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Julien Chauvin, Daniel Chatroux, Laurent Garnier, Philippe Azais, Rémi Vincent. Key points regarding electrical safety in small cylindrical Li-ion cell assemblies during overcharge or partial short-circuit.. PCIM 2023 - International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, May 2023, Nuremberg, Germany. pp.399, 10.30420/566091053 . cea-04250049

HAL Id: cea-04250049

<https://cea.hal.science/cea-04250049v1>

Submitted on 19 Oct 2023

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Key Points Regarding Electrical Safety in Small Cylindrical Li-Ion Cell Assemblies During Overcharge or Partial Short-Circuit.

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Abstract

Safety of lithium-ion batteries is a key criterion for large-scale deployment as for electrical vehicles. When Li-ion cells are abused, serious consequences can occur, the worst-case scenario being the thermal runaway. Although easy to manage for small devices, electrical safety is a new challenge for increasingly powerful systems. However, standards for electrical design and abusive testing do not always seem to be appropriate for these high power systems. In this work, an improved scheme of the overcharge test has been proposed, allowing representative stresses of the system to be applied to a cell. Tests on 18650 size cylindrical cells equipped with Current Interrupt Devices CID have made it possible to trace the beginning of the safety zone of this element for the first time. This work investigates the relationship between the size of a battery system, the electrical architecture, the constraints on cells in case of electrical defect and the switching capacity of the integrated elements of the cells.

1 Introduction

In less than 30 years, small cylindrical lithium-ion cells have moved from low voltage consumer applications (e.g. laptops or power tools) to much larger systems. A famous example is the first Tesla Inc. electric vehicles (Roadster, Model S, and Model X) which used thousands of 18650 type cylindrical cells.



Notebook battery
8 cells in 18650 size
4s2p type assembly
Max. open circuit voltage: 16,8 V



Tesla model S battery (2014)
8 256 cells in 18650 size
96s86p type assembly
Max. open circuit voltage: 403,2 V

Fig. 1 Example of two battery packs composed of the same cells format for a laptop and Tesla car.

For example, and as shown in Fig.1, small cylindrical cells were initially used in very low voltage applications, below 50 V, with on-board energies below 100 Wh, such as laptop batteries. Due to the low cost of this cell format and the production capacities already available, this cell format was then reused in applications such as electric vehicles, with voltages around 400 V and energies of more than 50 kWh. Although this format is not popular in the electric car sector in

favor of larger capacity cells, other more marginal applications or less renowned manufacturers continue to turn to small cylindrical batteries because of their ease of access. However, as systems have grown and diversified, the complexity and criticality of safety has increased and remains an ongoing problem. When a Li-ion cell is placed in an abusive situation (electrical, thermal, or mechanical), the degradation of the cell's components generates exothermic reactions that can lead to smoke, fire and explosion. This worst-case situation is called thermal runaway (TR) [1]–[3].

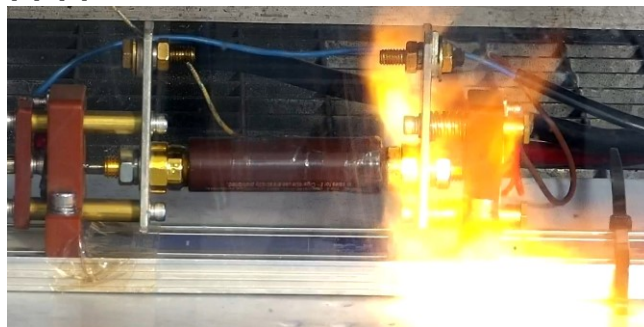


Fig. 2 Photograph of a cell during thermal runaway.

Regarding electrical protection, the batteries are mainly protected against overcharge and short-circuit at the system level. Nevertheless, if the fault occurs upstream of these protections, the cells are subjected to very high stresses. These cells can

be equipped with protection devices but this component is not specified and it's not possible to compare their breaking capacity to the real stresses in case of electrical defect.

In this work, the consequences of a fault not protected by the system protections of a battery pack are investigated. Firstly, by assessing the possible stresses applied to the cells in this case. Secondly, by studying the synchronization of the protections integrated in the cells, which can have an influence on the distribution of the stresses. Finally, by evaluating the breaking capacity of a CID integrated in a cylindrical 18650 cell, using a representative overcharge test scheme and a dedicated metrology.

2 Electrical safety in Li-ion battery packs

From an electrical point of view, Lithium-ion batteries must be protected in terms of voltage and current in order to remain within the safety zone of the electrochemical system [4]. For the voltage, cells must be kept within the recommended minimum and maximum voltage ranges (typically, 2.5 V and 4.2 V respectively for Nickel Cobalt Manganese (NMC) types cathodes vs graphite anode). This ensures that cells does not overcharge or overdischarge [5], [6].

Charge and discharge currents must not exceed their respective maximum values given by the manufacturer.

To ensure this, several system-wide protections can be placed. Safety devices are also integrated in cells.

2.1 System-wide protections and faults

Concerning the electrical protection of battery packs, safety is generally ensured by two means at system scale:

- The Battery Management System (BMS) composed of electronic boards and usually a system of opening the general circuit as a high power relay [7]. It provides voltage monitoring of all the cells as well as their balancing, current measurement and other more advanced functions. It therefore ensures normal system operation but also incorporates safety functions by interrupting the general charge or discharge current.[8], [9]

- General fuses. These fuses are installed in pairs on each pole to prevent short circuits between one pole and another point of the electrical circuit. These fuses are protection elements studied and designed to cut the fault current under the

maximum voltage of the battery pack. Their breaking capacity can reach several hundreds of thousands of amperes at 400V. Because of insulated circuit (IT), the minimum of two fuses is mandatory to protect the circuit with an insulation defect in the battery and the other on the rest of the circuit.

However, they do not protect the pack when the fault occurs upstream of them or in the case of a BMS fault for example or a double insulation fault inside the battery pack. In this situation, without additional fuses, elements integrated in the accumulators will have to interrupt the fault current.

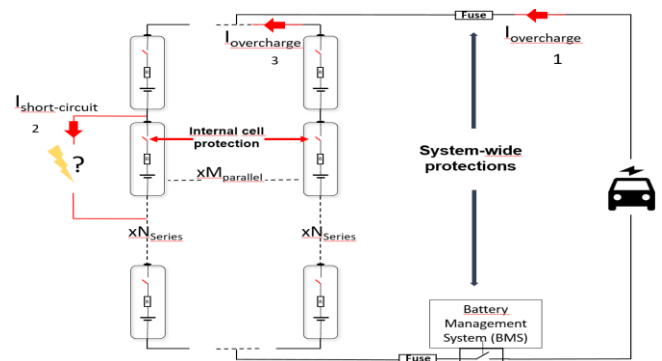


Fig. 3 Simplified diagram of a general overcharge (1) or a partial short circuit (2) leading to an overcharge of a parallel branch (3) in a battery assembly.

In this case, and depending on the architecture of the system, the batteries may be subject to strong positive (short circuit) or negative (overcharge) currents [10].

Fig.3 shows the case of a partial short-circuit in a cell assembly causing:

- A short circuit of the cells across the fault (2).
- An overload of the remaining cells of the branch by the parallel branches current (3).

2.2 Protections integrated in cylindrical cells

With the initial objective of electrically protecting very low voltage battery packs (e.g. for laptops) based on a few small cylindrical cells, manufacturers have developed and integrated protections aimed at separating the electrochemical core of the accumulator from the abusive circuit [11], [12]. These elements, which may or may not have been designed as current interrupters, are not specified as electrical protection and cells manufacturers give very limited information about them, even though their role may be central to the electrical safety of a battery.

Among the protections integrated in cylindrical accumulators, we can mention the Positive Temperature Coefficient (PTC, or resettable fuses)

which is a conductive material whose resistivity evolves exponentially with temperature [13]. Its limits in terms of breaking capacity have been demonstrated by previous studies. It has shown that its use was ineffective for voltages higher than about 30 V or more depending on the cell references [14], [15].

An even more popular integrated safety device in cylindrical cells is the Current Interrupt Device (CID). The CID is an element integrated in most of cylindrical cells with the aim of electrically disconnecting the positive terminal of the cell with the internal electrochemical core of this one as soon as the internal pressure of the cell exceeds a given value. It is composed of two disks linked together by one or more welds, which ensure their mechanical but also electrical connection. The lower disc is electrically connected to the electrochemical core of the cell. This is perforated to allow the generated gases to pass through. The gases therefore apply its pressure to the second disc, which can then deform and break the weld. This interrupts the electrical circuit simultaneously. When the cell is abused, especially during the overcharge, the materials generate gases [6], [16].

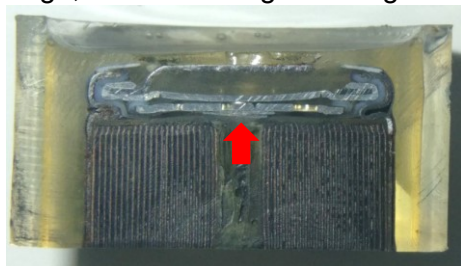


Fig. 4 Photograph of the cut and put in resin positive terminal of a cylindrical battery equipped with a CID.

As soon as cell's internal pressure reaches about 10 bars, the upper membrane deforms and breaks the weld, causing the electrical circuit to be interrupted [17]. Acting as a contact that opens inside the cell, it is also subject to breaking capacity problems.

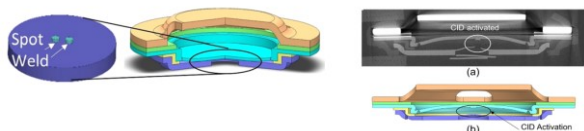


Fig. 5 3D model of a CID before activation (left) and CID after its activation (right; (a) X-ray (b) 3D modelling) reproduced and adapted according to [17]

Initially sized to interrupt twice the voltage and twice the current of a single cell, according to transportation standards, this protection and its

limits in terms of breaking capacity are more complex to study than other protections like PTC. Previous works [18], [19] have highlighted the limitations of the CID without specifically investigating the reasons, or without relating the limits of this element to the consequences on the cell [20].

3 Stress distribution of a fault in a battery pack

There are different ways of interconnecting the cells and these architectures can have different consequences on the electrical safety.

3.1 Influence of electrical architecture on cells stress distribution

The most popular ways to electrically connect cells are (Fig. 6):

- Series connection of parallel cells
- Matrix connection
- Parallel connection of branches in series.

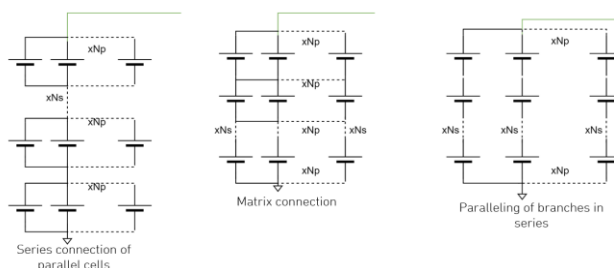


Fig. 6 Example of three classical battery pack architectures.

Depending on this architecture, the stresses applied to the cells during the event of a fault not protected by the system protections may vary. For example, “matrix” and “parallel branch” architectures may present cell overcharges between branches (Fig. 3). This is not the case in the “series connection of parallel cells” architecture.

However, in all architectures with cells in parallel, the fault current is distributed between them.

At this moment, the built-in cells protections must interrupt the current. If the opening of the circuit is synchronized, then the protections interrupt a fraction of the fault current (Fig. 7, left).

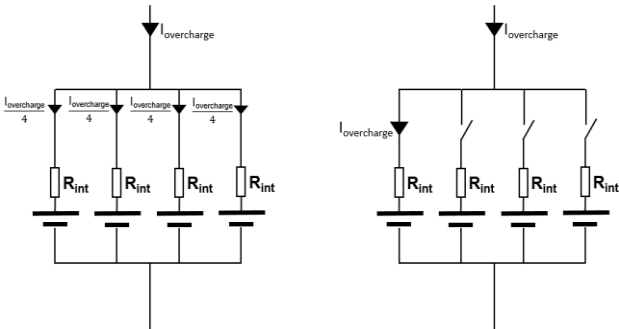


Fig. 7 Distribution of currents in the event of non-synchronization of the protections integrated in cells connected in parallel.

Otherwise, the last parallel cell or string to open must interrupt the total fault current under various voltage depending of the fault current loop (worst case been the full pack voltage) depending on the location of the fault (Fig. 7, right).

As far as we know, no data on the dispersion time of the opening of the CID between cells in parallel is available.

3.2 Time dispersions of CIDs in cells assemblies

When putting electrical switching devices in series and in parallel, it is essential to have them as synchronize as possible. Otherwise, a single switching device interrupts:

- the entire current under the full voltage of the fault current loop in a parallel connection
- the full voltage of the fault current loop in a series connection

This characteristic, much studied in power electronics (e.g. on transistors), does not seem to have been the result of such a study for cells with CID. It is therefore essential to know the temporal dispersion of these devices, to find out the maximum stresses experienced during a fault.

To investigate this, we performed overcharge tests on three cells in parallel (Fig. 8).

Identical cylindrical cells from the same batch were used. The voltage across the cells and the charging current of each cell were recorded (Fig. 9).

The results of this test demonstrate non-synchronization of the opening of the CIDs with time lags of the order of a second.



Fig. 8 Photograph of the experimental installation. Three cells in parallel in a test chamber before the experiment.

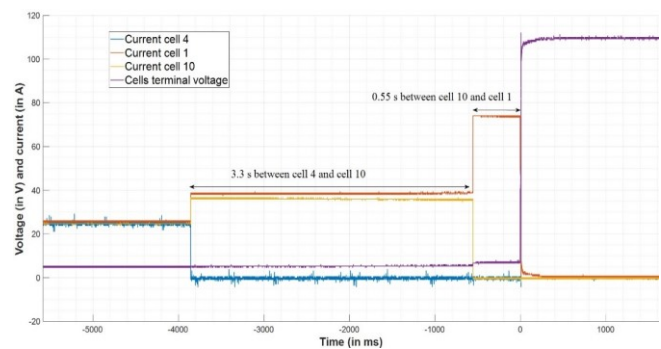


Fig. 9 Oscillogram of an overcharge test on three identical cells equipped with CID in parallel.

Indeed, as shown in Fig. 9, the current interruption timeline is as follows:

- Cells are overcharged by an equal current of 25.33 A per cell.
- The first cell to open is cell no. 4 at $T = -3859.6$ ms. The overcharge current of this cell is then distributed between the two others. The current is now 36 A for cell no. 10 and 38.75 A for cell no. 1.
- The second cell to trigger its CID is cell no. 10 at $T = -559.8$ ms, i.e. approximately 3.3 seconds after cell n°4.
- The last cell no. 1 then receives the full current, i.e. 75 A, until its CID is triggered at $T = 0$ ms. At this point, the CID of cell no. 1 must interrupt 75 A under a voltage of 110 V. There then follows a period of electric arcing when the current is interrupted and the cell vents, a phenomenon not observed on the other 2 cells. This temporal dispersion is mainly explained by the mode of operation of the CID. Although its mechanical triggering presents little pressure dispersion, the generation of gas inside Li-ion cells depends on a multitude of parameters.

4 Representative overcharge test of a single cell at system scale

The overcharge test is a mandatory normative test for Li-ion cells. It was originally designed for the transport of individual cells with e.g. the UN38.3 standard. It imposes an overcharge of the cell at twice its maximum voltage or more (e.g. 8.4 V for a battery with a maximum voltage of 4.2 V) at a current twice the recommended charge current.

As shown in the previous part, a single cell can end up interrupting currents and voltage that are proportional to the size of the system, especially due to the time dispersion of integrated switching elements like the CIDs.

In order to apply representative system-wide stresses to a single cell, higher voltage and current overcharge tests must be performed.

4.1 Overcharge test: a new representative scheme

Usually, the overcharge test is carried out with a stabilized power supply using CC (constant current) and CV (constant voltage) modes.

However, the overcharge test with a power supply connected to the Li-ion cell as suggested in the regulations is not correct due to the presence of filtering capacitors at the power supply output. Depending on the power supplies, the output capacitor value can reach several tens to thousands microfarads.

When the abused cell's CID opens, these capacitors produce a switching aid, producing zero voltage switching (ZVS).

The Fig. 10 shows an overcharge test performed according to the standard scheme.

The overcharge current is regulated by the power supply and the voltage is imposed by the accumulator (Fig. 10 central image phase 1). When the CID opens, the current is interrupted and the filtering capacity at the output of the power supply is charged to the voltage of the accumulator (phase 2). Finally the power supply charges its capacitors until it regulates at the required voltage (phase 3). In this case, the output capacitance of the power supply used is 7560 μF according to the data sheet.

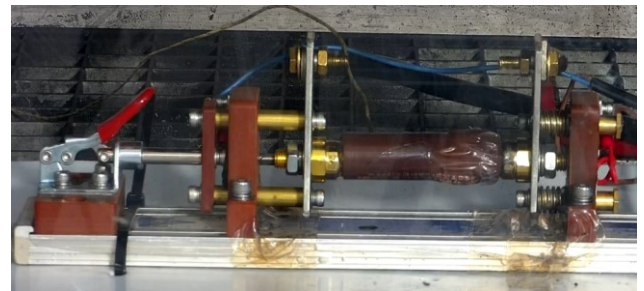
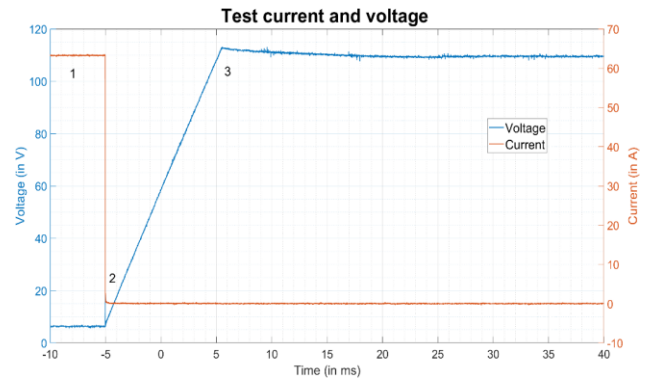
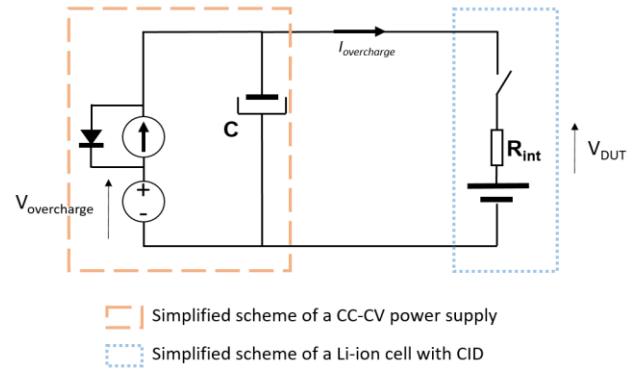


Fig. 10 Overcharge test (110 V and 63 A) on a Li-ion cell using standard circuit. Standard test scheme (top) - Waveforms during CID opening (Center) - Cell after the test (bottom)

The breaking capacity of the CID is not evaluated and the CID seems to protect efficiently the cell in this situation. To make the test realistic, a modified scheme of the classic overcharge test was implemented (top part of the Fig. 11).

In this test, a power resistor limits the current to apply the voltage directly when the CID is opening, as in a real case.

The value of this resistance can be calculated according to the following Eq. (1).

$$R = \frac{V_{Overcharge} - V_{DUT}}{I_{Overcharge}} - R_{int} \quad (1)$$

This resistance limits the overcharge current to the desired value.

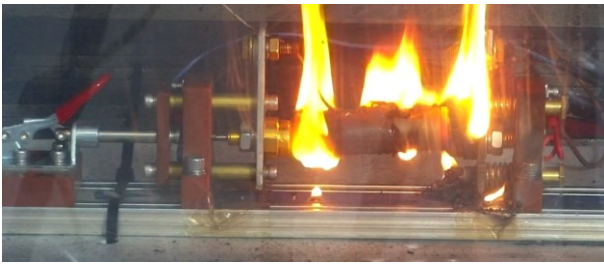
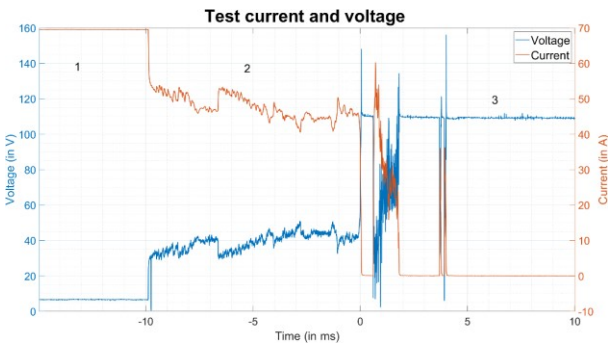
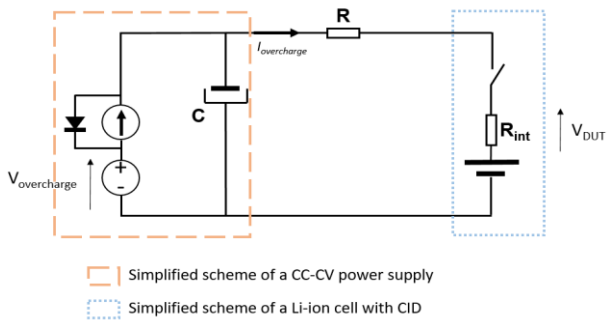


Fig. 11 Overcharge test (110 V, 70A) on a Li-ion cell using proposed circuit. Proposed test scheme (top) - Waveforms during CID opening (Center) - Cell during the test (bottom)

In this way, the power supply no longer operates in current regulation mode but in voltage regulation mode. As a result, the output capacitors are charged to the set voltage during the entire overcharge test. When the CID is opening (phase 2 of the central image), the voltage of the circuit is instantly reapplied, as in the real situation.

As shown in the figure above, an electric arc can be created and maintained, demonstrating a limit of the CID's breaking capacity. The current in the circuit is only interrupted when the battery is destroyed (phase 3 of the central image). This limit can lead to serious consequences for the safety of the battery, which will be studied in the next section.

4.2 Safety area of a cell equipped with CID

Cells equipped with CID have a safe operating area, which can be evaluated thanks to the proposed circuit. If this limit is exceeded, there is a risk of thermal runaway. To initiate the evaluation of this area, eight overcharge tests were carried out on the same cell reference.

The summary of the results is presented in Fig. 12.

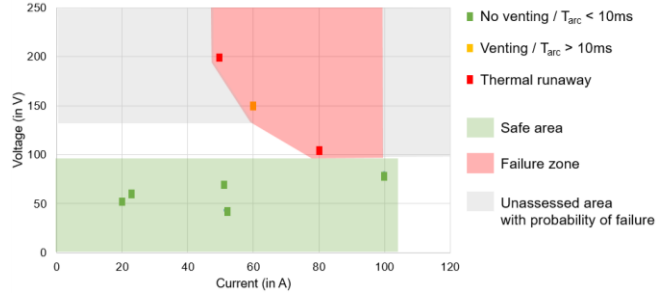


Fig. 12 Safety area of the cell tested with the representative overcharge proposed scheme.

The green dots represent the accumulators for which the CID was able to interrupt the current without the electric arc generated being maintained long enough to cause damage to the cell. An arc time of less than 10 ms has been observed in these cases.

For the orange and red dots, the electric arc during the opening of the CID was not interrupted before either the destruction of the cell (red dots) or an ejection of gas and additional overheating (orange dot). In both cases, the safety of the battery is no longer guaranteed.

The grey areas represent the areas that have not been tested but where it is probable that the breaking capacity of the CID is exceeded. Indeed, higher currents and voltages are favorable conditions to maintain the arc and therefore the assumption of non-interruption by the CID in these cases can be made. Further tests should be carried out in these areas, if the application requires it.

In conclusion, the safety area presented proves a limit to the breaking capacity of the CID for voltages above 100 V and a current of 80 A. These values are valid in the case where a representative test scheme is used and only for the tested cell reference. This safety area should be evaluated according to the battery packs specification for the selected cell.

5 Experimental details

All abusive tests were carried out with identical 3.0 Ah Nickel Cobalt Manganese (Ni-rich NMC811) cathode vs graphite + SiO_x anode commercial cylindrical cells (18650 format). Cells were from the same batch.

In order to perform high-frequency voltage and current measurements, specific metrology has been implemented. Indeed, due to the separation between the abusive test rooms and the oscilloscope with an unknown coaxial cable length for security reasons, conventional high-impedance metrology could not be used. Low impedance current and voltage probes were therefore produced. This specific metrology is the subject of a dedicated publication named "High-Frequency Voltage and Current Probes for Measurement at Distance with an Oscilloscope" also published in PCIM 2023.

6 Conclusions and outlook

A series of overcharge tests were carried out on small cylindrical cells (18650) equipped with CID.

On three identical cells overcharged in parallel, 3.85 s separate the opening of the first CID and the third. We have the same results for cells in series. As a result, in the event of an internal electrical fault in the battery pack, involving the cell protections:

- The last cell's CID in a parallel connection should interrupt the total current.
- The first stage of cells to open in a series connection will have to interrupt the current under the total voltage of the defect loop.
- The last cell's CID in a parallel connection of the first stage to open in a series connection should interrupt the total current under the total voltage of the defect loop.

The normative overcharge tests, which requires testing at twice the cell voltage and twice its rated current, are therefore not representative and higher current, higher voltage tests are required. In addition, the proposed scheme using a switch-mode power supply to carry out the overcharge is not representative due to the filter capacitors producing a ZVS on the CID under test.

For the first time, thanks to a representative overcharge test scheme and dedicated metrology, a safety area of a cell equipped with a CID could be started. For voltages above 105 V and a current of 80 A, for example, the breaking capacity of the

tested CID is insufficient and the cell is no longer protected which leads to thermal runaway. However, this assessment is only valid for the proposed cell model and the methodology presented will have to be re-used on a case-by-case basis.

In conclusion, in order to improve the electrical safety of the packs we suggest:

- To take into account the state of the art rules in terms of electrical design. Particular attention should be paid to the insulation, above all on creepage distances, which can be degraded by pollution or burning from cell projections.
- The electrical architecture of the battery pack will influence the stresses applied to the cells in case of a fault. These stresses must be estimated for the various fault cases.
- Knowing the potential stresses applied to the cells, they and their eventual integrated protection devices must be tested under these conditions, using the proposed methodology.

By taking these elements into account, it is then possible to set up system-wide protections allowing to remain within the safety range of the cell integrated protections.

7 Acknowledgments

The authors would like to thank David Brun-Buisson, Pierre Balfet, Jérôme Cognard and Kamel Bachir Elezaar from the CEA of Grenoble for their contribution, their help and their availability during the realization of the abuse tests.

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