Lithium-ion battery system design

8

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8.1 Introduction

The design of a battery system should ensure that an energy storage system operates efficiently, reliably, and safely during vehicle deployment for a very long period of time. Lithium-ion cells are the fundamental components of lithium-ion battery systems and they impose special requirements on battery design. Aside from electrochemical storage cells, the battery system comprises a multitude of mechanical, electrical, and electronic components with functions that need to be perfectly balanced. The electronic battery management system (BMS) not only monitors and controls the battery, it also provides data communication to the vehicle.

Battery system design and configuration take into account the specific technical characteristics of the lithium-ion cells in which the energy is stored. Suitable electrical and thermal management ensures that the storage cells permanently operate

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safely and reliably. Lithium-ion cells are sensitive to mishandling. This is the reason why the battery management system must be very reliable.

8.2 Battery system design

8.2.1 Block and modular design

Batteries can be designed in two different ways:with a block design or a modular design.

Block design: All storage components are combined to create a single block with an electrical collector structure, sensors, and other components. This block is then fitted with the necessary connections and peripheral components and is installed in the battery housing.

Modular design: A certain number of individual cells are combined to form a module, which constitutes a sub unit. These sub units are then used to build larger battery units. The advantage of the latter is that the components can be handled more easily during assembly and maintenance (replaceability).

Fig. 8.1 shows a typical block design example, the lithium-ion battery of the Daimler S-Class hybrid. Here, the cylindrical lithium-ion cells are connected to form a 35-cell block, which is the heart of the battery system. In Fig. 8.2, the battery of the Ford Transit Connect Electric is shown, an example of a modular design. This system consists of 18 individual modules, each containing 12 lithium-ion cells. Block designs are usually used for relatively small battery systems while larger batteries have modular designs, for the reasons mentioned above.

Fig. 8.1 Lithium-ion battery system with a block design, Daimler S400 hybrid (courtesy of Daimler AG)

Fig. 8.2 Lithium-ion battery system with a modular design (Ford E-Transit-Connect)

8.2.2 Serial and parallel circuits

The most simply designed battery systems consist of a certain number of cells connected in parallel. The battery voltage is the sum of the single cell voltages. The cell voltages depend on the specific electrochemical characteristics of the system they are based on and their specific electrode combination. For today's systems, they range from 2.2 V to 4.2 V per cell. It must be guaranteed that all lithium-ion cells comply with the upper and lower cell voltage limits. This can result in a high system outlay, especially for electrochemical systems that have lower cell voltages and, therefore, higher numbers of individual cells. Voltage and system characteristics also enable a parallel connection of lithium-ion cells. Series and parallel cell connections open up possibilities for different battery system designs.

Parallel connection of cells connected in series Here, two or more strings of cells connected in series are connected in parallel. The outlay of such a design with several strings is relatively high since the voltage of each individual cell must be monitored.

Additional outlay is caused by the connection of the individual strings to an entire system, requiring an additional higher-level battery management system to coordinate the individual strings function.

Serial connection of cells connected in parallel For this configuration, cells with the same design are first connected in parallel. This results in a higher capacity, depending on the cell quantity, for the same voltage. These cell packs are then connected in series. The circuitry permanently electrically connects the cells and therefore it suffices to monitor their overall voltage.

If voltage variations occur during operation or idling, an automatic charge exchange will take place, balancing the voltage and the state of charge (SOC).

This serial connection of cells connected in parallel is usually very simple and cost-efficient because the monitoring outlay is lower. However, it is usually used for cells with a relatively low capacity only.

8.3 Functional levels of battery systems

The basic requirements for a battery system and its management can be divided into four functional levels.

Mechanical integration This involves mechanically and purposefully integrating the individual components into a battery assembly. Designing the individual components and their connection ensures that the battery assembly fulfills the mechanical requirements over the entire service life of a vehicle without compromising on functionality and safety.

Electrical management Electrical management ensures the battery system's electrical functionality in all situations occurring during vehicle operation. This includes providing the electrical power required for the vehicle drive during operation and managing the charging procedure during external charging as well as regenerative reloading during vehicle operation, displaying safety-relevant statuses such as faulty electrical isolation, short-circuits, overheating, overcharging, deep discharge, and triggering the appropriate reactions to these statuses.

Thermal management Lithium-ion cells are based on electrochemical components. This makes their performance characteristics and service life extremely dependent on the ambient temperature. Their restricted current capability applies to both charging and discharging characteristics. Discharging performance is considerably reduced at lower temperatures. This is caused by the specific electrochemical cell kinetics, which increases internal cell resistance, but also reduces discharging capacity, especially for higher currents. Charging currents must be limited for lower temperatures because of increasing electrical internal resistance and restricted charge-accepting capability of the negative electrode. If the maximum permitted charging current is exceeded, metallic lithium can plate on the negative electrode's surface. This lithium plating directly impairs cell capacity and performance. Thus it is important that temperature and charging currents are reliably monitored.

In general, lithium-ion cell aging depends very strongly on the temperature. It is therefore necessary to always keep the battery in an appropriate temperature range. The thermal management system design must guarantee that the resulting heat losses are dissipated efficiently.

Communication with the vehicle The battery of an electric vehicle is one of the most important system components and is therefore directly integrated into the electrical vehicle environment. This requires permanent data exchange between the battery system and the vehicle. These data are of paramount importance for the vehicle's operation and the battery. Current data are exchanged on the state of charge, electrical performance, current-accepting capability, and internal resistance. Safety-relevant signals that guarantee that the overall system is safe in case of malfunctions are also essential.

8.4 System architecture

Fig. 8.3 displays the fundamental system architecture of a lithium-ion battery system. The most important system components and their functions are described in detail.

Cell block with electrochemical storage elements The cell block comprises the electrochemical storage cells; they are the battery system's core components. The battery system design's task is to ensure that they function optimally. The cells are connected by means of the electrical collector system. All thermal management components are usually integrated into the cell block. In air-cooling systems, these are the air ducts that are customized to meet the relevant requirements. Incoming

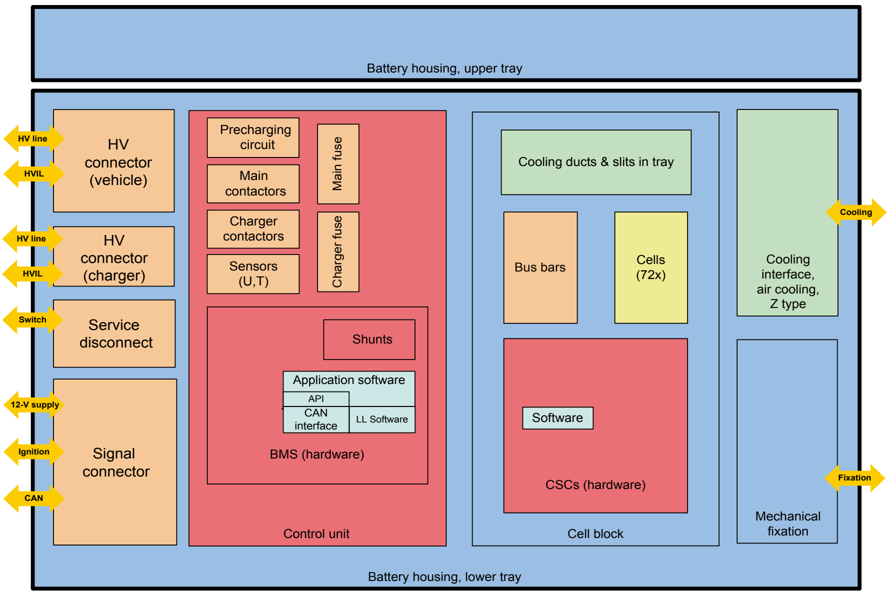

Fig. 8.3 Lithium-ion battery system architecture

air is guided across the cell surfaces, taking on heat that is then dissipated through air outlet ducts.

Liquid-cooled systems work differently: Chillers with a cooling medium flowing through them are installed in close mechanical contact with the cells. This cooling medium circuit takes on the cells' heat and dissipates it into the environment by means of an external chiller. Generally, the cooling medium is a mixture of water and Glycol®. More advanced chiller systems are also implemented; they use a technical refrigerant provided by the air conditioning system's compressor.

Monitoring components The battery monitoring system comprises the components that are necessary for monitoring the battery, its subcomponents, and components in the vehicle.

The monitoring components are voltage sensors which measure the cells' and modules' voltages. Other components are the temperature sensors, which measure the temperatures at characteristic points in the module and cooling system, and the current sensor, which registers the current flowing through the battery.

Cell voltages and temperatures are monitored by the cell supervisory circuit (CSC). This component's design, location, and functionality vary depending on the manufacturer. Figs. 8.4 and 8.5 display Johnson Controls lithium-ion modules, in which the cell supervisory circuit is directly integrated into the individual modules.

In lithium-ion systems, overvoltages and undervoltages pose safety hazards and can reduce the system's service life. This is why the voltage of each individual cell needs to be monitored. The cell supervisory circuit (CSC) transmits the measurement data to the battery management system or battery monitoring unit (BMU) by means of an internal data bus. The BMU uses these parameters to assess the current battery state to predict its performance.

An important parameter is amperage. Recording the charge flow by means of current-time integration makes it possible to determine the battery's current state of charge. The most common method for determining the current amperage is to indirectly measure the voltage drop at a precision resistor (shunt) integrated into the current path. Additional sensors can be installed in the battery, depending on the application. For example, a humidity sensor is often used in liquid-cooled battery systems.

Control components The battery management system or battery monitoring unit (BMU) is the core component of active control. It processes the signals transmitted from the cell supervisory circuit (CSC). These data are used to determine electrical parameters that are important for operation, such as current state of charge, maximum electrical discharge performance, and maximum charge acceptance capability. The battery management system also controls the main relays (main contactors) integrated into the battery's circuit.

Overcurrent protection is a passive control component. Battery systems have one or more fuses, which can disconnect the circuit in situations in which the battery

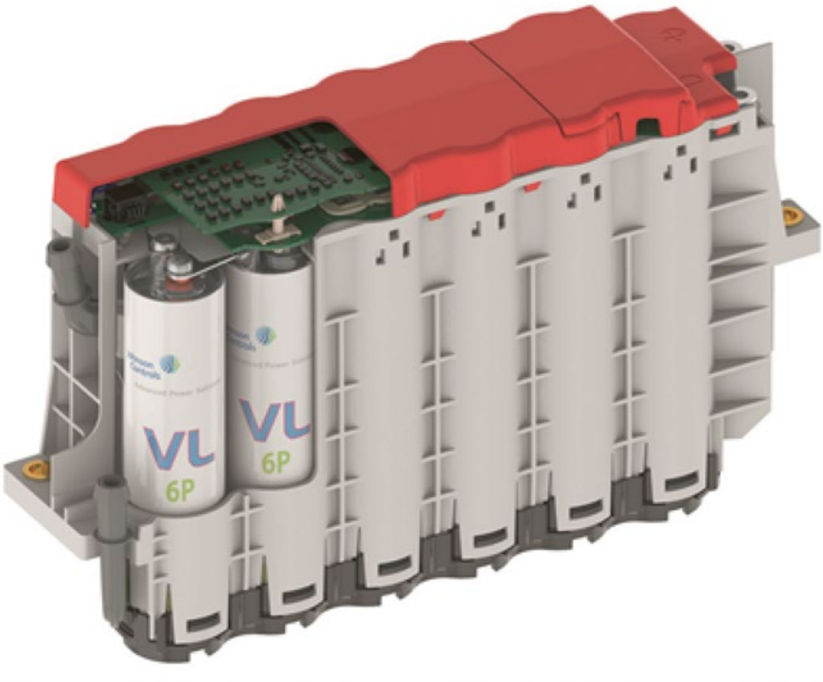

Fig. 8.4 High-performance lithium-ion module comprising cylindrical cells with integrated cell supervisory circuit and cooling system (Johnson Controls)

management system can no longer control a current that exceeds predetermined limits.

Interfaces Interfaces with the vehicle are those devices and components that are used to transmit electrical power, connect with the vehicle's coolant supply system, and exchange operational data. The electrical system comprises high-voltage connectors, by means of which the battery is charged and discharged, as well as the respective data transmission devices. An additional safety measure is the electrical service disconnect accessible from the outside of the vehicle. It is often used for service purposes and enables persons to disconnect the battery in a simple manner.

The interfaces play an important role in terms of data transmission. They enable the battery system to communicate with the vehicle's electrical control system. The data type and volume depend on the vehicle. Information on the state of charge, performance capability, and operating temperature is typically transmitted from the battery to the vehicle. Data needed for safety purposes are also included, such as data on electrical isolation resistance. Vice versa, the vehicle transmits information to the battery system that is important for its operation. It includes signals for

Fig. 8.5 Lithium-ion high-energy module comprising prismatic cells with integrated cell supervisory circuit and cooling system (Johnson Controls)

switching the battery on and off as well as signals that ensure immediate interruption of operation in an emergency. When such an emergency is signaled by the crash sensor, for example, the battery is switched off at once.

The cooling medium connection of the battery housing is the mechanical interface with the vehicle's cooling medium supply system.

Battery housing and fixation system The active and passive battery system components are installed in the battery housing, which therefore plays an important role in regard to functionality, safety, and the service life of the energy storage system. It protects the sensitive components from harmful environmental influences such as water, humidity, and dust, and is essential for the battery's long-term safe and reliable operation. Usually, traction batteries are installed outside of the passenger area, mainly in the vehicle's floor. Thus, the housing is exposed to extreme environmental influences such as temperature, humidity, spray, salt spray, dust, and stone-chipping. This means that considerable mechanical stability and corrosion resistance even under extreme circumstances are of great importance.

These environmental influences mainly concern the housing surface and its tightness. During driving, however, the internal and external fixation systems are subject to considerable mechanical and thermal loads. The overall system therefore has to be designed and configured in such a way that the battery system can operate without malfunctions throughout its entire service life. For this purpose, car manufacturer have drawn up mechanical load profiles (vibration, shock) in order to determine the system's mechanical stability, which undergoes extensive testing.

8.5 Electrical control architecture

Fig. 8.6 displays a modular lithium-ion system's basic electrical control architecture. As mentioned above, the cell block consists of the cells and their respective monitoring components. The modules are electrically connected with the power connector system by the main relays. When the main relays are closed, the connection with the vehicle's electrical drive system is established.

An internal data bus (private network) is used to exchange data between the modules and their measurement and control components on the one hand and the battery management system or battery monitoring unit (BMU) on the other hand. The vehicle's 12-V on-board electrical system provides power for the battery control system. It is independent of the lithium-ion traction battery.

The battery management system actively controls the following subsystems of the battery:

Main relays: The BMU operates the main relays that provide the connection to the high-voltage connectors. For safety reasons, a high-voltage battery has two main relays. One of them is arranged between the positive terminal

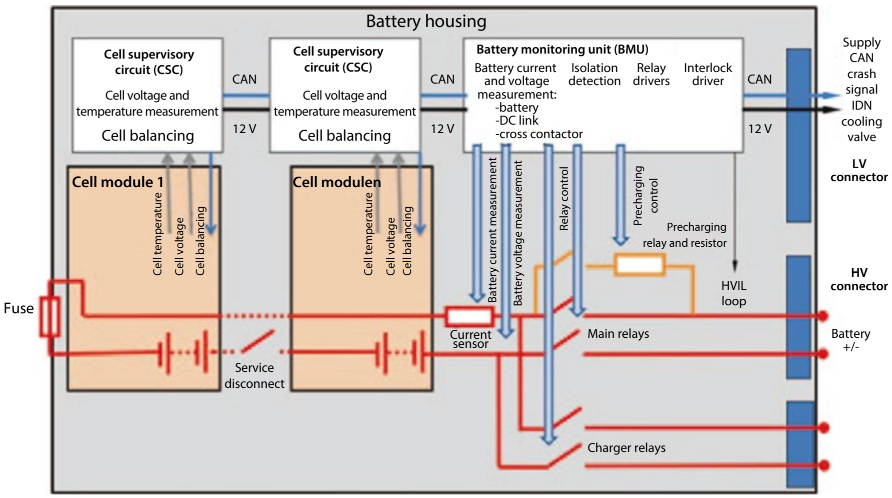

Fig. 8.6 Electrical architecture of a modular lithium-ion battery system

of the cell assembly and the positive external connector. The other one is located between the negative terminal of the battery pack and the negative battery terminal. When the battery voltage is switched onto the power connector, only one relay is switched on. The other one is initially precharged to operating voltage level. This technology prevents the main relays from closing under full system voltage because this would negatively influence their service life.

The actual switching routines (on and off) are customized to the technical parameters based on the vehicle's requirements and the battery system's possibilities. The battery system is only switched on when it is technically in perfect condition and when there is no malfunction. In the event of malfunction such as faulty electrical isolation, short-circuits, or defective cells, this switching process is blocked. Depending on the malfunction type, the switching-off processes can be immediate or gradual.

High-voltage interlock circuits (HVIL) are a very important safety measure for both the battery system and the entire vehicle. They immediately and automatically open the main relays and disconnect the battery terminals if the high-voltage system in the battery or in the vehicle is interrupted, for example because of a loose connection or a broken cable.

Thermal management system: The temperature data recorded by the battery management are used to control the cooling system. In a liquid cooling based system, these data are required to control the flow rate and the temperature of the cooland. In an air-cooled system, on the other hand, the power of the cooling fan and the airflow rate can be used to control the temperature. The heat is dissipated in a cooling liquid-based system by a chiller, which is installed outside of the battery or, if a technical refrigerant is used, by means of the air conditioning system compressor.

The liquid circuit can also be used to heat the battery, if it is configured and designed accordingly. This is especially advantageous for lower temperatures because the battery reaches its perfect operating temperature much more quickly.

Charge balancing electronic system: In Section 8.4, the cell supervisory circuit (CSC) was presented. Its main function is to provide monitoring technology, but it also has an additional active function. It is controlled by the battery management system or battery monitoring unit (BMU) and wired in a specific way to ensure that the cells in the battery assembly can be charged to a uniform state of charge. This is achieved by a targeted discharging of all cells of the system to that state of charge of the cell with the lowest state of charge. Over time, individual cells self-discharge differently, which is generally the reason for different states of charge. Lithium-ion cells usually self-discharge only minimally. Hence, most manufacturers implement targeted discharging technology to achieve a uniform state of charge, which is important for perfect operation.

8.6 Electric vehicle geometrical installation and operation

Designing and constructing a complete battery system is determined by the individual components' specific technical requirements but, most of all, by the vehicle itself. Space requirements play an important role in this respect. It is essential to fully utilize available space and to integrate the battery into the vehicle so that it requires as little space as possible and can still be fitted into the vehicles' safety architecture without any problems.

Fig. 8.7 shows how this can be achieved with the example of the Opel Ampera battery system. The battery was designed in such a way that all available space in the vehicle was utilized completely. Here, modular technology is used which involves connecting a certain number of prismatic lithium-ion cells (pouch cells) to modules. These subsystems are the basis for constructing the overall system described above, which is then integrated into the vehicle together with the other components.

Fig. 8.7 Opel Ampera lithium-ion battery system (courtesy of Adam Opel AG)

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