COBalt-free Batteries for FutuRe Automotive Applications

COBRA

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EXECUTIVE SUMMARY
In this deliverable, a prioritized list of sensors to enhance cell performance, safe operation, etc. will be established. The sensor requirements will be re-evaluated and updated after initial sensor test results are available. Related to Task 5.1

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1 Introduction

This deliverable discloses smart sensors that will be integrated into the Battery Management System (BMS). The smart sensors are proposed to enhance the vital functionalities of BMS such as increasing the accuracies of State-of-Charge estimation, State-of-Function estimation, State-of-Health estimation, and their subcomponents as well as the failure diagnosis component.

In this project, to increase the accuracy of state estimations and resulting in high efficiency of energy management of battery packs, various smart sensors are aimed to be used. It is expected to see improvements overall in the core functions of the battery management system with the combination of newly available information directly measured from the cells.

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2 Battery Management System (BMS)

Battery pack and cell functionalities are monitored by the Battery Management System (BMS), and countermeasures of failure modes such as over-charging, over-discharging, short-circuit are provided by the BMS. There are two commonly utilized types of BMS structures which are centralized BMS and distributed BMS. In a centralized BMS system, wiring harnesses are spanning throughout the pack connecting to all of the cells to the main control unit, while in the distributed BMS topology, there are several control units (host) that monitor the cells, and these module control units are connected to master controller. While the centralized BMS structure rises the required wiring in the battery, the distributed BMS design offers higher functionality and control inside the system [1]. BMS shall be in communication with inside the system and be connected to other control units to optimize the performance of the battery pack. The power and energy flow to the vehicle side is the responsibility of the BMS. It assures the battery pack is utilized in an optimized configuration and limits. Therefore, it can be said that BMS can help to achieve aimed lifetime by managing power and energy. To optimize this, BMS requires the information of available energy and the power which can supply to the vehicle. Therefore, state estimation of BMS has crucial importance on battery pack systems.

The Battery Management System (BMS) consists of software and hardware parts, which include a module control unit and battery control unit, with its main functions and tasks. BMS's main functions are data acquisition, calculation of battery state, safe operation and protection, charging control, energy management, thermal management. In order to perform its main functions, BMS hardware includes various sensors, actuators, controllers, etc. Depending on the information taken from the sensors, BMS diagnoses the failure modes on the cell level and pack level which includes overcharge, over-discharge, fire, over-current, extreme temperature, short-circuit, etc. After the diagnosis of failure, BMS must take countermeasures immediately to assure that the vehicle remains in a safe state. Also, with the contribution of hardware parts, state information of battery pack and cells is determined to control required energy and power flow to the vehicle. All these can be achieved by collecting data of voltage, current, and temperature measurements which can be used in software

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algorithms to estimate the State-of-Charge (SOC), State-of-Health (SOH), and State-of-Function (SOF) [2].

2.1 Battery Management System (BMS) Core Functions

In order to estimate State-of-Charge (SOC), State-of-Health (SOH), and State-of-Function (SOF) of the battery, collecting the data such as terminal voltage, current and temperature is necessary for the BMS. These can be observed by conventional or smart sensors, controllers, so BMS can estimate the essential information of the battery pack.

2.1.1 State-of-Charge (SOC)

The SOC of the battery pack defines the ratio of remaining energy in a battery to the full battery capacity [3]. Accurate estimation of SOC has a significant impact on the reliability of the battery pack, besides of remaining energy. Since each cell is different from the other, the capacities of the cells are often different. This is due to the reasons such as self-discharge, manufacturing variations, exposed temperature. The SOC estimation with higher accuracy is contributed to better management of charge and discharge processes [4]. Using SOC information, BMS can control the power and energy transfers from the battery and optimize the usage of the battery pack to achieve the intended lifetime.

2.1.2 State-of-Health (SOH)

The lifetime of batteries became an important topic with the spread of electrical and hybrid electric vehicles. Accurate SOH estimation can provide the degradation rate information of the cells, especially rapid changes in SOH in case of a failure. Then countermeasures can be taken by BMS [5]. The SOH gives information about how the battery deteriorated in time. The capacity of the battery reduces when compared with the first charge level by each charge-discharge cycle, and SOH defines this deterioration with a ratio of measured capacity to the rated capacity [3]. The SOH information is defined in percentage and at the beginning of life SOH is 100%.

If the capacity is decreased to 80% or the resistance increased to 250%, it can be said that the battery is at its end of life and it is not suitable for vehicle application anymore [6]. By having an approach to measure voltage, current and temperature with more precise methods

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will provide a more accurate outcome of SOH estimation which is naturally crucial for automotive industry.

2.1.3 State-of-Function (SOF)

SOF is used to describe the current, voltage, and power capability of the system. Also, it can be viewed as a function of SOC, SOH, impedance and temperature of the system [3]. Since one of the main functions of BMS is energy management, effectively estimating the current, voltage, and power capabilities became critical. For the instantaneous power request from the vehicle for the cases acceleration, regenerative braking, or climbing, SOF prediction with high accuracy is essential to prevent the over-charge, over-discharge or over-temperature of the battery [7]. Thus, it is critical for the durability of the vehicle to maintain the required lifetime.

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3 Measurements For BMS

There are three values actively measured for BMS state estimation algorithms; voltage, current, and temperature. In this chapter, the importance of these measurements is detailed.

3.1 Voltage Measurement

Voltage information is of paramount importance to monitor and control the battery pack. This information is used in many components in the BMS such as keeping the cell voltages in between the safety region and to do the state estimation (SoX), especially SOC depends on voltage data. For example, voltage data is generally used for the initialization of the SOC calculation. It can be measured on a cell level, module level, and pack level and provided to BMS.

Even though measurement on cell level increases the hardware cost, this provides balancing between cells and ensures safety in case of over-charge and is generally preferred by professionals [8]. Also, total pack voltage increases with the number of series-connected cells, measuring this high voltage can be harder due to insulation problems or the requirement of components that can stand higher voltages [9].

3.2 Current Measurement

For vehicles, current sensing is of crucial importance to control the modes of driving, recuperative braking, charging, and state estimation. The battery management system monitors battery current value and provides protection for any over-current case can be danger for the system. Accurate current measurement is required to control and to maintain functional safety. For this purpose, usually, two current sensors are used to obtain the required accuracy and redundancy. Besides, usually current data is measured at pack level, since the series-connected cell has the same amount of the current.

One of the common approaches, as known as the coulomb counting method used in the industry, makes use of the current information to estimate the SOC. It simply relies on the integration of the current signal over a time window. Lower accuracy on current measurement causes state estimation with low accuracy since the error rate is accumulated in long time application [10].

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3.3 Temperature Measurement

The state-of-the-art is monitoring the temperature within the scope of battery module and pack as a function of battery management system by using temperature sensors e.g., NTCs. In principle, temperature sensors are placed at critical points in the module and the measurement data from inside the module is made available to the BMS for monitoring the cells. But, monitoring the temperature value with a colossal tolerance value is leading a new approach which scopes measuring temperature in cell level, by estimating the temperature based on impedance change or measuring the temperature directly by using suitable sensors.

During charging and discharging cells generates heat which is dissipated to the environment. Hence, internal temperature rises, measuring the temperature becomes more challenging while causes rapid aging. Depending on the aging, the SoH of the battery pack also decreases promptly. In case of the temperature rises higher values because of the abnormal conditions, it can result in thermal runaway. Also, temperature information is one of the vital inputs to the core functions of the battery management system. Dependent on the temperature, some chemistries show differences in the OCV curve and it can cause high deviations if the temperature information is not considered. The cell capacity and resistance are also a function of temperature, we observe significant changes in the battery cell capacity and resistance at extreme temperatures and for that reason, the temperature has to be measured and used in the algorithms. Temperature sensing with high accuracy is thus required for the protection and to ensure maximum efficiency [11]. In order to estimate the available power from the batter, it is also necessary to have an accurate measurement of the temperature. Indeed, the available battery power depends of the cell impedance, which are strongly dependant on the temperature.

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4 Advanced Measurements

In the scope of COBRA Research project, to estimate the State-of-Charge (SOC), State-of-Health (SOH) and State-of-Function (SOF) with better accuracies, new battery concept configuration with new communications strategies, parallel hardware architecture, smart sensors, battery models, state algorithms, and control functions will be integrated into the Battery Management System (BMS).

Temperature measurement on each cell-level, strain measurement, pressure measurement, impedance measurement, and gas measurement are among many newly introduced parameters that we are, as the COBRA consortium, aiming to receive from the battery pack. In the end, this information will be the key to unlock the accurate estimates of the state of the battery cell as well as the more agile reaction to the failure modes in the battery.

4.1 Strain Gauge Sensor

Strain gauge sensors are one of the key instruments that have been the topic of many researches that investigated the behavior of lithium-ion batteries. Numerous researches point out that there is a change in volume during operation that is strictly tied with the levels of voltage as well as the State-of-Charge [12-14]. This information could be quite vital to support the state estimation algorithms as the State-of-Charge estimation is a crucial parameter to foresee the remaining energy.

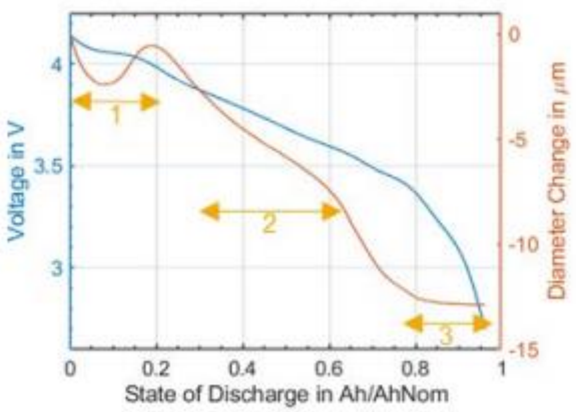

Figure 1: Voltage versus the change in mechanical properties of the cell [12]

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The strain gauge sensors are not just used for voltage or State-of-Charge estimation but also create meaningful input to the State-of-Health [14,15]. Redundancy is one of the best-known practices to ensure safety. In a situation where there could be problems with other measurements/systems, it could be also used as the diagnosis input to check whether or not voltage measurements are done correctly or the State-of-Charge, State-of-Health estimations are estimated within the right bounds.

Strain gauges are sensitive devices that are used to measure the strain (mechanical deformation in one direction) of the surface of an object. They are composed by a resistive trace, often enclosed inside an insulating film, which needs to be fixed to the surface that we want to monitor, in order to be completely solidary with it and undergo the same deformations.

The resistance value of the trace usually is of some hundreds of ohms and the variation of this value, depending on the mechanical strain, is predicted by the strain gauge factor, typical of each strain gauge and mainly depending on its material and temperature. The aim of the strain gauge test is to experimentally detect early battery cell swelling.

When the cell is in use, the increase of charge will mostly translate into an increase of size and not pressure as the cell volume will adapt to a new shape. This might indicate that the strain gauge is more suitable for SOC/SOH correlation. On the other hand, if the cell swelling presents a large deformation that can lead to any dangerous situation, as a thermal runaway, it can be detected by the strain gauge and activate an alarm trigger. It will be analyzed if a strain gauge placed on a module can also detect, as well, such alarm situation

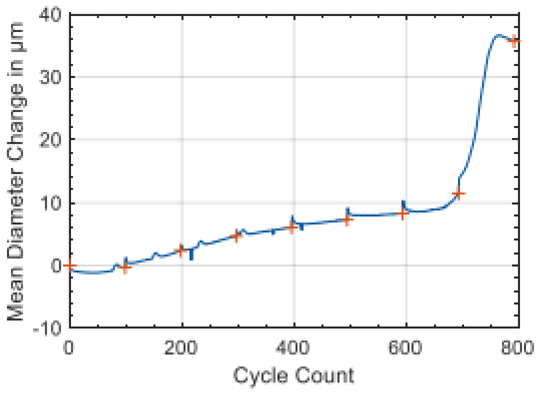

Figure 2: Cycle versus the change in mechanical properties of the cell [12]

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Indeed, strain gauges have proved to provide critical information regarding thermal runaway prevention [16]. Indeed, on some operating conditions such as overcharge, during a thermal runaway test on a Li-Ion cell, thermal runaway precursors can be read on the strain gage signal far more in advance than on temperature measurements (several minutes before).

Strain gauge sensors could be considered as one of the reliable measuring tools. Experimental applications of the strain gauge sensors had been tested and it is showing promising results with up to 100,000 cycles the calibration of the strain gauge sensors is found to be precise through lifetime [12]. Example products can also be found in the market with ease to utilized in the battery systems to measure the deformations or the elastic changes within the battery cell [17,18].

4.2 Cell-Level Temperature Sensor

With the specific advantages that lithium batteries have in a very wide range of applications, they have become the mainly preferred battery type in recent years, including in the automotive industry. Due to this expectation, plenty of different cell types, in different forms and chemistries were discovered and developed to satisfy variable project requirements. As we know, as well as the other functions the BMS have, they are designed to monitor and control the states of a lithium-ion battery system. State-of-Charge (SOC), State-of-Health (SOH) and temperature values are some of the main parameters to be stated by BMS.

Decreasing battery performance, rapid degradation and, even worse cases are the outcome of poor measurement of the values which get used during the state estimations. Since any battery developer or manufacturer does not want to face an earlier end-of-life status, they attach much importance to the precision of state estimations.

As an approach to improve precision, placing individual sensors to monitor cell temperature can be chosen. Of course, as any new approach did, this approach is also coming with questions such as, where the sensors should be placed, inside or outside of a cell, or which sensor type should be chosen for better data acquisition?

To answer these questions, during recent years, for intracellular and external cell temperature monitoring many researches have been made. To give a detailed perspective for the monitoring methods, a few different research results are presented in the following.

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Raijmakers et al. [19] proposed below methods for temperature indication methods;

- Thermo-resistive devices
    - Thermistors
    - Resistance temperature detectors
- Thermo-junctive devices (Thermocouple)
- Fiber Bragg-grating sensors
- Impedance-based temperature measurements
- Johnson noise thermometry
- Thermal imaging and liquid-crystal thermography

Each of these methods has different usage options related to their physical and data acquisition properties. Lee et al. developed a resistance temperature detector (RTD) [20] by using the physical vapor deposition (PVD) technique and placed it inside of a pouch cell as shown in Fig. 3. This method is very suitable for monitoring current collector temperatures for the cells manufactured in spirally wound form. At the same time, the physical strain-dependence of RTD sensors comes as a disadvantage. The coupling of these data strings is not wanted due to its bad effect on the accuracy of state estimation.

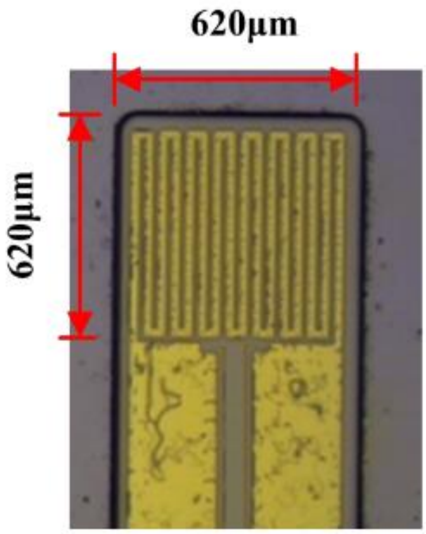

Figure 3: Optical microscopic photograph of the flexible micro temperature sensor.

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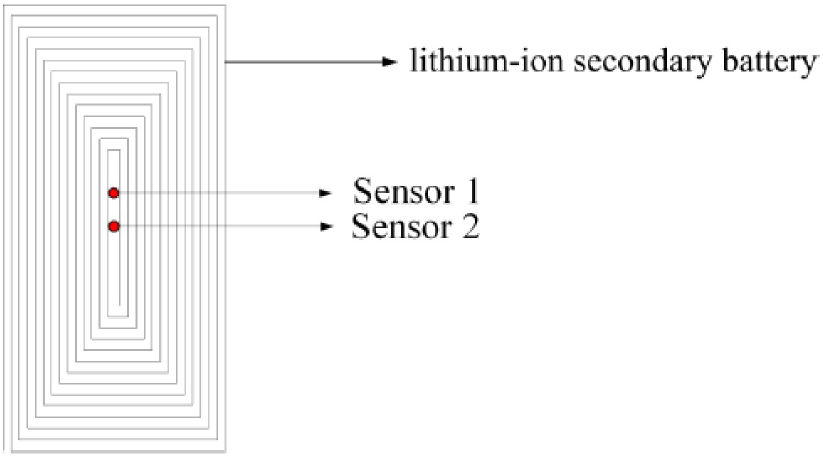

Figure 4: Position of micro temperature sensors in lithium-ion secondary battery.

In another study, Mutyala et al. developed a micro thermocouple by using a technique to fabricate polyamide embedded Thin Film Thermocouple (TFTC) sensors on glass substrates and later transfer them onto thin copper foils [21]. Mutyala et al., also placed the sensor inside of a spirally wounded pouch cell as shown in Fig. 5 by following the same placement method that Lee et al. used. But these intrusive methods come with some key requirements which the sensor shall have, like not tending to react with or dissolve in the battery electrolyte and shall not restrict the transfer of lithium ions between electrodes. Finally, a general requirement for any sensor can be to be suitable for different cell manufacturing methods.

Figure 5: Position of micro temperature sensors in lithium-ion secondary battery.

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The other cell types manufactured by using different methods, e.g. jelly roll or stuck structures, may be considered as other forms to imply micro temperature sensors. Non-specified thermistors have been used to monitor the temperature inside the mandrel of cylindrical cells since the cylindrical cell forms have non-uniform internal temperature distributions.

Another intrusive method for intracellular applications is using fiber Bragg-grating (FBG) sensors. Due to advantages such as small size, lightweight, passive nature, tolerance to electromagnetic and radio-frequency interference and high sensitivity, FBG sensors are capturing increasing attention.

A class of FBG is a microstructure within the center of an optical fiber that consists of a periodic modulation of the underlying glass material's refractive index. As broadband light directed inside the center collides with this periodic microstructure, one wavelength of the light is reflected while all other wavelengths of the guided broadband light pass through unaffected.

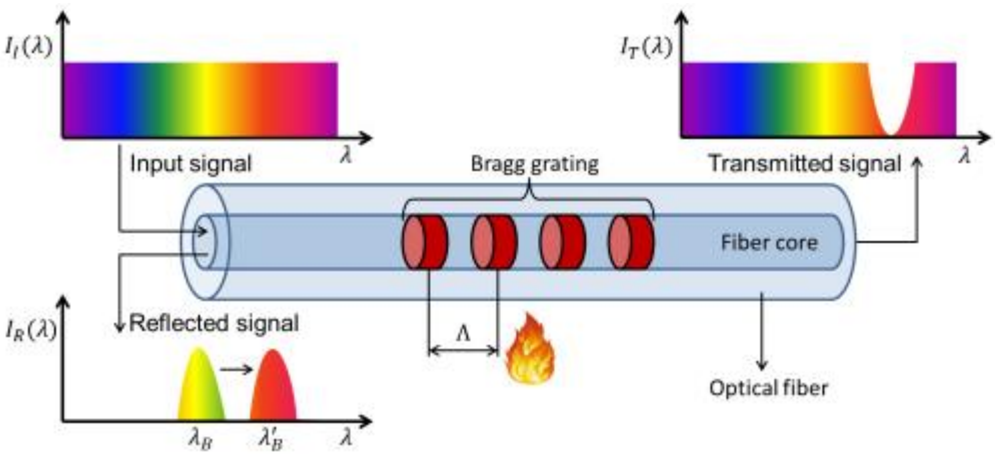

Figure 6: FBG sensor under the influence of heat

As another edge-cutting technology to monitor for example temperature, Electrochemical Impedance Spectroscopy (EIS) can be presented as a non-destructive technique for analyzing electrochemical mechanisms' behavior. EIS is widely used during cell characterization to measure kinetic and transport properties of electrode materials, as well as for aging studies, modeling, and SOC and SOH determination.

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However, by relating impedance parameters such as phase shift, real part, or imaginary part to temperature, EIS can also be used to evaluate the internal battery temperature.

In conclusion, the definition of suitable sensor type for the chosen cell type needs evaluation of different parameters e.g.; data acquisition quality, physical properties, chemical exposure durability, etc. The outcome of choosing the suitable sensor type will be more accurate state estimation and satisfaction of customer expectation about life duration.

4.3 Pressure Sensor

Pressure sensors are used for several purposes in battery packs. Placing a pressure sensor at the cell-level can be used as a safety indicator or placing it at module-level or pack-level can be used as a detection method of thermal runaway and venting which is an indication that at least one of the cells have a critical problem. During thermal runaway events not only, but extreme heat occurs also there can be observed toxic and flammable gas, which is also called venting gas [22]. This flammable gas output can increase the air pressure. At last, usually, these gases will be released because of the occurred high pressure by safety vent. However, after a short time, cell inside pressure will rise with temperature increment which results in rupture of the cell. Therefore, thermal runaway is wanted to be detected on cell level before it affects other cells [23]. For this reason, pressure monitoring is one of the significant methods for the detection of thermal runaways.

Koch et al. [24], investigated thermal runaway detect methods by comparing the different types of sensors. He chose also a pressure sensor, because the gas output, which is the outcome of electrochemical reactions during thermal runaway, can increase the internal pressure of the cell. In the study, it can be observed that the pressure sensor can detect thermal runaway approximately 5 seconds earlier than the temperature sensor. According to Chen et al. [25], pressure monitoring for lithium-ion batteries is an impressive method to diagnose the existence of thermal runaway, especially before the instantaneous temperature increase. Therefore, using a pressure sensor in addition to a temperature sensor is recommended.

Another purpose of usage of the pressure sensor in battery packs is using for SOC estimation. Yu et al. [26] established a State-of-Charge estimation model depending on based on stress measurement. Gross stress is measured by a pressure sensor during charging and

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discharging cycles. Further, as it can be seen in Fig. 7, the stress of the cell has a direct relation with SOC.

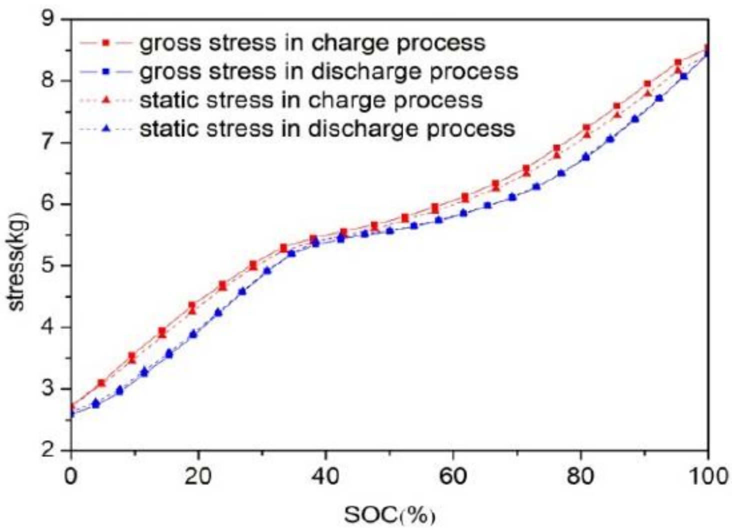

Figure 7: The stress curves under a charge/discharge cycle [26]

Due to the advantages of the pressure sensors, nowadays it is used in battery pack applications. For example, Sensata Technologies has a "Battery Pressure Sensor" for the detection of thermal runaway in battery packs [27]. In COBRA research project, a pressure sensor was also evaluated, and it will be used due to its contributions.

4.4 Electrochemical Impedance Spectroscopy

To ensure proper battery usage in electric vehicles, a variety of methods based on electrochemical impedance spectroscopy (EIS) have been proposed to have significant potential in estimating; SOC estimation, SOH estimation, cell core estimation and thermal prediction, which are key states to characterize battery condition. The change of EIS's low-frequency impedance has a significant influence on SOC. It is the only existing method to have a look into the cell without opening the cell mechanically.

EIS also changes as the battery ages and reaches a certain health state, demonstrating the ability to predict power fade or SOH. But, since the methods based on the relation are temperature sensitive, it's getting difficult to estimate the SOH at variable SOC.

Middlemiss et al. [28] describes the degradation parameters which can be evaluated to increase the accuracy of SOH and other related state estimations by using EIS as following;

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- Changes in porosity
- Decrease in electrode surface area
- Oxidation of conductive additive
- Current collector corrosion

Especially the ionic transportability is the main parameter being affected due to impedance change in the cell.

Wang et al. stated that the most suitable method to integrate EIS outcome is implying the measured EIS measurement data to battery management system [29]. To determine the Impedance of the cell an alternating current signal is applied to the cell and this current generates a voltage drop across the cell impedance to be measured according to $\mathbf{Z} = \Delta\mathbf{v}/\Delta\mathbf{i}$, as observed from the following figure, the shape of a Cole-Cole plot, as known as Nyquist plot, can be used to estimate its internal resistance.

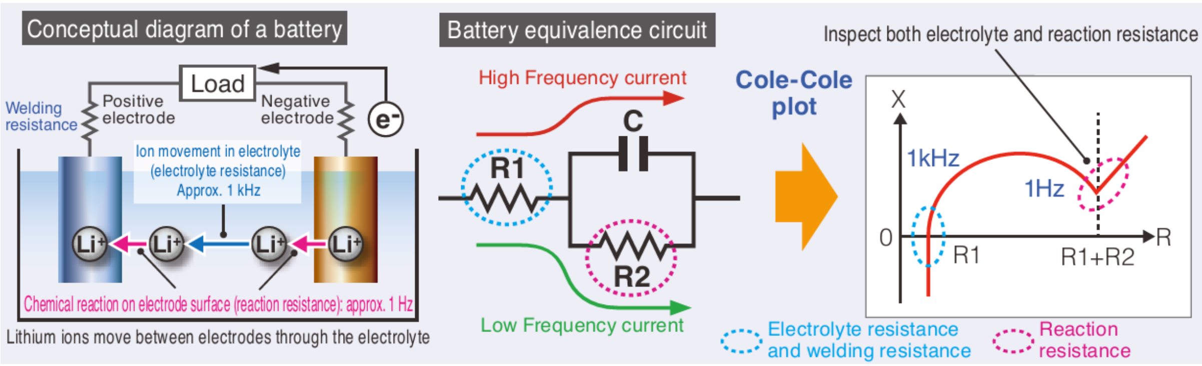

Figure 8: Principle of Impedance measurement

Middlemiss et al. [28] also used a method named third-electrode Fig. 9 which using a reference electrode between the anode and cathode, placed between a sandwich made by separators. This half-cell measurement gives us the separated electrode impedance data.

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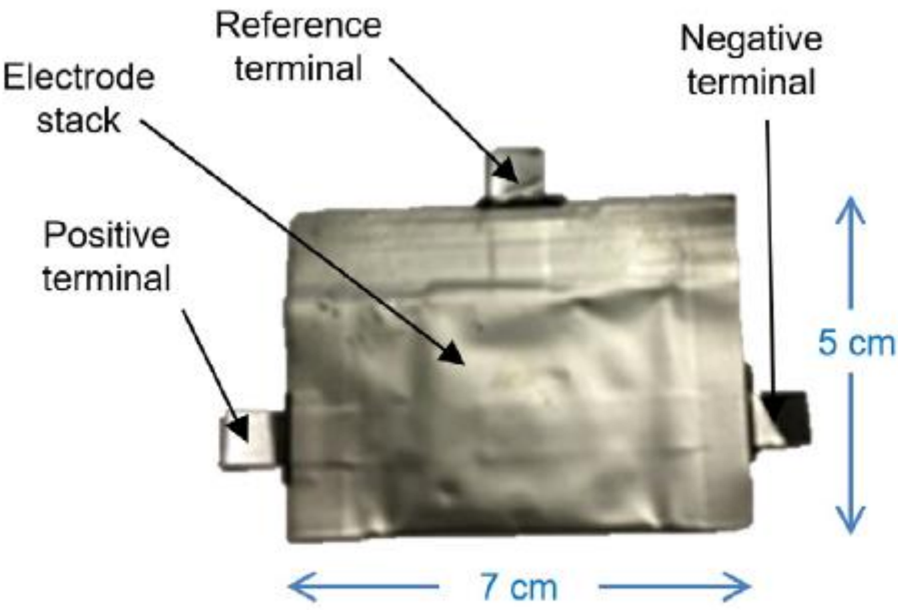

Figure 9: Three-electrode pouch cell which Middless et al. built

The conclusion can be given as that EIS measurement is quite important to provide more accurate state estimations. It will be investigated in more detail throughout the COBRA research project.

4.5 Gas Sensor

Gas sensors are used in HV battery packs for the failure diagnosis of the hazardous situations in which gas leakage occurs in a battery pack. A lithium-ion battery can be dangerous in case of extreme conditions, resulting in fire or explosion [30]. If a lithium-ion battery is exposed to external mechanical stress and overheat, or if there are abnormal electrical conditions such as over-charging, over-discharging, and external short-circuit, failure can be observed in a lithium-ion battery. Consequently, exothermic reactions, which are the reason for rapid temperature increase, can occur in lithium-ion battery and it can cause thermal runaway events [31]. Therefore, fault detection is significant to prevent thermal runaway and ensure safety.

There are several methods depending on voltage, current, and temperature measurements to detect battery failure. However, researches show that as a result of handicaps of these methods, gas detection has gained importance. Because fundamentally, gas sensors are easy to

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implement and have faster response [32]. According to Liao et al. [31], at the beginning of thermal runaway event, temperature, voltage, and current measurements are not clear to diagnose failure mode by the battery management system. Indeed, in a battery pack configuration with a significant number of cell in parallel on each stage, if one cell of the stage experiment abnormal condition and start to vent, this will neither easily nor quickly be detected on electrical signals from conventional voltage/current sensors.

Nonetheless, a distinguishable amount of gas can be observed, as a result of electrochemical reactions inside the lithium-ion cell. For this reason, gas sensors can provide failure detection earlier than other detection methods with high accuracy. As can be seen in Fig. 9 [31,33], temperature sensor, voltage sensor, and gas sensor are compared depending on their diagnosis and their reaction during thermal runaway. While the gas sensor detects around 7 minutes earlier than the appearance of thermal runaway, voltage sensor and temperature sensor detected fault signal approximately 6 minutes, 30 seconds respectively. In case of thermal runaway developed, if the necessary countermeasures have not been taken, thermal runaway will escalate to a hazardous stage in few minutes. After that, it is quite hard to reduce the destructive effects of thermal runaway. Hence, to prevent complete thermal runaway urgent measures must be taken after the fault signal is detected. Moreover, Fig. 10 also shows that while early detection of thermal runaway process provides protection of individuals, it also prevents fire or explosion of battery which results in important economic savings [31].

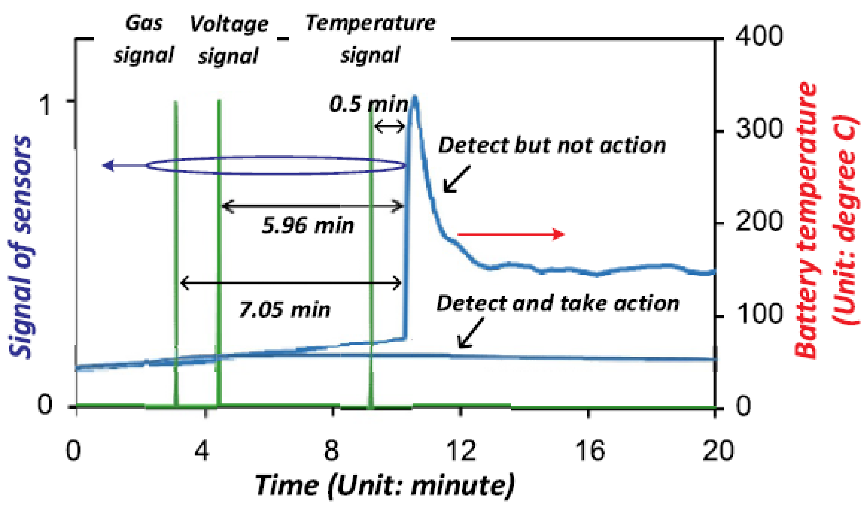

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Figure 10: Thermal Runaway Monitoring with Voltage Sensor, Temperature Sensor and Gas Sensor [31,34]

With the realization of advantages of the gas sensing, investigations and improvements on gas sensing technology of the HV battery pack has gained importance, and gas sensors came into use. There are several types of gas sensors. For example, in the study [1], catalytic type sensors are used for gas detection by Mateev et al. In consideration of CO (carbone monoxide) and CO_2 (carbone dioxide) concentrations can be compared easily with inherent levels, "Hanwei Electronics/MQ-7 [34]" gas catalytic type sensor is used. Thus, in this project, the necessity of a gas sensor has been considered, consequently, gas leakage detection will be provided by a developed gas sensor, based on photo-acoustic technology, with very high sensitiveness and accuracy.

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5 Summary

Current state-of-the-art battery packs consist of measurements of voltage, current, and module-level temperature measurements. These measurements create a strong basis for numerous state-estimation algorithms as well as the failure diagnosis components in the battery management system software. However, with increasing demand for electric vehicles and their hybrid combinations requires better estimates of the battery conditions mainly guided by the governments. While the current electrochemical, electrical, and data-driven machine learning methodologies provide sufficient accuracy, there is room for improvement and the suggested measurements that have been listed as "advanced" under this research are believed to support these state-of-the-art algorithms. Strain measurement, cell-level temperature measurement, pressure measurement, impedance measurement, and lastly the gas measurement provides a stronger basis for state estimation algorithms like State-of-Charge, State-of-Function, State-of-Health components as well as the diagnosis components to detect problems related to thermal runaway, sensor faults, measurement faults, communication problems, etc. These measurements could be used as an input to support the algorithms as well as provide redundancy in other forms of measurement. It is desired in many applications to use redundancy methods to measure certain quantities (e.g.: measuring pack-level current with various types of measurement methodologies). In particular, the importance of detecting thermal runaway a few minutes before it occurs with these advanced methods is receiving great attention in the literature, as human life is at stake. Since accuracies also increased with the state estimation algorithms, one can expect not only an increase in efficiency but also a significant increase in safety. These driving points form the basis of our research in the COBRA research project to investigate the data obtained from these advanced sensors to use them in the battery management system to get better estimates of the states and accurate representation of the battery cell models, as well as increased response times with earlier detection mechanism.

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