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Approach for a Systematic Derivation of Risks During Disassembly of Traction Batteries

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Abstract: As a delayed consequence of the upswing in electro mobility the recycling industry faces an increasing volume of batteries from electric vehicles that have reached the end of their service life. Returned batteries are either thermally recycled or disassembled in order to recycle the component material or to prepare individual components for reuse in second life applications. Both manual and automated dismantling of high-voltage batteries is associated with risks that have so far been little studied. The literature review, which was carried out at the beginning of the investigations, shows that the dismantling process with regard to potential risks has so far only been considered selectively. Moreover, the few risks mentioned are mostly formulated globally and can only rarely be assigned to concrete dismantling steps. This paper presents an approach to systematically identify risks in battery disassembly. Thereby it focuses the automated disassembly process of high-voltage lithium-ion batteries from electric vehicles up to the recovery of individual battery modules. Using the derived methodological approach the paper shows the potential dangers of the individual dismantling steps chronologically, considering the disassembly process of various batteries. The underlying causes are named and appropriate preventive measures are presented. Using the respective probability of occurrence and the corresponding severity of damage as evaluation criteria, the risk of the identified hazards is finally assessed in three stages.

Keywords: High-Voltage Battery, Disassembly Process, Risk Assessment

1. Introduction

With measures such as the creation of purchase incentives, the expansion of the charging infrastructure and the granting of tax advantages, the German government is giving electric mobility a boost. The trend in new registrations in recent years shows that electric cars are becoming increasingly popular among the population. According to a forecast by the national electro mobility platform, one million electric vehicles are expected on German roads by 2022 (BMWI, 2020b). The figure is expected to increase almost tenfold by 2030. This boom in acquisition will be reflected in the disposal figures for end-of-life vehicles with a certain time lag. The most valuable element of a disused electric vehicle is its battery, which accounts for about 40% of the vehicle's total value added (BMWI 2020a).

The recycling of batteries that have reached the end of their useful life in electric cars can be done with different intentions. One is the recovery of valuable materials such as cobalt and nickel, the other is the reuse of individual modules in less-demanding applications like stationary energy storage (Deng, Denlinger & Miller 2020). Both options require in preparation the disassembly of the battery, which is currently done manually. Through targeted dismantling, material can be recovered in higher quality, the function of subassemblies can be maintained and harmful materials can be separated directly.

The major challenges to partially or fully automate the process are flexible handling of highly variable battery designs and small volatile batch sizes (Kwade & Diekmann 2018). However, the expectation of enormously increasing recycling volumes strengthen the efforts to automate the process.

In both the manual and automated dismantling process of batteries safety plays a central role. Two different viewpoints of the relevant regulatory requirements have to be considered, which sometimes are overlapping. On the one hand, there are regulations for the safety of the product, which is later placed in the market. For a battery pack you have to ensure e.g. the requirements according UN 38.3 [UN 38.3] for safe transportation. Addressed in the standard are failure modes which (mainly) leads to a potential thermal runaway. Such thermal runaway can cause severe risks or even damages in use [Williard, He, Hendricks & Pecht, 2006, Wang et al., 2012] but also have to be considered as potential risk during production [Abada et al., 2016]. On the other hand there are legal requirements for the safety of the machines in the manufacturing process. For European production and machinery built for these production facilities the European machinery directive is mandatory [Directive, M. (2006)]. Aim is to ensure worker safety during set up, operation, maintenance and troubleshooting. For this a risk analysis according to according to EN ISO 12100:2011 for the machine is required. Besides the risks of the machinery itself it also has to include the risk originated of the product during the production process, e.g. regarding Fire prevention and fire protection according to the harmonized standard EN ISO 19353:2016, which is also listed under the harmonized standards belonging to the machinery directive. While the standards and regulatory requirements demand that the risk have to be considered in the planning phase of the machinery design they do describe the methodology to derive the detailed risk causes. Since the risks in automated battery disassembly have been poorly considered so far, this paper presents an approach to identify risks and their causes in battery disassembly systematically. Thereby it focuses the automated disassembly process of high-voltage lithium-ion batteries from electric vehicles up to the recovery of individual battery modules.

2. Literature review

At the beginning of the study, a literature search was carried out to obtain an overview of the already known and documented risks in battery dismantling. It turned out that potential risks are never directly linked to individual dismantling steps. Instead, the potential risks involved in the general handling of batteries are dealt with. They can be classified into four categories: electrical, thermal, chemical and mechanical hazards. (Enderlein, Krause & Spanner-Ulm 2012, Gentilini, Mossali, Angius & Colledani 2020). Despite this classification, the various hazards are strongly interrelated.

Electrical hazards exist especially when the battery is not deep-discharged at the beginning of the process and all work must be done under voltage. This is the case if the battery is dismantled for the purpose of a second use of the modules. The present voltage level is >60V and the short-circuit current is up to ~2kA, so that simultaneous contact of both poles with an electrical conductor or even a body part should be strictly avoided (BMU, 2011). The current flow caused by a bypass also causes a strong temperature development, which can lead to overheating and a self-explosion. The occurrence of jet flames, the rapid spread of fire and flying parts in a small area are among the potential dangers to the immediate surroundings (Kabza, 2017). But even the disassembly of deeply discharged batteries involves risks due to the handling of health- and environmental critical materials. Mechanical damage to gas-tight sealed components of the battery results in gas leakage and the formation of health-critical or even toxic compounds. The gaseous reaction products are usually highly flammable and provoke a pressure rise of surrounded and gastight aggregates, which in turn increases the risk of explosion (Kwade & Diekmann 2018). Unintended mechanical forces on the battery cell can also lead to a thermal runaway (Zhu, Wierzbicki, & Li, 2018).

3. Systematic approach for the derivation of risks in battery disassembly process

While a classical Process-FMEA (VDA 2019) could be used to identify the risks during the disassembly process it would also be a very time consuming procedure (Cristea & Constantinescu, 2017). A reason for this is, that the process-FMEA is focused on all failure effects and not only on safety critical failures during production. But the structured analysis along the production process can be used to identify risks and potential mitigations as shown in Ranzinger for assembly processes for traction battery series assembly. (Ranzinger, 2012) Therefore the presented approach was developed to link the general risks briefly presented above to the individual steps of dismantling. This procedure allows the efficient identification of risky work steps and the prevention of hazards during disassembly through the early definition of appropriate preventive measures.

3.1 Determination of the sequence of the dismantling process

The basis for determining potential risks in individual work steps is knowledge of the exact process sequence. This must be determined anew for each battery type, since there are big differences in the design (compare Collijn & Johansson, 2019). To determine the dismantling sequence, a method in three steps was applied. First of all, the objective to be pursued by the battery disassembly was defined. Depending on the further processing of the individual components, it can be determined how finely the battery must be disassembled and which tools can be used. A possible goal of the disassembly can be, for example, the use of intact modules in another less-demanding application. For this purpose, the battery pack needs to be disassembled down to the module level under the condition that the end-of-life battery is not deeply discharged in the beginning.

In the next step, the sequence in which the individual components can be dismantled is developed. Assembly or disassembly instructions for the respective battery pack are helpful in accomplishing this task. In addition, the Internet provides not only literature sources but also freely available image and video material on dismantling common battery models. If dummies are available, they can also be used to test and optimize the considered sequence. If the dismantling sequence is fixed at component level, the required work steps are added in the last step. This results in a detailed sequence plan for dismantling the traction battery. Figure 1 shows the described procedure graphically.

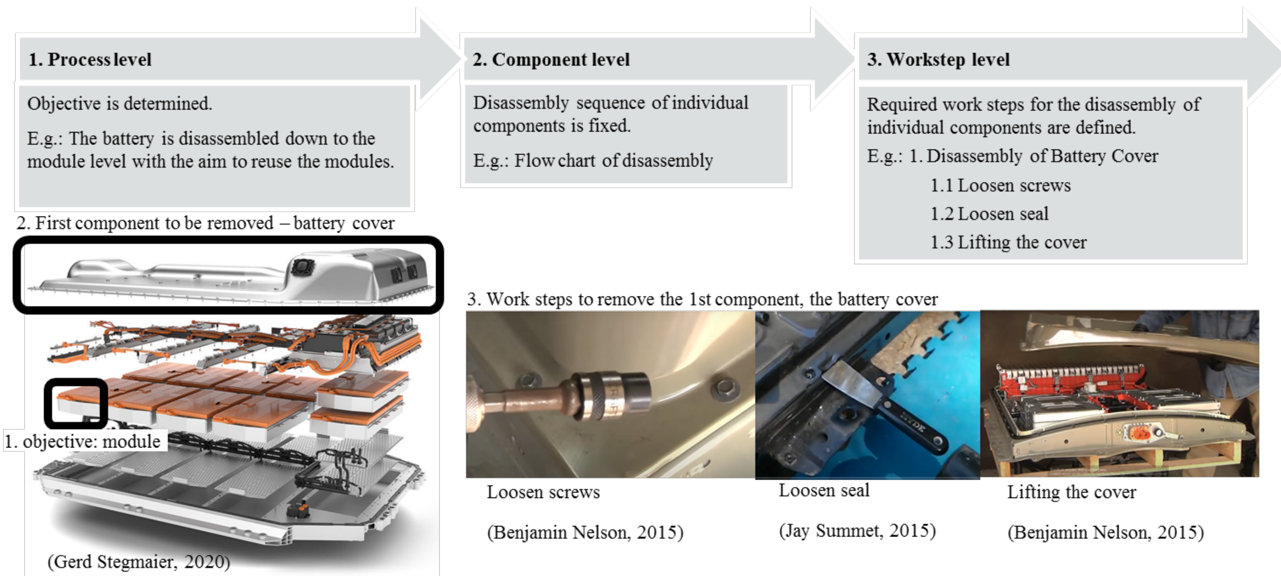

Figure 1. Determination of the sequence of the dismantling process

3.2 Examination of each individual work step regarding potential failures

Based on the dismantling procedure worked out in the previous step, the individual work steps are now examined for potential failures. An important factor in the consideration of possible errors are the used tools, their control and handling. In addition, the error determination is not only based on the disassembly of a faultless battery, but also considers batteries that show clear signs (Kwade, 2018) of use or wear. For example, it is taken into account that the screws to be removed jam during dismantling due to heavy rust. For each possible error a failure type, a cause of failure and an appropriate preventive measure are defined. The results are documented as shown in table 2, which shows the results of the first process step “Disassembly of battery cover” as an example.

Table 1. Template for examination of individual dismantling steps

Tool	**Type of failure** **(failure mode)**	**Cause of failure**		**Preventive measure**
1. Remove of battery cover				
1.1 Loosen screws of battery cover				
robot-operated screwdriver	Mechanical forces on the cell	Collision of screwdriver with cover	A	Ensure secure guidance of robot-operated screwdriver through e.g. pre-visualization of the robot movement
		Screw sticks so that battery is released from clamping	B	Screwdrivers with torque limitation
1.2 Loosen seal of battery cover				
Chisel	Electric contact	Chisel inserted too deep into battery	C	Define the maximum distance the chisel may be inserted
	Mechanical forces on the cell	Chisel tip meets not only seal but also housing	D	Ensure a controlled and guided application of force with appropriately thin chisel
1.3 Lifting battery cover				
Robot arm with vacuum lifter module	Electric contact	lifter loses battery cover	E	Ensure a secure grip by considering the battery cover geometry, tolerances and surface finish
	Damage to the diagnostic connector	Cover jams during lifting process and exerts lateral forces on diagnostic connector	F	Take into account the center of gravity of the cover in order to an evenly lifting

3.3 Risk assessment of potential failures

The risk posed by the identified causes of error is estimated on the basis of their probability of occurrence and the expected severity of damage. The German accident insurance VBG proposes a five-level evaluation scale, resulting in either a low, medium or high risk (VBG Ihre gesetzliche Unfallversicherung, 2019). Due to the consideration of a new process with hardly any previous experience, a three-step scale is recommended, which leads to the same result. The evaluation is carried out in a matrix as shown in Table 2 for all potential failure identified in the previous step. For the unambiguous assignment of risk to cause of failure, each cause of failure is assigned a capital letter in Table 1, which can also be found in the risk matrix in Table 2.

Table 2. Adapted template risk matrix (VBG 2019)

1. Disassembly of battery cover		**Severity of damage** No health effects	Moderately severe consequences (no permanent injuries)	Severe consequences (irreparable permanent injuries possible)
Probability of occurence	Nearly impossible			E, F
	Quite possible	A, B, D		C
	Almost certain			

low	medium	high

3.4 Representation of the results

For a first planning step of the automated disassembly and to get a comprehensive overview a condensed risk table along the disassembly process was derived based on risk table as shown in Table 2 for an analysis involving two different traction batteries: Nissan Leaf and General Motors Bolt. This battery types have been chosen to evaluate the proposed risk analysis due to the available online resources for the disassembly process (Nelson, 2015, n.n., 2012, Summet, 2015, Kelly, 2017).

For the overview all possible failure causes for each failure are added up (see Table 3). Note that each failure cause can occur multiple times in one process step which is not reflected in the table (e.g. if the chisel has to be inserted n times to unseal). The risk matrix gives therefore the possibility to reflect where the focus for additional engineering efforts to minimize the risk due to additional preventive actions should be addressed.

Table 3. Risk matrix for all disassembly steps

			disassembly steps																																						
			1. Remove upper housing and seal			2. Remove electrical connection plugs			3. Remove cover from battery isolating relay unit			4. Remove charger connector plug			5. Remove battery isolating relay unit			6. Remove inner coolant hose			7. Remove Battery Management System			8. Remove wiring harness (low + high voltage)			9. Remove diagnosis connector plug			10. Remove busbars			11. Remove battery module connectors + separators			12. Remove high voltage heating system			13. Remove battery modules		
Failures	1	Short circuit HV	1	2						1			1			1			1			1						1				1					1				
	2	Electrical short circuit														1							1																		
	3	Mechanical forces on cell				1			1				1				1		1			1					1					1		1	1						1
	4	Electrical short circuit HV		4												2			4				2									1									
	5	Electrical shortcut signal/diagnosis Lines		1																			2		2																
	6	Damage to high voltage terminals				2																																			
	7	Damage charge connector										1																													
	8	Damage Battery Disconnector Relay													1																										
	9	Damage busbars													1																										
	10	Damace connectors																1																							
	11	Damage coolant hose																1																							
	12	Damage Battery Management System																					1																		
	13	Damage temperature Sensors																						1												1					
	14	Damage low voltage connectors																						1																	
	15	Damage pole cover																														1									
	16	Drop and damage to the battery																																1							
	17	Damage to the coolant connection																															1								
	18	Damage to the insulation pad																															1								
	19	Damage to high-voltage heating systems																																		1					
	20	Damage to busbars on Pack																																					1		
	21	Damage to the individual modules																																						1	
		Sum of potential causes	1	7	-	3	-	-	1	1	-	1	2	-	2	4	1	2	6	-	-	2	6	2	2	-	1	1	-	-	-	4	2	2	1	2	1	-	1	1	1

4. Conclusion

The presented approach already achieved promising results for the derivation of requirements due to safety for the planed automated disassembly unit for traction batteries. Since the concepts for each step of disassembly are in an early design phase a permanent update along the development process for the machinery of the disassembly unit will be carried out. The results will used as an input for the mandatory risk analysis according to machinery directive as well as for the Process-FMEA to ensure the product quality in later design phase.

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