of rechargeable (secondary) batteries impresses with long runtimes, fast charging intervals, high energy density (high cell voltages and capacities), and a barely noticeable self-discharge at operating temperatures of -20°C to +60°C. Commercially available lithium-ion cells are based on a combination of transition metal-based cathodes, liquid electrolytes, and carbon or Titanate-based anodes.

The market share of BEVs batteries by cathode chemistries in 2020 can be seen in Figure 2. Batteries cells with a cathode made of lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), and a graphite anode are the most widely used. With these cell types, average cell voltages of 3.6 to 4 V can be achieved. Figure 3 compares the NMC, NCA, and LFP-based battery cells regarding their cost, safety, specific power, specific energy, and lifespan (0 is the worst, 4 is the best).

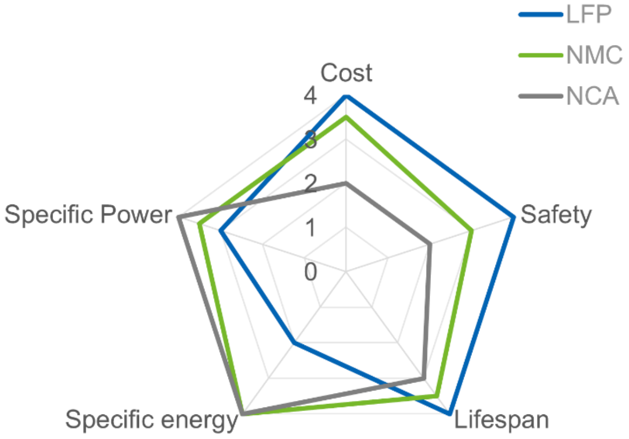

Figure 3: Comparison of different cells by cathode material,
based on [Gaizka Saldaña, JoséIgnacio San Martín, 2019, Analysis of the Current Electric Battery Models for Electric Vehicle Simulation] [Nikola Vekic, 2020, Lithium-Ionen-Batterien für die Elektromobilität]

Application in BEV

The use case of a BEV sets high requirements to the battery technology due to the broad and specific requirements. In general, goals for a powertrain system in BEVs are: excellent **safety**, high **specific energy**, high **specific power**, good **temperature characteristics**, long **lifespan**, low **cost**, no **maintenance**, low **self-discharge**. With regards to a closed value chain and a sustainable future, the focus has shifted to minimal **environmental impact** as well as good **recoverability** and **recyclability**. In BEV, the specific energy determines the overall **driving performance** in the all-electric drive mode; the specific power determines the **vehicle dynamics**, such as the maximum acceleration/climbing-ability and the maximum vehicle speed; the cycle life (number of charge/discharge cycles) and the cost of the battery-system have a direct impact on the manufacturing and operating costs. For a long time, battery technology has been a bottleneck in the BEV development, the challenge of today's development is to achieve all of these goals **simultaneously**.

Although LIBs are widely used in portable devices with their superior performance, they have limitations in the application of BEVs, the main reasons are summarized below.

1. To achieve the required power and energy level, a large number of large-capacity batteries must be used in BEVs through series and parallel connections. Unlike a single battery, grouping management in a battery pack also requires more advanced technology.
   Common arrangements are specified by the manufacturer. e.g.: Tesla 74P6S = 74 in parallel, six in series.
2. **Heavy dynamic load** due to high working currents and extreme current fluctuation. During acceleration and braking, battery current is high (maximal value over 350 A) and changes rapidly (the time to change from 300 to 0 A is <0.5 s).
3. **Limited space** increases the difficulty of the conceptual- and cooling-design as well as the assembly process. If the battery operates in a locally fluctuating, high-temperature environment for a long period of time, the decrease of the battery capacity will be accelerated, and inconsistencies of the battery pack may occur which may result in a thermal runaway causing a safety risk.

In addition, a compromise between cost, lifespan, performance and efficiency must always be made in the design. To meet the requirements described and to achieve these necessary performance targets, more complex consideration of the battery system and the management of many cells in the network is necessary.

Significance of BMS

Mostly, large battery packs consist of multiple modules. These modules are constructed from cells, which are connected in series and/or in parallel. The cell is the smallest unit. In general, the battery pack is monitored and controlled with a board which is called the Battery Management System (BMS).

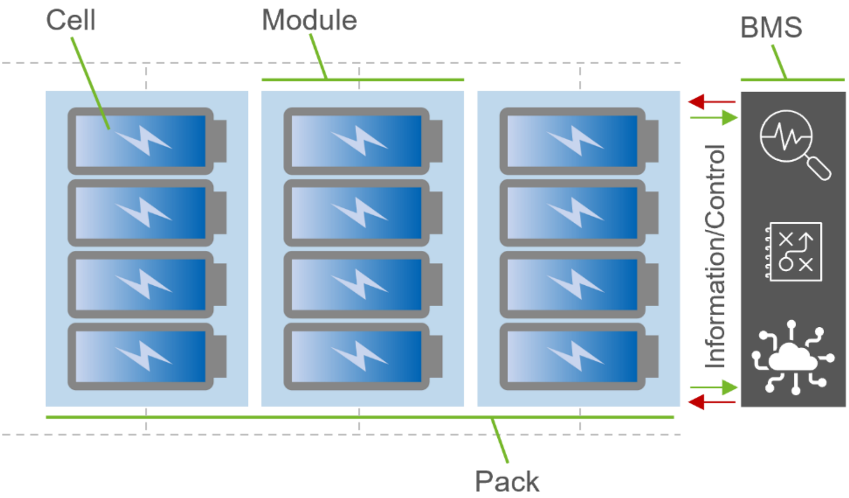

Figure 4: conceptual battery design

The technical specification of the manufacturer determines only the battery performance under specified conditions. During the operating process, the battery parameters are always changing with the operating environment, working conditions, and aging conditions. Therefore, in order to avoid misuse, unreasonable and possibly dangerous use, the control strategy of the batteries must be in accordance with the change of the battery parameters. Battery management technology aims to optimize this use.

- **First**, this technology aims to avoid misuse and wrong/dangerous use and extend the life of the batteries.
- **Second**, it can detect/estimate the condition of the battery in time.
- **Third**, it should maximize the performance of the battery to ensure that the vehicle can be operated efficiently and driven comfortably.

Condition monitoring

Condition monitoring as a key function of a BMS is realized by measurement of the major parameters, voltage, current, and temperature.

- **Voltage measurement**: Normally, cell voltage and pack voltage are measured in a battery pack. The voltage is measured with analog to digital converters. Important criteria include sampling rate, accuracy, and isolation.
- **Current measurement**: Depends on the design, cell current and pack current can be measured in a BMS. The current measurement is achieved with shunt resistors or Hall-sensors.
- **Temperature measurement**: Cell temperature and pack temperature are measured by NTC-thermistors. In general, the measurements indicate the surface temperature.

Voltage, current, temperature measurements are then transmitted to other functional units of the BMS for state estimation, protection, and so on.

State determination

State of Charge – SOC

The State of Charge (SOC) in electric vehicles is the key battery state indicator and has a similar function to the fuel gauge in traditional combustion cars. In general, the SOC is defined as the ratio of the amount of charge (Coulomb in Ah) that can be discharged from the battery (Q_{Act}) over the total charge when fully charged Q_{max}:

$$SOC = \frac{Q_{Act}}{Q_{Max}} \times 100\%$$

Thus, the SOC is indicated as a percentage of the fully charged state.

The SOC provides information for optimizing the operation of a vehicle during driving, improving the utilization rate of the battery capacity and energy, allowing the application to make rational control strategies to save energy, and preventing overcharging or over-discharging hence ensuring safety and durability of the battery. There are several methods for determining the SOC, that can be clustered into two categories: (i) direct measures, which can be divided into offline approach (where the battery is fully discharged from the current state to derive the SOC) and online approach (for instance, Coulomb counting), and (ii) indirect measures which include look-up table based approaches (OCV-SOC mapping), model-based approaches (for instance, Kalman Filters), and data-driven approaches (for instance, Neural Network).

State of Health – SOH

A battery's state of health (SOH) is an abstract concept that attempts to reduce the complex phenomena of battery degradation to a simple metric indicating how far the battery has progressed from the beginning of life to the end of life.

There are mainly two indicators for SOH estimation, namely, capacity C and internal battery resistance R_{int}. In general, a 20% reduction in capacity is treated as the end of life (EoL) of the battery. The SOH can then be defined as:

$$SOH = 1 - \frac{C_{BoF} - C}{0.2 \times C_{BoF}} \times 100\%$$

where C_{BoF} is the battery capacity at the beginning of life. C is the current battery capacity. 0 ≤ SOH ≤ 1, the battery is fresh if SOH=1, and vice versa.

Another method is to use internal battery resistance R_{int} which is normally measured by carrying out the hybrid pulse power characterization test. Normally, double or triple of the initial R_{int} is considered to be the battery's EoL.

Protection

Safe Operation Area (SOA)

The Safe Operation Area (SOA) of Li-ion cells is determined by the operation range regarding temperature, voltage, and current. For Li-ion cells, the safe operating temperature varies from -20°C to 60°C and the safe operating voltage ranges from usually slightly below 2V to about 4V as shown in the figure below. For most Li-ion cells, the charging/discharging current rates are within the range of 0C to 20C depending on the battery chemistry and it is common that discharging current boundaries are higher than the charging current boundary. However, the charging/discharging current rates are also bounded by the operating temperature. Thus, the SOA is mainly illustrated with boundaries from temperature and voltage as shown in the figure below. If the terminal voltage goes too high or too low, there would be degradation like dendrites formation and anode dissolution. If the temperature is too high, the battery might break down, release heat, and eventually go to thermal runaway. If the temperature is too low, it might cause cathode damage, short circuit, or lithium plating.

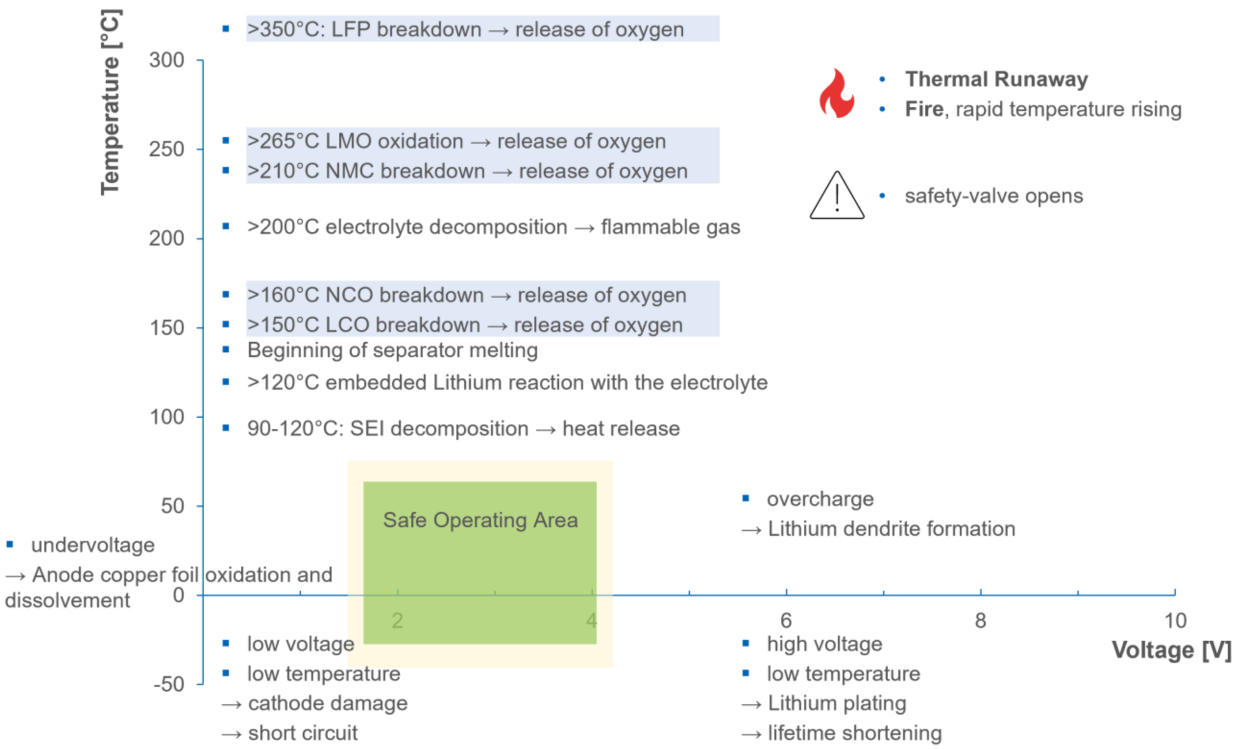

Figure 5: Safe Operating Area of LIBs,
based on [Hossain Lipu, 2018, A review of state of health and remaining useful life estimation methods for lithium-ion battery in electric vehicles]

To ensure the cells are operating within SOA, there are mainly three protections required, overcharge/discharge protection, over current protection, and temperature protection. Potential consequences are illustrated including the corresponding countermeasures.

What is the **C-rate**?

The C-rate is a **measure of the rate at which a battery is charged/discharged relative to its maximum capacity**. A 1C rate means that the discharge current will discharge the entire battery in 1 hour.

Over charge/discharge protection

- **Potential consequences**
  - Li-ion cells are quickly damaged and can go into flames if overcharged beyond certain voltages.
  - Most Li-ion cells will be damaged if they are charged/discharged above or below certain voltages.
- **Countermeasures**
  - Prevent the voltage of a cell from dropping below a limit by stopping the discharge current or by prompting it to stop.
  - Prevent the voltage of a cell from exceeding a limit by stopping the charge current or requesting it to stop. This is a safety issue for all Li-ion cells.

Over-current protection

- **Potential consequences**
  - The lifespan of Li-ion cells is shortened if they are discharged at a very high current or charged too quickly.
  - Li-ion cells can be damaged if operated at high pulse currents for more than a few seconds.
- **Countermeasures**
  - Prevent the charge current from exceeding a limit (this varies with cell voltage, cell temperature and previous current) by reducing the current or stopping it directly.
  - Prevent the discharge current from exceeding a limit as described in the previous point.

Temperature protection

- **Potential consequences**
  - Lifespan is drastically reduced if they are discharged outside a certain temperature range or charged outside an even narrower temperature range.
  - Li-ion cells can thermally run away and ignite if they exceed a safe temperature.
- **Countermeasures**
  - Prevent the temperature of a cell from exceeding a limit by stopping the battery current directly, requesting it to stop, or requesting it to cool.

Thermal Management

Thermal management of Li-ion batteries needs special attention for better performance, high efficiency, long life, and safer operation. If the heat generated in the battery cell is not removed properly, the temperature rise triggers further heat-generating exothermic reactions (e.g. electrolyte decomposition/burning). This results in increased battery cell temperature, which causes a thermal runaway situation. Sometimes the thermal runaway situation may not arrive, but battery capacity degrades undoubtedly by continuously operating at high temperatures, i.e., above 50°C. Therefore, the heat generated in the battery cell should be adequately removed, adopting an effective cooling mechanism.

The temperature range of Li-Ion cells is better than for other chemistry’s but is still worse than what is required by many applications (such as the automotive environment: −40 to +85°C). Therefore, some applications require thermal management of the pack.

The most important function of the thermal management system is to maintain a safe operating temperature range and a uniform temperature distribution within the battery cell, module, and pack at high charge/discharge rates and extreme external environmental conditions. A state-of-the-art thermal management system has the following four essential functions:

i. cooling to remove heat from the battery

ii. heating to improve the battery temperature when the temperature is too low

iii. insulation to prevent sudden temperature change of battery

iv. ventilation to exhaust hot gases from the battery

These functions have to be achieved under design aspects and frameworks like compactness, lightness, low cost, high reliability, easy maintenance and easy packing, making the implementation more so difficult and costly

An indication of the effects on the battery capacity can be seen in the picture below.

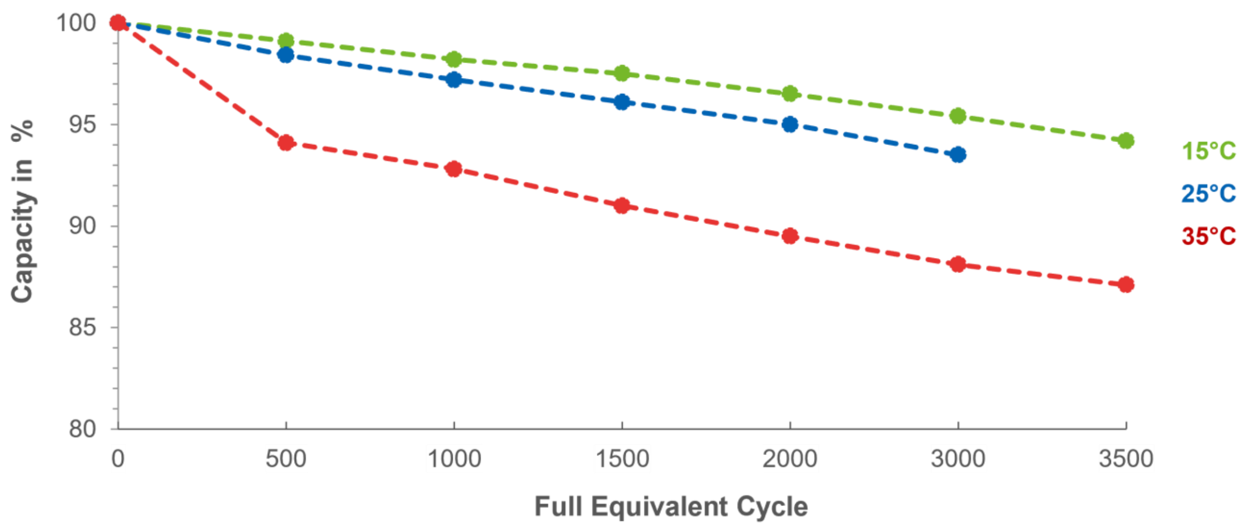

Figure 6: Long-term cycling: Temperature dependency,
based on [Sandia National Laboratories, 2019]

Energy management

To operate the batteries correctly over time, an energy management system is necessary. There are mainly two tasks to fulfill for the energy management, balancing and charging/discharging. By fulfilling these two tasks, the energy management system makes sure that the battery works with its full potential.

Balancing

Balancing is the term used for the process of bringing the SOC levels of cells in a battery closer to each other, to maximize the battery's capacity. Balancing leaves room for more charge, without overcharging/discharging the most charged cell. The final goal of the balancing process is to bring all connected single cells to the same SOC. Without proper management, battery imbalance will not correct itself over time.

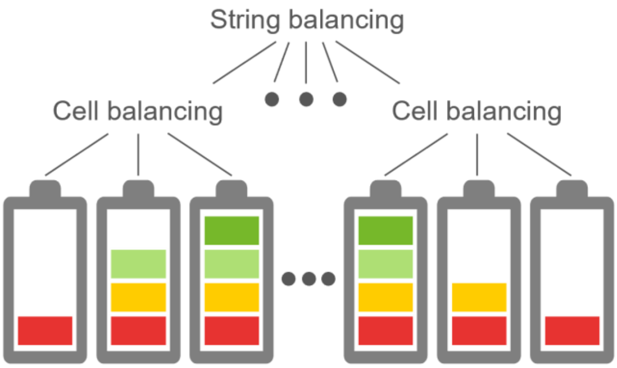

Figure 7: Concept of cell-balancing;
based on [Ming Liu, Yenan Chen, Youssef Elasser and Minjie Chen, 2021, Dual Frequency Hierarchical Modular Multi-layer Battery Balancer Architecture]

The weakest cell determines the behavior of the entire battery system.

Balancing can be:

- **Passive**: energy is removed from the most charged cell and is wasted in heat; or
- **Active**: energy is transferred between cells and therefore it is not wasted

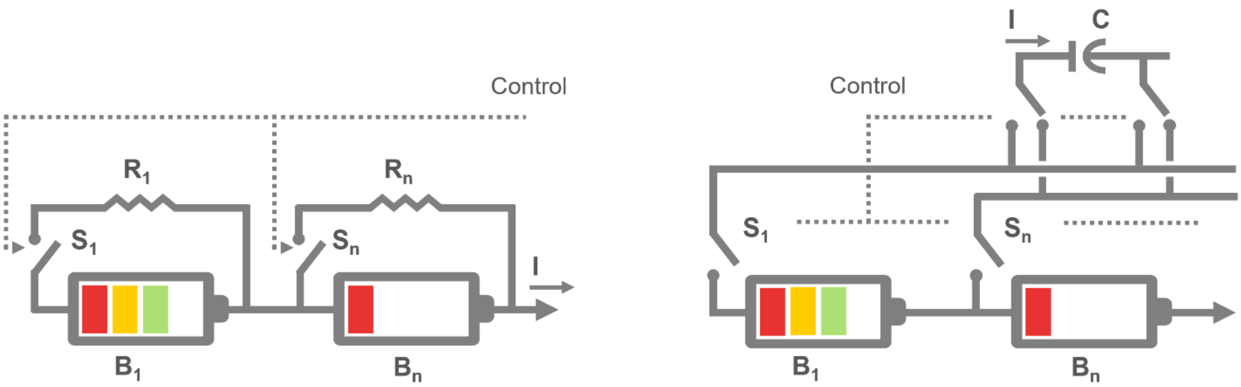

Figure 8: passive balancing (left) and active balancing (right),
illustration based on [Stephen W. Moore, 2001, A Review of Cell Equalization Methods for Lithium-Ion & Lithium Polymer Battery Systems]

Without balancing, the battery would age faster and produce less energy. These problems would reduce the electric range of electric vehicles and the lifetime of the battery.

Charging/Discharging

The SOC has a significant impact on battery life. Each battery has a specific number of charging and discharging cycles depending on its used chemistry and depending on the SOC ranges the battery is used in. BMS must check for the most efficient way for charging and discharging procedures. Additionally, a BMS must maintain the proper SOC so that the battery lifetime will be maximized. To ensure management in this area, BMS performs the following tasks:

Control the charging current, turn on/off active switches between the pack and load/charger, run the pre-charge sequence, set dynamic power limits, and conduct active and passive balancing.

LIBs are generally charged with a Constant Current-Constant Voltage (CC-CV) or Constant Power-Constant Voltage (CP-CV) approach. These are the most popular approaches in practical application. However, due to the long charging time and the unique characteristic in each charging phase, researchers intend to find the optimized charging profile. So far, a number of profiles have been investigated including Boost Charging (BC), Multi-stage Constant Current (MCC) charging, Pulse Wave (PW) charging, Sinusoidal Wave (SW) charging. A combination of these profiles forms the complete battery charging protocol. **BC:** During BC, the battery voltage is kept at V_{Bst}, while the current drops rapidly with the maximum current limits to V_{Max}. **MCC:** MCC charging generally consists of two or more CC stages and each stage is assigned a different current value. **PW**: PW charging refers to the charging process in which a square wave is used. **SW:** SW charging uses a sinusoidal current with a DC bias.

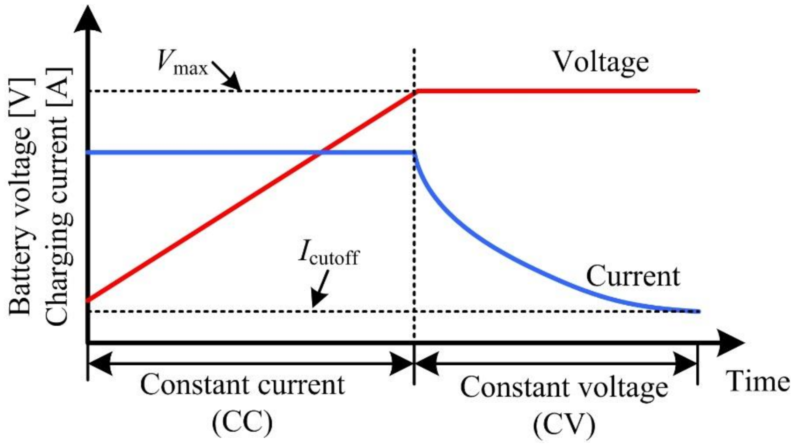

Figure 10: Charging concept of CC-CV

Communication

The communication unit can be divided into two parts according to its function dedicated circuit and data link. There are two kinds of dedicated circuits, one for analog signal and the other for digital signal. The data link is referred to different ways of communication, for example, wired communication like RS232, Controller Area Network (CAN), and Ethernet, wireless communication like Bluetooth. The communication unit includes the communication of BMS with other units inside and outside the BEVs. Communication function within EVs can be realized with RS232, CAN (widely employed due to its fast speed, reliable data transmission), and Bluetooth. This kind of BMS communication includes functions like sending signals to the BEV control part to adjust the output power, change the charging conditions, and so on. The communication with the device outside BEVs is generally realized with Ethernet. This is mainly used for remote control and monitoring.

Data-Acquisition

Battery management systems gather and maintain information about the environmental conditions that the batteries have been exposed to during their lifetime. Battery suppliers as well as the end-user are interested in the dependency of battery longevity and performance on the operating history, and, therefore, storage of this type of data is expected to be part of modern battery management system requirements. Typical values stored are, voltage, current, resistance, SOC, SOH, temperature, total time in service, amp-hour and watt-hour throughput, Charge/Discharge-Cycles, max- and min current. The introduction of Big-Data acquisition and evaluation can generate a deeper understanding of the batteries' behavior over the complete lifetime as well as make a comparison between batteries of the same type produced in different places, times, and suppliers. Hence, determine single or systematic errors of batteries installed in the field. Challenges in implementing such systems are the sensitive customer data that need to be addressed and usage of these may have to be regulated dependently.

Standards

Well-designed battery management is critical for the safety and longevity of batteries. Due to the market penetration and performance value increase of electrified systems in stationary systems as well as in the e-mobility sector e.g road vehicles, there is a trend to equip these systems with increasingly powerful BMS. These systems address both the described safety requirements and new requirements in the area of digitalization and sustainability, such as data collection and analysis of collected characteristic values over the lifetime of e.g., the battery of electric vehicles and their battery systems as well as reuse after reaching the first life cycle or the use case of Second Life. Battery management thus plays an essential role beyond the entire product life cycle and can enable the safe and sustainable use of batteries. To this end, it is necessary to set requirements for the system that define a minimum standard for BMS in terms of functionality, safety, robustness against environmental influences, interfaces, data security, and other factors. Furthermore, test procedures should be standardized to make performance comparisons based on a transparent metric. For this reason, it is important to set standards that systematically define the current state of the art transparently and thus help to leverage further economies of scale for battery management systems a set one further milestone for the necessary circular economy.

The VDE (VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V.) promotes the interests of German industry and science at national, European and international level. The DKE (DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE) focuses primarily on electrotechnical safety aspects and consumer protection. In the standardization committees, experts discuss and deliberate on the issues of tomorrow and jointly discuss how Germany can assert itself as a business location in international competition. These activities include, for example, the work of the committee DKE/K 371 "Accumulators", as a mirror committee to CLC/TC 21X “Secondary cells and batteries” and IEC/TC 21 und IEC/SC 21A. This includes standards for all secondary cells and batteries related to the product (sizing and performance), safety (including labeling and marking), testing, and safe use (installation, operation, and maintenance) regardless of design, application, or configuration (Hybrid, Standalone, Modular).

Outlook & Conclusion

Batteries are a fast-growing industry that offers Europe enormous economic opportunities in the race for zero-emission road transport and towards a climate-neutral society. Due to difficult, inaccurate, and reactive monitoring of batteries, the secured range usually must be limited significantly to ensure reliability and safety. This makes battery utilization inefficient and does not provide a complete guarantee against unsafe situations or battery damage. Standardized BMS functions and architecture can help to increase reliability of battery systems and the reliability in testing procedures for BMS as well as increase efficiency of batteries. Such standardization can lead to a cost reduction due to interchangeable components, specialization, competition, and economies of scale.