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Approach for a Systematic Assessment of Electrical Risks During Disassembly of Traction Batteries

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Abstract: The increase in sales of lithium-ion batteries for electromobility applications will be reflected in the development of waste generation with a corresponding time lag. In mobility applications, a battery already reaches its End-of-Life (EoL) at 80% of its initial capacity, which roughly corresponds to a useful life of 8-10 years. In this state of health, the batteries can either be thermally recycled or transferred to a stationary and therefore less demanding second-life application. The latter option is preferable from an environmental point of view, but confronts the recycling industry with the challenge of dismantling the battery in a non-deeply discharged state. Once battery cells are deeply discharged, they can no longer be reused, only recycled. However, during the disassembly of a non-deeply discharged battery there is a high risk of unintentional short circuits, which in the worst case lead to a thermal event. In this context, the present paper presents a method to systematically assess the hazard potential of individual disassembly steps regarding unintentionally caused short circuits. Based on a defined catalog of questions, a three-stage classification of the hazard potential is carried out. The results of the evaluation enable the derivation of efficient safety measures, such as a change in the disassembly sequence or the temporary use of pole caps. The developed method is exemplarily applied to the disassembly of a Nissan Leaf battery. In addition to the theoretical assessment, an Arduino-based sensor concept is presented, that can be used in combination with a battery dummy to measure conditions during a disassembly process, that would have led to safety-critical electrical currents under real conditions. In this way, the theoretically elaborated potential risks can be confirmed or mitigated by measurement.

Keywords: Traction Battery, Disassembly Process, Risk Assessment, Electrical Risk

1. Introduction

Due to the increasing demand for electric vehicles, the global demand for batteries is growing exponentially. This is accompanied by the demand for corresponding raw materials. Some materials contained in lithium-ion batteries are subject to supply risks due to geopolitical instabilities and resource scarcity (Kwade & Diekmann, 2018). Their extraction in general is associated with negative ecological impacts. Against this background, the sustainable design of the entire life cycle of lithium-ion batteries is becoming increasingly important. Battery systems of electric vehicles reach their EoL as soon as they have about 80% of their original capacity (Guenther, Schott, Hennings, Waldowski, & Danzer, 2013). This corresponds to a service life of around 8-10 years. Subsequently, the battery modules can be recycled with the aim of recovering raw materials, or they can be transferred to a less demanding second-life application. Both recycling strategies are preceded by the partial disassembly of the EoL-battery. To minimize the electrical risks during disassembly, the battery can be deep-discharged in advance. However, this excludes a second-life application. The safe dismantling of a battery that has not been deep-discharged in advance, requires a detailed and systematic analysis of the prevailing electrical risks and the derivation of appropriate safety measures. This paper presents a suitable method for this purpose.

2. Literature review

The risk potential of lithium-ion cells is based on their highly reactive active material chemistry. Thermal, mechanical or electrical overstress lead in worst case to a thermal runaway. During this event, exothermic chemical reactions are triggered inside the cell, allowing the oxygen of the cathode to react with the electrolyte. The chemical energy stored in the cell is explosively converted into heat. The resulting combustion can be self-sustaining and lead in worst case to complete destruction of the battery (NHTSA, 2014). In lithium-ion cells, this reaction is particularly strong due to the comparatively high energy density. In addition to external influences, a thermal event can also be the result of battery design errors or faulty implementation of charge, discharge and battery protection circuits. Cell-level failures resulting from manufacturing problems can also lead to thermal runaway of a cell. The presented paper focuses on the external influences on the battery during disassembly. In particular, the risk of causing a short circuit through moving parts like applied tools or dismantled parts is considered. In the following, we will refer to a short circuit caused by "moving parts".

2.1 Factors influencing the criticality of electric currents

Basically, the criticality of electrical currents during disassembly is subject to the influence of various factors. The heat caused by electrical currents and the associated probability of a thermal event, for example, depends on the internal resistance of the lithium-ion cells. This increases with age and doubles after about 350 charge and discharge cycles (Ji et al., 2021). Furthermore, the intensity of the thermal event is correlated to the state of charge (SOC) of the cells. However, due to other influencing factors, no critical SOC value can be specified, below which the occurrence of a thermal event would be practically impossible (Joshi, Azam, Lopez, Kinyon, & Jeevarajan, 2020). A significant influence on heat generation and dissipation in the event of a short circuit have the type and temperature of the medium surrounding the battery during disassembly (Mikolajczak, Kahn, White, & Long, 2011). The thermal stability of the cell itself depends on the composition of the anode material or age-related phenomena such as lithium deposits on the anode surface (Feng, 2019; Joshi et al., 2020).

In addition to the factors already mentioned that influence the criticality of electrical currents, there are many others that are not all mentioned here. Basically, a distinction can be made between those that must be taken as given and those that can be specifically influenced before dismantling in order to reduce risks. The latter includes, for example, the state of charge of the cells. Prior to disassembly the battery system can be discharged to a level that reduces the probability of a thermal event without being deep-discharged. Similarly, the ambient temperature could be reduced. However, the risk assessment method presented in this paper focuses on external influences that occur due to the disassembly process. The spotlight is on short circuits caused by moving parts.

2.2 Internal and external cell security mechanisms

To minimize the potential risks in case of a short circuit, lithium-ion cells are equipped with various safety elements to limit current flow or reduce temperature. For example the separator, a microporous layer between the anode and the cathode, serves a protective function. In the event of an unusual temperature rise in the cell, the resulting heat softens the polyethylene and closes its micropores. The so-called "shutdown" of the separator stops the ion transport between the electrodes and the current flow is interrupted (Laman, Gee, & Denovan, 1993). Moreover safety valves can be implemented, which open due to a sudden increase in pressure inside the cell and allow gases to escape. This prevents uncontrolled bursting of the cell housing and lowers the temperature inside (Balakrishnan, Ramesh, & Prem Kumar, 2006; Yao, Kong, & Pecht, 2020). The use of current interruptive devices, mechanical safety connections whose structure is destroyed when a critical internal cell pressure is reached, interrupts the flow of electrical current when gas develops inside the cell and places the battery in a de-energized state (Doughty & Roth, 2012). Positive Temperature Coefficient (PTC) thermistors reduce the flow of electrical current once an external short circuit occurs. The resistance of the PTC thermistor increases with increasing temperature. In this way, the current and the corresponding heating effect are greatly reduced. The change in the PTC thermistor is reversible. As soon as the battery temperature returns to the normal range, the PTC thermistor also returns to its low-impedance state, allowing the cell to function normally (Yao et al., 2020). In the event of failure, a PTC thermistor no longer exhibits electrical resistance. This can lead to a chain reaction in which the short circuit spreads to the other cells connected in series and destroys their PTC thermistors until all cells are short-circuited (Darcy, Davies, Jeevarajan, & Patel; Yao et al., 2020).

The safety of individual lithium-ion cells is demonstrated by manufacturers in certification procedures. However, a reliable function of cell-internal safety mechanisms in cell clusters is questioned in the literature (Jeevarajan; Pesaran, Kim, Smith, & Darcy, 2016). For this reason, other safety elements external to the cell are being integrated into traction battery systems. These include overcurrent protection devices such as fuses or conductor fuses.

3. Systematic assessment of electrical risks during disassembly of traction batteries

During the dismantling of traction batteries, different electrical subsystems are present with their respective connection points. When dismantled parts such as flexible cables are removed, there is a risk that two connection points with different potential could be connected unintentionally. The criticality of unintentionally caused electric current is systematically assigned to three criticality levels in this paper.

3.1 Questionnaire for the classification of criticality

In addition to the influences already mentioned in chapter 2, the probability of a short circuit occurring is also determined by the condition of the battery system at the time of the disassembly step, the disassembly process and the moving parts. For an evaluation of the criticality, it must first be clarified which electrical subsystems are present in the respective disassembly step and how far from each other the exposed connection points are. Only if it is possible to link the connection points of the electrical subsystems through the moving parts in the planned work sequence, a potential risk must be assumed.

Its severity depends on the electrical resistance of the moving parts. For the sake of simplicity, a distinction is only made between conductors and non-conductors. If two connection points of an electrical subsystem are linked by non-conductive battery components made of ceramic, glass or plastic, no safety-critical electrical currents are expected.

Otherwise, the short-circuit strength of the system is crucial. As presented in chapter 2.2 safety elements are integrated into the cells to limit electrical current and make them short-circuit proof. According to BAM, short-circuit proof simply means that the system does not exceed an "external temperature of 170 °C and no decomposition, crack, or fire occurs during the test or within six hours after the test" (Bundesanstalt für Materialforschung und -prüfung, 2018). However, without special tests, no statement can be made about how several electronically interconnected short-circuit-proof units behave in the event of a short circuit.

The mentioned considerations regarding criticality are shown in the flow chart in Fig.1. A low hazard potential is assumed if no electrical connection can be made between the exposed poles by the moving parts. If this is possible, the short-circuit strength of the system determines whether there is a medium or high risk.

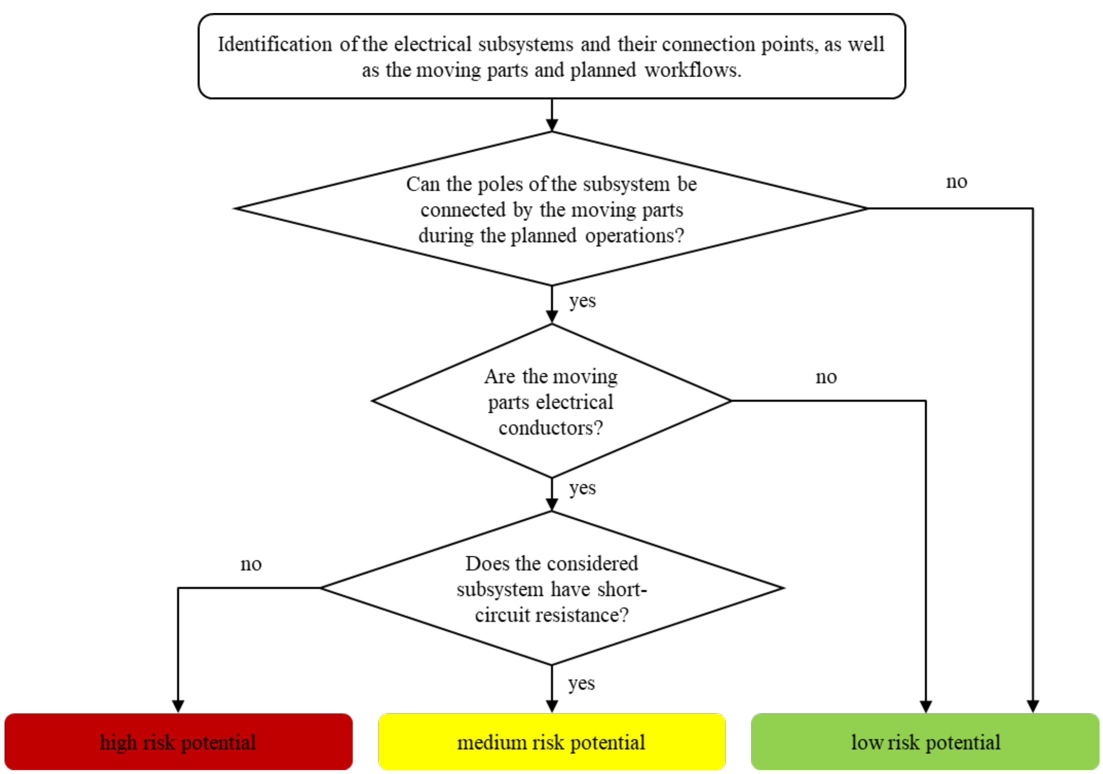

Figure 1. Flowchart for the evaluation of electrical risks during disassembly of traction batteries

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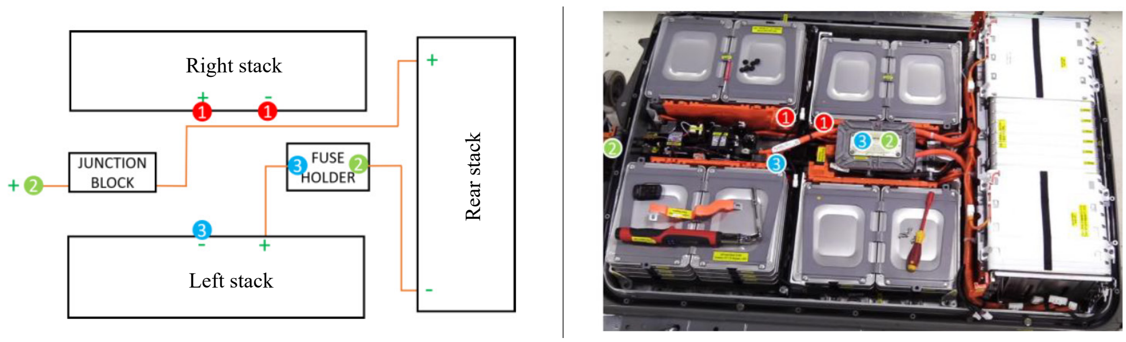
3.2 Application of the method to the disassembly of a Nissan Leaf battery

The risk assessment process shown in Figure 1 must be run through for each disassembly step. Before evaluating individual disassembly steps, the respective battery condition is analyzed first. For this purpose, the present electrical subsystems and the position of their exposed poles are recorded schematically as shown in Figure 2 using the example of the fourth disassembly step. In this disassembly step, a current-carrying connecting bridge between the two lateral battery stacks is removed.



Source: own representation Source: (Kelly, 2019)

Figure 2. Battery condition Nissan Leaf before disassembly step 4

Subsequently, the risk potential is classified for each combination of pole pair and dismantled part according the presented flow chart. As soon as a high risk potential is identified for a combination, the entire disassembly step is classified as highly critical. The results are documented in a comprehensible and clear table format. Table 1 shows an excerpt from the assessment of the disassembly of the Nissan Leaf battery.

Table 1. Excerpt from the evaluation of electrical risks of disassembly of the Nissan-Leaf-Battery

Disassembly step	*Disassembled part*	*Electrical subsystems with accessible connection points*	*Q1*	*Q2*	*Q3*	*Risk assessment - subsystem*	*Risk assessment - disassembly step*
Step 4	Connecting bridge	1	yes	yes	no	high	high
		2	no	yes	no	low	
		3	no	yes	no	low	

Once the evaluation of the entire disassembly process has been carried out in analogy to the procedure presented, the evaluation and derivation of necessary safety measures can be started. For the Nissan Leaf battery, a high risk potential was determined for 24 of the 48 disassembly steps. Particularly critical are the connection points of the right-hand battery stack after the removal of current-carrying connecting bridge (step 4) and of the left-hand battery stack after the later removal of a further connecting bridge. After the mentioned disassembly steps the pole positions are exposed and can be short-circuited by further dismantled parts until the stacks are removed from the battery housing. Another critical section during the disassembly process is between the removal of the plastic cover of the busbar and the separation of the modules coupled to it. Ten of the disassembly steps inbetween are classified as highly critical. By isolating the corresponding pole locations, the number of critical disassembly steps could be reduced from 24 to 4 in case of the Nissan Leaf battery.

4. Sensor concept for the detection of safety-critical electrical currents during the dismantling of traction batteries

In order to create a possibility to verify the theoretically determined risk potentials in the test field, a sensor concept was developed, that allows the detection of conditions that would lead to safety-critical currents during the dismantling of traction batteries. The detection of electrical currents on original battery systems is excluded due to the high risk potential. Alternatively, the measurement of electrical currents shall be performed on a battery dummy with a non-hazardous voltage level. The sensor concept is intended to detect conditions during the automated disassembly of this dummy that would lead to safety-critical electrical currents under real conditions.

4.1 Sensor concept

It is assumed that the battery dummy in which the sensor concept will be used, corresponds to an original battery in terms of its material properties, dimensions and the arrangement of the electrical contacts. However, the module housings do not contain lithium-ion cells, but are empty. Thus, they can be prepared with sensor modules. The sensor modules each consist of one voltage source, one resistor and one current sensor. The voltage source, for example a commercially available AA battery with a cell voltage of 1.5V, enables electrical currents that are measurable but harmless to humans. The current sensor is used to detect these. The resistor protects the voltage source from excessive discharge currents in the event of a short circuit. In order to detect and localize all short-circuit currents occurring during the dismantling of a battery system, each electrical subsystem is equipped with at least one of these sensor modules consisting of voltage source, current sensor and resistor. Figure 3 shows the setup schematically on three modules.

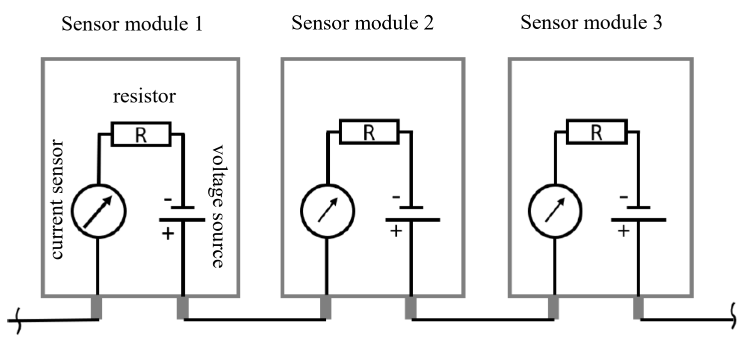


Figure 3. Sensor concept schematic

4.2 Technical realization

The sensor concept presented in chapter 4.1 was realized in an Arduino-based experimental setup. The individual hardware components were selected on the basis of a detailed requirements analysis. The decisive factor for the choice of power supply is the overall voltage of the system, which has to be in a range that is not critical for humans. At the same time, it must be ensured that the resulting electrical currents are large enough to be detected by the current sensor. The electrical resistance of the current-carrying components and moving parts that could cause a short circuit during disassembly have also be taken into consideration. The technical parameters of the individual hardware components must therefore always be adapted to the given framework conditions.

The core element of the realized experimental setup is an Arduino Mega with eight sensor modules. These each consist of a power supply with 1.5V, a current sensor ACS712 and a 2.7Ohm resistor. Each sensor module is assigned to an analog input pin of the Arduino so that localization of short circuit currents is possible. In order to record time and duration of the short-circuit current in addition to the modules involved, the RTC module DS3231 is integrated. For storage and later evaluation of the information a SD card module is implemented. The circuit diagram of the experimental setup is shown in Figure 4.

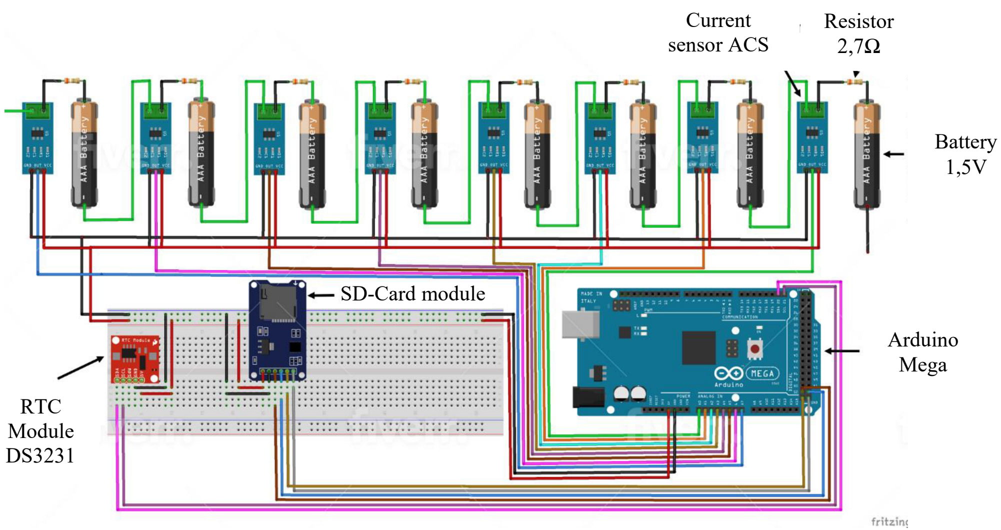


Figure 4. Circuit diagram experimental setup

After the setup of the individual components, each current sensor is checked in the program sequence with regard to the exceeding of a defined threshold value. If the threshold value is exceeded, a warning message is issued via the serial monitor of the Arduino's integrated development environment (IDE). The information about time and location is additionally stored on the SD card. If the threshold is not exceeded, it is checked whether it was exceeded in the previous time step. If this is the case, a message about the end of the short-circuit current and its duration is output and stored. If this is not the case, the state of the next module is checked.

5. Conclusion

This paper shows a method for systematic evaluation of electrical risks during disassembly of traction batteries. Based on a series of questions, which consider in particular the possibility of bridging two poles by a dismantled part, the electrical conductivity of the dismantled part and the short-circuit strength of the system, the classification is made into three levels of criticality. The evaluation of the disassembly procedure of a Nissan Leaf battery shows that about half of the disassembly steps have a high risk potential regarding unintentionally caused electrical short circuits. This evaluation enables the identification of safety-critical connection points of electrical subsystems during the disassembly process and the derivation of efficient safety measures, such as a change in the disassembly sequence or the temporary use of insulating pole caps.

In order to be able to confirm or mitigate the theoretically determined potential hazards of the disassembly steps by means of measurements in the field, an Arduino-based sensor concept was developed. This sensor concept can be used in combination with a battery system dummy and enables the detection of conditions that would lead to safety-critical electrical currents under real conditions.

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