Review on Battery Management System perception of Hardware Concepts

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Abstract: This study is concerned with the hardware elements of electric vehicles and stationary applications in the Battery Management Systems (BMS). The aim is to provide an overview of current concepts in state-of-the-art systems and enable readers to estimate what needs to be considered to develop a BMS for a particular app. Following a brief study of the general requirements, many alternative battery pack topologies and their repercussions for the complexity of the BMS are considered. Examples are four battery packs taken from widely accessible electric automobiles. Subsequently, implementing components of measuring the physical variables necessary (voltage, current, temperature, etc), and balancing problems and techniques, will be examined. Finally, questions of safety and reliability are examined.
Keywords: BMS, Battery pack topologies, Technology, Electric vehicles; BMS-ASIC; Balancing.

Introduction:
In many applications now, lithium-ion batteries range from personal electronic devices such as cell phones to the upcoming electric vehicle class. Due to its fragile nature, a comparably advanced monitoring is necessary for safe operation as compared to lead-acid or NiCd batteries [1].

Depending on the unique application, the complexity of the battery management system (BMS). In simple instances, such as mobile phone single-cell batteries or e-book readers, the integrated circuit "fuel gauge" (IC). In general, these ICs can measure voltage, temperature, and current, using basic methods for estimating the battery's current charge state (SOC). The BMS must do more advanced duties in more complex equipment, like as electric cars. In addition, it is necessary to measure basic characteristics like cell tension, cell temperature and current. However, advanced algorithms are required, for example, in order to compute the cruising range reliably, the available energies must be estimated.

This paper focuses on the hardware components of lithium-ion battery management systems that deliver the abovementioned capabilities. The first section presents a set of hardware requirements for a BMS, including measurement of necessary values and electromagnetic interference and insulation of galvanic elements, contactors, and redundancy issues. A summary of possible BMS topologies is next offered. Differences are illustrated in this section of the study from easy-to-use cases such as portable and complex electronic devices such as electric vehicles (EVs) and aviation. The section ends with the description of four real examples of electric battery packs [2]—section 4 details how to comply with the physical value measuring criteria and highlights some typical problems. The main theme of equilibrium is covered later. There are described and contrasted different ways to charge equalisation. Finally, it concentrates on the topics of security and reliability. High voltage lithium-ion battery packages and potential countermeasures are demonstrated as the key hazards. The final portion provides a brief overview of various isolation measurement methods and some corresponding standards.

Requirements of battery management system:
Designing a BMS is a complex undertaking that involves taking account of the specific needs of the application, system context, and characteristics of the selected battery cells. A list of system requirements can be drawn from these factors. This section is designed to identify and provide short explications for each element that is normally considered. In the later sections of the paper, implementing considerations and examples are discussed.
Operational requirements and the following BMS component are often important:

- **Temperature Acquisition**

One of the most difficult jobs when creating a BMS is to know the most precise temperature attainable. The different sensor types (full digital or analogue) must consider the advantages and disadvantages and where the temperature of the package can be measured. The number of cell temperature sensors required is hence required. The perfect arrangement for a minimal number of sensors could be necessary to find simulations. Sometimes, the acquisition of peripheral temperatures can also be crucial, such as those of contactors, fuses or even electric busbars carrying the battery pack. This could only be essential if a battery pack that operates at its thermal limit is assumed to operate. Suppose a battery pack is to be optimised with respect to the small weight. In that case, hefty copper busbars should be eliminated so that the design engineer is forced to manage likely thermal peaks during high-power operation and therefore requires thermal observation of the busbars. The cell-based temperature within a battery pack is the next priority, having talked about thermal features of peripheral systems. Temperature sensors are normally available for a 2:3-to-2:12 channel sensor ratio, meaning that for a final example, only two surface temperature sensors for a cell composition of 12 can be installed. These ratios are based on analogue front-end ICs commonly accessible.

At general, three applications must be considered: charge, discharge and storage in a temperature requirement. The cell manufacturer should be consulted in view of the safe operating range. In too low or too high temperatures, batteries based on lithium cannot work correctly. Even within these limits, however, it is important to know the temperature correctly. Lithium plating can have a substantial effect at excessive current levels in the usual temperature range. Temperature, voltage and current must be known accurately in order to prevent lithium placing. The requirement should also address the importance of thermal time constants such as anisotropic thermal conductance as the main features of the battery pack and its thermal capacitance. Battery cells have a substantial thermal capacity and are well-behaved (in some geometric pathways), which are influenced and limited by thermal insulation layers (housing, the geometry of cells, etc.) [3]. Misreading's and thermal blind spots can happen when temperature sensors are not positioned appropriately.

- **Voltage Acquisition**

A traditional lithium-based battery management system requires at least one voltage acquisition channel per serially connected cell. Moreover, most automotive applications have supplementary protection built-in that the precision of the primary tension acquisition is not achieved: it usually contains a configurable window comparator to alerts the BMSmaster in the event of a cell being operated beyond the permitted tension range. Usual resistor arrays are used for the over-and underground power ranges [4].

The voltage collection data conversion rate varies greatly, depending on the application. Rates up to several Kilohertz are achievable but are rarely employed because, in many circumstances, battery time constants are quite large. If over-sampling is decided to have a favourable effect on system behaviour, high data capture rates are preferable. Furthermore, faster monitoring may be necessary when significant pulse currents occur in the application. Common B MS front-end chips are usually equipped with 1 mV absolute precision and a complete 12 to 16 bit scale that results in around 380 μV resolution (14 Bit resolution for BQ76PL536A). This can be critical if battery-chemistry estimation approaches, for example lithium-iron-phosphate cells, have a very low SOC voltage reaction. The two plots of Lithium Nickel Manganese Coball Oxide (NMC)- and Lithium Irone Phosphate (LFP)-type each exhibit in Figure 1. The graph displays the CTV over the SOC of each cell type. For this case, any hysteresis effects are ignored. The effect on the precision of the BMS's limited voltage is the focus: the CTV value at 50 per cent SOC is an example of the acquisition voltage for both chemicals; (the absolute voltage value is of no relevance here). The CTV(50 percent SOC) is added to each horizontal line for error of ±1 mV. The intersections between the voltage inaccuracy lines and the real CTV curve lead to vertical lines which are inaccurate according to the SOCs. As can be observed, a base error of 0.2 percent can be expected if the accuracy of ±1 mV voltage is employed to compute SOC on NMC lithium cells. If the same mimic for the acquisition of a SOC for LFP cells is applied, it is necessary to anticipate a base error of 5.9 percent. This easy example shows the substantial impact on the estimate of SOC for different cells of the voltage acquisition. The steeper the CTV vs.-SOC curve is, the lower its impact.

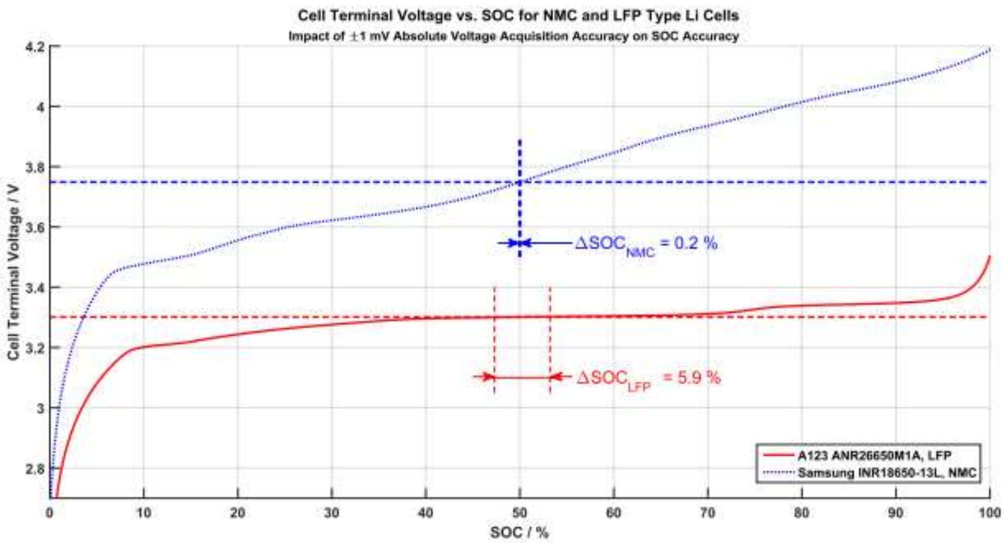

Figure 1: Comparison of SOC uncertainty depending on a ±1 mV voltage accuracy

- **Current Acquisition**

The importance of voltage precision was described in the previous paragraph on SOC determination. While SOC measurement is of the greatest accuracy during stand-off periods during open circuit tension (OCV), the measurement of dynamic SOC in operation uses the measured current value, coulomb counting, an alternative technique of estimation of SOC. This approach simply incorporates the current into a battery or from it. After calibrating the system in a certain state, the SOC can be measured by a coulomb counter alone to track the true SOC, i.e. 100 per cent after a full state detection. However, depending simply on coulomb counts for accurate calculation of SOCs seems problematic, as current sensors are also non-ideal systems which are the basis of a specific drift, offset and temperature error. Furthermore, the current sensors employed often have to meet contradictory needs at the same time: it is typically possible in car applications that current sensors may detect current from the milliampere to 1000 ampere at the same time. The sensor could need a large bandwidth in order to catch rapid current fluctuations depending on the application. The accuracy of the current sensor should also be taken into consideration and the immunity to EMI noise. The defined SOC will differ from the real SOC as a result of all this, particularly if the battery is utilised in the low-current system, where noise and minor offsets play a large role. The associated SOC estimating issues are overcome with ways that combine the available data with acceptable values utilising algorithms and parametrised models. However, this work is beyond the scope of the paper.

- **Communication**

In order to offer status information and receive commands and parameters, BMS normally requires to interface with an overall system (e.g., electrical power, power management or vehicle control unit (VCU) within a vehicle). To do so, the modes of communication given or needed by the system must be taken into consideration. The requisite speed, robustness, and dependability of communications should also be assessed. Should the data be transferred at minimum speed to do safety-related duties, or can a hierarchical communication take place, which is slow enough to preserve power while still ensuring the time required for the application? Decisions on these factors may have been made at the system level already and require BMS to adjust. One example would be the necessity to equip the system with a Controller Area Network (CAN) interface that defines certain limitations in terms of speed, resilience and dependability. In addition to the system level, communication is also needed between the BMS components. The way it talks about "slave" modules which, among others, are responsible for the data acquisition or the control of players, needs to be established for modular systems that are dispersed over numerous Printed Circuit Boards (PCBs). The same factors as extensive communication of the system are essentially relevant for this.

- **Electromagnetic Interference**

If EMI does not get adequate attention, it might be an issue. All sensors are generally susceptible to EMI. In the worst situation, the acquisition sensor could only be minimally distorted to prevent the BMS master from identifying bogus values. The other extreme case would also lead to the entire inefficiency of data points, but would be noticeable at least. Electrical equipment, electronic power components and other charges must be well-designed for EMI in order to minimise their influence [5]. As a result, proper EMI filters, such as common chokes and blocking condensers, are advised to be used. The filter units should be mounted to capture the system disturbance, e.g., defined by ISO7637-1, as close as practicable to the sensor measures pathways [6].

- **Contactors**

Most battery packs require that at least one of the two battery poles can be galvanically disconnected. The battery pack requires contactors large enough to carry the principal current and be capable of cutting huge DC currents in the case of a hazardous failure. To fulfil this requirement. Because, contrary to the Alternating Current (AC), DC has no repeating zero current events, it demands additional attention in the DC case to disconnect and extinguish the electrical arc in the blades of the contactors. Contactors therefore feature magnetic arc extinctors that remove the arc from the pins. When using such devices, this results in a preferred current flow direction. For the creator of a battery system, this is crucial to comply, otherwise, the switch-off capacity can be significantly reduced [7]. Contact welding is extremely risky for a battery pack, as the package cannot be separated from the application completely. When the blades are heated and are forced forcefully against one another, contact welding takes place – this scenario must always be avoided. The contact pins will not touch in the heated and off-state while switching a contactor off under complete loads. Another dangerous case involves switch-on action while a potential lies between non-closed contact blades (resulting from not yet charged DC-link capacitors). If the blades are closed, they bounce (as are all mechanical switches), and an electrical arc is drawn on every bounce, and the blades heat increasingly. When the rebounds end, the blades are closed and the extremely thermal blades are forced to each other and finally welded, particularly at the very high densities of current that occur when the contact blades are not completely in touch. A particular circuit must guarantee zero potential across contactors so that this does not happen: zero power switching during any switching action must be ensured, and a preset unit is required. The pre-charge unit is composed of an additional resistor series contactor. It is attached to the main contractor and activating to gently boost the voltage of the DC connection to the pack voltage level to enable the main contractor to be switched on without power.

- **Other Requirements**

Additional criteria not particular to a BMS may develop from the request and should also be taken into account. For example, some limitations on space and system expenses need normally be taken into account. Furthermore, mechanical hardware ruggedness may be important. Weight and power consumption will also be important for aerospace-related systems at least. These and other issues are certainly not irrelevant but are not the topic of this work and are therefore not studied in detail.

Topologies of BMS:

An overview of different structures of battery systems and the resulting consequences for the BMS will be provided below. In many instances, numerous battery cells must be coupled to make a battery pack in order to meet electrical requirements (e.g. stored energy, power, Voltage range, maximum current) needed for a single system. For various types of batteries, different connection topologies are basically feasible [8].

The cells have to be connected in a series, with a parallel connectivity, in order to achieve a specified voltage range at the battery pack level, which minimises the current drawn for that power value. One conceivable option in today's systems would be to employ several cells with limited capacity in parallel to construct modules that would be joined into series in order to enhance voltage, see the example below for Tesla Model S. The use of high capacity battery cells connected in series is another variation. In terms of BMS complexity, both versions are the most reasonable. A parallel connection of several strings of battery cells would raise the cell tension monitoring and balancing costs by one factor of the number of parallel strings (for specific redundancy requirements for example), and only one voltage metering channel per connected n cells will be necessary.

Battery modules are even designed without single cell monitoring and balancing in certain circumstances in which size, weight and electricity usage are very crucial. E.g. the Mars Express and the Rosetta Sondes of the European Space Agency (ESA). There are three battery strings that connect them to the main bus, each with unique DC/DC converters. However, no single cell surveillance is provided for strings. Single cell surveillance is not necessary for the specified application because rigorous cell selection and testing are provided. The cells should come from the same lot, which indicates that the process runs without interruption using the same raw ingredients. However, other research demonstrates that, although the cells tested at the time of selection seemed equal, their ageing behaviour. Therefore, even if carefully chosen cells from the same lot seem to be completely equal when producing, can be neglected to do single cell monitoring. It is doubtful. Certainly, the advantage of carrying electronic battery monitoring would be limited, since the spaceship was started and there would be no means to exchange faulty cells. In addition, an electronic failure could lead to failure of the complete system. Furthermore, the lack of single cell surveillance for tiny systems with just a few series cells can be less critical. Especially if the overall voltage of a stringe remains in one zone (assuming that each cell has identical voltages) where each cell remains well below its allowed maximum tension and below its allowed minimum voltage, the likelihood is fairly modest for a single cell to get critical. Well-known semiconductor manufacturers provide a few application-specific integrated circuits (ASICs) to provide the fundamental monitoring capabilities required for the safe functioning of batteries. Since there are a large range of components accessible, only typical examples are presented that are available or used at the moment of writing.

- **Modularisation**

The battery pack must consist of many cells for applications requiring greater power and/or greater energy demand. ICs for such systems are offered, which monitor several cells simultaneously and provide equalisation instruments that in a single cell system are not necessary [9]. More complex features are frequently used in such systems on a central module (ECU), commonly known as the 'BMS-Master.' This type of system is used. The structure of the class's typical system is shown in Figure 2. The master can provide examples for activities such as advanced SOC assessments or algorithms for power forecasting which need some computing capacity.

Then the modules that carry the front-end ICs are frequently called "BMS-Slaves." It is employed for fundamental functions such as signal acquisition, filtering, etc., performed by the abovementioned monitoring ICs. The names for this are: Bq76PL536A (used in Tesla Model-S (Palo Alto, CA, USA), or Smart fortwo ed, Linear Technology's (Milpitas, CA, USA) LT6802G-2 (used in the i-MiEV Mitzubishi motors (Tokyo, Japan))); MAx11068 (used in the VW e-Up), Maxim Integrated's (San Jose, CA, U.S.); and AMS' (Premstätten, Austria) AS8506C. A passive balance is provided in TI bq76PL536a, MAX11068 and LT6802G-2, whereas AMS can also be utilised for passive balancing topologies but also for the active balancing of an external transformer. See Section 5 for more on balance. When writing, most of the listed ICs, for example TI bq76PL455 or LTC6811, already have replacements accessible. A certain degree of redundancy in voltage monitoring is normally desired as described in this section on requirements. In conjunction with the described ICs (or even the same package), so-called secondary protection ICs can often be employed to give additional safety levels. Another option would be the use of a fully redundant BMS, which would, however, increase expenses substantially.

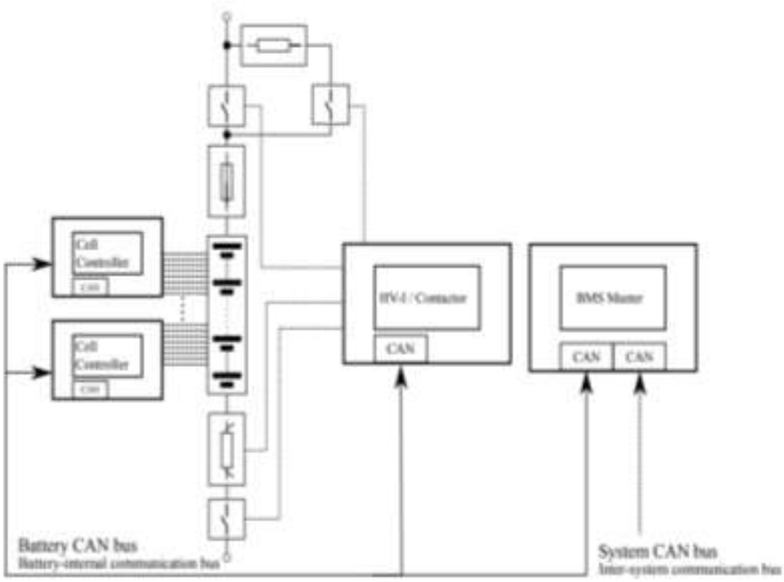

Figure 2. Structure of a typical BMS for EV applications.

- **Communication and Data Transfer**

Use the front-end ICs in a larger cell stack can be daisy linked. For example, the MAX11068 has two I2C ports for connection to the lower next chip in the stack and the higher stack. Like the MAX11068, TI bq76PL536A likewise provides high- and low-level interfaces to the stack. It also provides a specific interface for connecting to a microcontroller, whereas the lower I2C port on the stack is used for MAX11068. With the Serial Periphery Interface (SPI) bus the LT6802G-2 can be connected. The interface of the chip does not allow several chips to chain directly, however it is feasible to connect numerous chips to the same SPI bus through other digital isolators. In many circumstances, connecting numerous ICs to one PCB is via the daisy chain connections. Usually a low-cost microcontroller is used to interface to the rest of the system and control the functions of

BMS ASIC. For connecting other PCBs to other modules and connecting to the BMS master, a field bus like CAN is commonly utilised to make communication more durable. The same applies to the link between the master and the remainder of the system.

Measurement:

This section provides an overview of HV battery systems measuring technologies. The measuring technology is a vital component in a battery system that allows the definition of state variables such as SOC, health status (SOH) and state of function (SOF). Cell voltages, the overall battery voltage, the total current and temperature are frequently included in the measured variables [10]. The battery system, for example, can be prevented from overcharging or deep draining by understanding the status variables. The state variables allow an efficient exploitation of the battery system and ensure safety-related functions.

- **Current Measurement**

In particular for determining the status variables of the battery system, the current measurement is of major relevance. According to figure 1, the cell voltage shows a low SOC dependence, depending on the battery type. A perfect meshing of the whole current enables the integration of the current to determine the SOC. The following present and compare established methods of current sensing. Current purchase equipment may be split into two fundamental sensor technology: galvanically linked and isolated. The widely-used shunt resistor sensing method is part of technology with galvanically connections. The electromagnetic properties of the current are used to acquire the magnetic field intensity using hall sensor, an example of the isolated current acquisition. The position in the battery pack must be taken into consideration in addition to the sensor technology [11]. If the battery system comprises multiple switchable string devices, one main current controller and one device for each battery string may be crucial to implement. This is needed in order to monitor power imbalance in operation.

- **Voltage Measurement**

Usually each cell voltage, as well as the total pack voltage, may be determined in battery packs made from lithium-ion cells. The cell voltages can reach values of over 800 V while the cell voltage is merely a couple of volts. Therefore, cell voltage measurement and pack voltage measurement must be differentiated. It is a feasibility condition that the sum of the individual cell voltages should be equivalent to the total pack voltage.

- **Temperature Measurement**

The Negative Temperature Coefficient (NTC) (metal oxide) or Positive Temperature Coefficient (PTC) (Semiconductor) type are common temperature sensors that monitor temperatures in the region that are significant to battery management applications. These sensors vary their resistance depending on the temperature – with increased temperature, the resistance reduces for NTC and vice versa. Measurement is carried out by capturing the voltage drop as the resistor flows with a continuous current. They are normally suitable for use in areas between −50 and 150 C, they are relatively cheap, easy to apply and linear in a certain range but not linear in adjoining temperature ranges (e.g., very low and very high temperatures), BMS front end ICs generally supply one or more temperature measuring ADC channels, whereas NTC thermistor use is widespread. It is clear from non-linearity that a search table needs to be established for the right temperatures from recorded voltages in the digital processing chain (i.e. the Smart Cell Controller Board). More convenient are other sensors using a digital interface and providing an easily determined temperature measurement. The DS18B20 (Maximum Integrated) is an example of a sensor with an integrated digital ("1-Wire") interface. Texas Instruments (TMP100), LM75 etc. have similar sensors with I2C connection available. These sensors can be connected to the environment of a microcontroller. However, although digital sensors are normally known for their robustness, caution should be taken when placed adjacent to the high-power channel in a battery pack to reduce failure caused by EMI.

- **Data Transfer**

Communication is necessary, as already indicated, between different BMS modules as well as between BMS and the system as a whole. The CAN bus is currently one of the most prominent buses in car environments as the number of bus members and the noise resistance are quite variable. The simpler, widely used local interconnect (LIN) bus has the disadvantages of being slower, less flexible and non-differential, but it is also less expensive as hardware is decreased. The SPI interface, I2C interface or the One wire bus is also mainly utilised over small distances, such as Chip to Chip communication. Because of its non difference, they are less resilient in a longer, more exposed line against disturbance, such as inter-module buses. The above CAN bus is an excellent solution for the latter task. The Flex Ray bus appears appropriate if the CAN Bus is too slow at its top speed of 1 Mbps or a need for deterministic capacity in real time. Ethernet connections may also be employed, especially if high communications speed and huge data quantities are needed, to connect the Battery System to the application.

Balancing:

For many causes, the values in a serial cell connection can vary at a particular period in the SOC. The reasons for inhomogeneity between single cells un the battery pack are illustrated. Production-related variances and various operating and environment circumstances, i.e. temperature, on the one hand, are the reasons for this inhomogeneity. These reasons may contribute to distinct beginning circumstances, varying levels of ageing and self-delivery, which ultimately lead to different SOCs, capacity and resistance levels. In this part, the discrepancies between the SOC and capacity are not addressed by the inhomogeneities regarding the inner resistance of the cells. Changes in the capabilities of several cells in a load of 18,650 consumers with the same initial capacities, under the same load profile. Even though each cell is chosen for the same initial capacity, after several cycles the capacity varies. The 18,650 cells examined revealed a cycle life between between 1000 and 1500 cycles when a remainder of 80% is used as the end of life criterion. This diffusion indicates that selecting equal battery cells at the beginning of life is not enough to provide a permanently identical capacity after using some batteries. In fact, it is better to monitor and, if necessary, manage the capability of each cell. Although our work did not relate to an evolution of the cell self-discharge rate, this parameter may also be varied. There was a comparable resistance to self-discharge input and 4 cells were saved to 40 μC. Though the kind of cell and the storage circumstances were identical, the cell resistance to self-discharge ranged from 10 k to 14 k percent, a 40 percent rise from the weakest to the strongest cells. In addition, Arrhenius is demonstrated to depend on the temperature from 20 C. Because the battery packs are always unhomogenised in temperature, a deviated self-deployment rate can also be noticed for distinct battery cells in one pack.

Safety and Reliability:

The use of a BMS is mainly aimed at minimising the risk associated with lithium-ion cell operation in the battery packages. Some examples are provided in the next part of the typical safety features of a BMS. Design issues are examined in the following connection with the safety of the BMS itself. High voltage exposure, arcing, fire, ventilated gas fuelling and vented gas poisoning are the main risks in the lithium-ion battery packages. The safety functions of the BMS should decrease the likelihood and severity of occurrences together with the appropriate battery pack design. The high-tension safety of the battery pack can be ensured by insulation monitoring (further described in the following section) and interlocking circuits. This also minimises the possibility of arcing events resulting from pollution or condensation in the battery pack, as they may be recognised in an early stage, which also affects the insulation strength. BMS hardware design should follow appropriate standards for the suitable creeping and clearance distances for the PCB and all connectors. The galvanic isolation from high battery voltage must be ensured for communications interfaces with other control units or auxiliary power (low voltage electric power system). The selected insulation device must be ensured during the design, since it must ensure enough protection against the electric shock. It fulfils the "reinforced insulation" condition. Optocouplers were traditionally employed for the isolation of galvanic signals. In recent years ICs have joined the market, promising greater performance particularly with regard to dependability and ease of use, including so-called "digital isolators." These ICs have a capacitory or inductive internal isolation barrier and signal transmission circuitry.

The risk of fire can be reduced if temperature sensors are placed in the package and the critical temperature readings are properly reacted. Furthermore, sensorless approaches such as electrochemical impedance spectroscopy can be employed employing indirect sensing methods. New wire harness temperature acquisition methods can also be used to increase safety. Complex electrical systems.

Conclusions:

This paper provided an overview of typical concepts for BMS hardware, starting with a series of generative criteria that would be discussed later on. Including as many parameters as feasible is vital for a design process. However, the criteria should be determined according to the requirements of the target device, namely that a small electrical implant device is most probably different from those of an aviation-use battery system. Any consideration of the battery pack design should be based on the given thinking about the requirement established. The structure of the battery system affects topology of the BMS. Examples of the application where very unconventional techniques to monitoring have been prescribed in favour of weight reduction or complexity. There were demonstrated and compared four commercial EV batteries. The identical application, for example, made use of CAN for interacting with the car, has resulted in other commonalities. The variations in integration efforts and BMS internal communication were interesting, with considerable cabling efforts in relation to the highly integrated smart battery considering the extreme examples of the Central BMS module of the VW e-Up. This page provides details on how to achieve and transmit the necessary physical values. For most measurement purposes, various methodologies have to be chosen with the limits and needs of each application in mind. It has outlined the use and creation of associated sources of the imbalance of charge between serially connected cells and various techniques of compensating for their impacts. It may be claimed that passive balance still appears to be the most generally employed strategy at the time. Finally, a summary of the safety aspects was provided. The main difficulties found are the compliance with the prescribed operation ranges of the battery cells employed to ensure their long service lives and protect the user against potential hazards due to high voltage. State-of-the-art isolation monitoring systems have been published, indicating that the standardised insulation monitoring setup includes a voltage measurement, a simple switch and a well-known insulation resistor. However, it was emphasised that risks that can occur at the level of the system must be considered when the battery is turned down for its own reason. If these are potentially hazardous but are kept in a safe position by refusing to charge them again, a battery destroyed by a deep discharge might be the least evil.

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