CAMX Power Technologies for Battery-Integrated Internal Short Circuit Detection

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Abstract: *We present recent advancements in CAMX Power technologies for sensitive, early detection of incipient internal short circuits in cells of lithium-ion batteries. Results demonstrating high-sensitivity detection performance in complete battery system demonstrators are reported for both our Universal Detection Technology (UDT) and Real-time Detection Technology (RDT). We further present results for UDT implemented as a stand-alone, portable diagnostic instrument for scanning batteries for the presence of internal shorts.*

Keywords: lithium-ion; internal short circuit; battery safety; early detection.

Introduction

The superior energy and power on both a weight and volume basis of lithium-ion (Li-ion) battery technology has made this chemistry the clear choice for a number of DoD applications. However, utilization of this high-performance battery chemistry has been limited by safety concerns. Under certain triggers, Li-ion cells can experience thermal runaway, i.e., a rapid increase in cell temperature accompanied by venting, vent-with-flame, ejection of cell parts, fire and explosion. Internal short circuits (most typically attributable to metal contaminants in the cell) are the most commonly identified mechanism by which such battery failure events occur in the field. Internal short circuits causing failures in the field typically develop after some period of normal cell operation and service and occur in cells that passed all manufacturing safety and quality control screening. In many DoD operational scenarios, it is important to minimize the likelihood of these failures and maximize safety and reliability of fielded Li-ion systems. Doing so requires effective management of the threat posed by internal shorts. As internal short-induced battery failures can occur after months or even years of battery service life, there is need for technologies that can detect internal shorts as early as possible before they pose an imminent threat to the safety of the battery and surrounding assets, and while opportunities to productively intervene to avert internal short-induced catastrophic failure are still available.

Challenges of detecting internal shorts: Detecting an internal short with enough sensitivity to deliver early warning of a fault condition, requires that certain hurdles be overcome. When a short first appears, it is small in magnitude, high in resistance and draws little current, with its electrical signature being heavily masked by much higher currents associated with normal cell operation. Further, a minor short (e.g., 1000 ohms) has essentially negligible impact on cell impedance characteristics (e.g., 1ppm at 1kHz on a cell with 1 mΩ internal resistance) unless impedance data are acquired at very low frequencies with accompanying lengthy acquisition times (e.g., hours or longer depending on cell characteristics). The default approach for detection of internal shorts is to monitor cell voltage over a sufficiently long period of time that voltage loss due to self-discharge through the internal short can be identified and adequately quantified (doing so requires that the cell is at rest and fully equilibrated). This engineering perspective, coupled with actual laboratory trials, led us to look for other means to achieve the sensitivity and rapid detection necessary for in-pack safety monitoring. In doing so, we identified reliable electrical signals that are obtained only when internal shorts are present in a cell. This knowledge has been utilized in the development of two distinct, non-invasive and chemistry-agnostic technologies for sensitive early detection of internal shorts in Li-ion (or other) batteries before the shorts pose a thermal runaway threat. These technologies are based on extensive research into the underlying electrochemistry governing internal shorts, and on experience gained through safety audits of failures of Li-ion batteries in the field. They comprise hardware and software developed specifically to acquire and interpret the specific electrical markers we have identified that indicate that internal shorts exist in a cell and deliver warning signals proportional to short severity. These technologies provide early warning of incipient internal shorts that may lead to unsafe conditions in a battery and can be implemented either independently of, or integrated with, the battery management electronics employed in Li-ion battery packs.

Characteristics of internal shorts: We have been studying the nature and underlying electrochemistry of particle-induced internal shorts in lithium-ion cells for a number of years. Figure 1 depicts, in a generic manner, evolution of a fault that progresses to cell failure - thermal runaway, often accompanied by release of significant heat, sparks, flame, particulate matter, toxic and hot flammable gases: stage 3 in Figure 1. This heat release can drive neighboring cells to failure (stage 4) in a process known as *cascading* or *propagation* and, in the worst case, can progress to a large-scale fire or equipment damage, presenting catastrophic hazards to surrounding assets and to personnel. The evolution of a fault progressing to cell failure, as depicted in Figure 1, can be viewed in terms of four stages. First, the fault initiates. This fault could be the very first point of formation of, for example, an internal short resulting from Foreign Object Debris (FOD). In stage 1 the fault grows in severity until reaching stage 2 where the fault has become "critical" in that it is severe enough to trigger a thermal runaway. In stage 3, the cell exhibits thermal runaway, which may then result in cascading/propagation of the failure to adjacent cells (stage 4) and, potentially, the rest of the battery in a worst-case incident. The greatest opportunity to manage a fault in a cell, and avoid a catastrophic failure of even one cell, is present when the fault is detected at or near the point of initiation, where the fault is still small and harmless. Later detection (i.e., the longer one waits) increases risks. For example, waiting until a first cell actually fails at stage 3 (smoke, flame, etc.,), may not allow sufficient opportunity for productive intervention to avoid widespread violent failure.

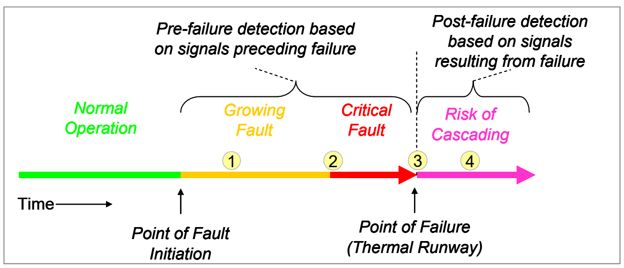

Figure 1. Representation of the timeline of a single-cell failure (thermal runaway) with subsequent risk of cascading of failure to other cells. CAMX Power technologies support pre-failure detection of faults in cells, i.e., stage 1, identifying a fault well before any cell gets "close" to thermal runaway, providing more time to implement preventive actions to suppress cascading of thermal runaway.

We have created well over 1000 particle-induced shorts in our laboratories under a variety of conditions using methodologies we have developed to reproduce particle-induced internal short-based cell failures. From this body of work, we have found that internal shorts typically progress through several phases, initiating as very minor cell faults of high resistance (thousands of ohms or more), growing slowly for a period of time, followed by a period of more rapid growth, sometimes abruptly, to higher severity (or runaway). Aspects of this pattern of short development are seen in the data shown in Figure 2. We believe that internal short detection capability must be of sufficient sensitivity to identify shorts *before* they grow severe enough to trigger thermal runaway and while productive intervention to avoid catastrophic cell failure is still possible. It must also be recognized that internal shorts not severe enough to trigger a thermal runaway event can still critically compromise battery performance and reliability, leading to sudden unexpected loss of battery function which could be unacceptable in mission-critical applications.

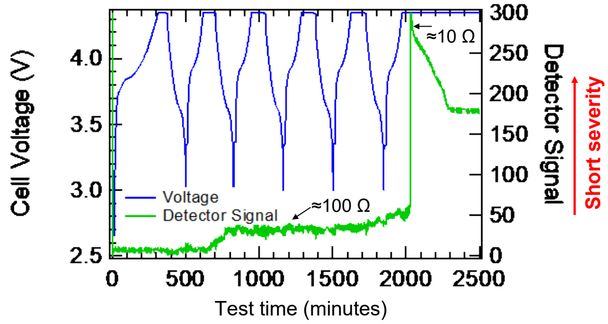

Figure 2. Cell voltage and output from our detection technology for a short created in a Li-ion cell by implantation of a metal particle. The detection signal (lower trace) shows the short initiate in the second cycle, grow to a moderate level (~ 100 Ω) for several cycles, and then abruptly spike to more dangerous levels (~ 10 Ω) in cycle six.

We have developed two distinct technologies for battery-integrated monitoring of lithium-ion energy storage systems for the presence of internal short circuits: the Universal Detection Technology (UDT), so-named because of its applicability to batteries of any cell configuration, and the Real-time Detection Technology (RDT), which provides real-time monitoring for internal shorts whether the battery is at rest or actively cycling. Both technologies have been demonstrated for a wide range of lithium-ion chemistry variants, are functional over a wide range of temperature (tested from -30°C to +55 °C to-date), and are sensitive enough to detect internal shorts at least three orders of magnitude weaker in severity than the levels needed to trigger a thermal runaway, irrespective of the shorts' root cause. Attributes of UDT and RDT include:

- *Universal Detection Technology (UDT)*
  - Minimally disruptive to battery design, easily integrated with BMS.
  - Can utilize existing voltage-sense wiring (no changes in the pack).
  - Performs monitoring diagnostic while battery is at rest.
- *Real-time Detection Technology (RDT)*
  - Real-time monitoring including under complex current profiles and at rest.
  - Delivers detailed state-of-health monitoring for the battery.
  - Utilizes a network of sensors placed at certain strategic points in the battery.

The following sections present results for UDT and RDT demonstrating performance and sensitivity, and recent hardware advances that implement the technologies in compact form-factors for direct integration into battery systems.

UDT: Detection performance, implementation in a Full Battery Demonstrator, as a stand-alone diagnostic instrument, and in a compact module for all UDT applications.

The Universal Detection Technology (UDT) executes electrical diagnostics on Li-ion battery systems while the battery is at-rest (i.e., no charge or discharge processes occurring) to scan for the presence of internal short circuits. The high detection sensitivity of UDT is demonstrated by the data, presented in Figure 3, for detection trials carried out on a 2.6Ah 18650 cell. Detection sensitivities to 20,000Ω - an internal short more than four orders of magnitude weaker than levels that could trigger thermal runaway – are achieved. For reference, prior work in our laboratories (including experimentally validated finite element analysis modeling) has shown that the threshold for thermal runaway in an 18650 cell (in free air) is an internal short of about 4Ω. As seen in Figure 3, raw detection responses for all resistances tested – from 50 to 20,000Ω - are well-distinguished from scans for the no-short condition. Analysis metrics applied to raw UDT responses provide semi-quantitative grading of the severity of any detected internal short circuits and are used in implemented UDT systems to trigger alerts of potentially unsafe conditions.

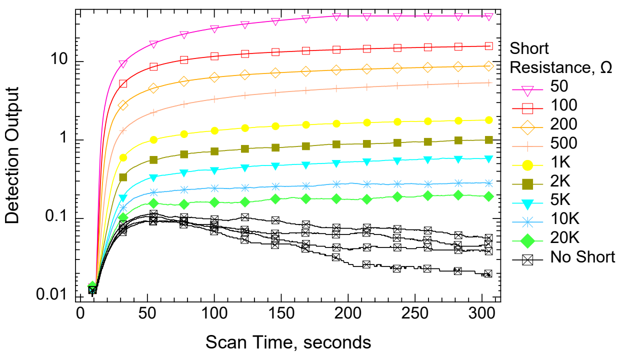

Figure 3. UDT Scans for a 2.6Ah 18650-format cell.

We have now implemented and demonstrated UDT monitoring for internal shorts in a variety of battery configurations including a "Full Battery Demonstrator" in which UDT was integrated into a 28V (7S), 25Ah battery built-to-specification for a DoD application. When performing a diagnostic scan on the battery, the UDT system scans each of the seven 25Ah cell blocks of the 7S battery in sequence. Figure 4 shows detection trial results for the Full Battery Demonstrator for one of the 25Ah cell blocks scanned with five scans at each test resistance, demonstrating consistent, reproducible UDT responses. Internal shorts of 3000Ω - three orders of magnitude weaker than levels that could trigger a runaway- in a single cell of the 60+ cell battery are easily detected.

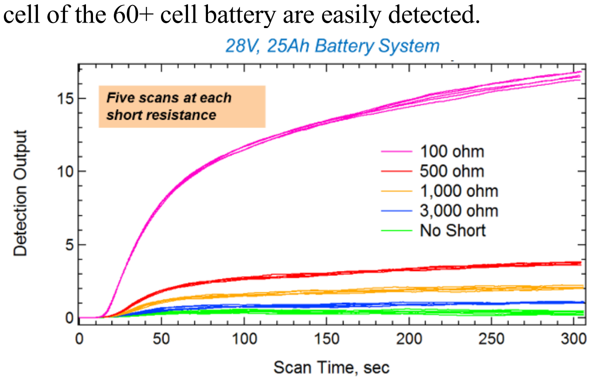

Figure 4. Scan results for a UDT-Equipped Full Battery Demonstrator.

Our present standard UDT system configuration is designed to accommodate batteries of up to eight cells/cell groups in series. Using a modular implementation directly analogous to that practiced in battery management system design, UDT monitoring can be configured for batteries of arbitrary stack size to >1000V.

Another application area for UDT in which we have made significant advancements implements UDT as a stand-alone diagnostic instrument for laboratory or field assessment of batteries for internal shorts. A number of such UDT-based instruments have been constructed to date, including units delivered to a DoD customer and units used both in-house and for remote on-site evaluations of Li-ion cells and batteries. A photograph of a UDT diagnostic instrument kit is shown in Figure 5. The kit includes the USB-powered UDT diagnostic instrument (right) and a connection harness (left).

Figure 5. Stand-alone UDT-based diagnostic kit.

UDT implementations share a common "detection engine" core that carries out the UDT electrical interrogation to scan for internal shorts. To broadly support implementation of UDT in different applications, we are implementing this UDT detection engine as a compact, surface-mount module (Figure 6) that provides core electronics common to essentially any UDT application.

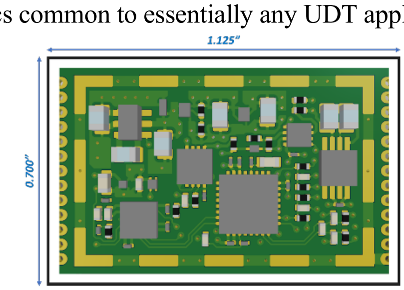

Figure 6. UDT Core module circuit board.

This UDT Core module will be qualified for, and demonstration in, DoD battery applications with the objective of full integration for safety monitoring of the associated Li-ion systems.

RDT: Capabilities and 300-cell battery implementation

The Real-time Detection Technology (RDT) continuously monitors Li-ion batteries for the presence of internal short circuits using proprietary hardware and algorithms and a sensor network within the battery. RDT monitoring is able to discern electrical signatures that are markers for internal shorts irrespective of battery state – whether the battery is at rest, charging, or delivering power – and irrespective of the underlying cause of the short. An example of detection of an internal short in an actively cycling battery is shown in Figure 7. During this test, the battery was subjected to an automotive drive cycle test protocol and a load resistance was placed across one cell of the battery as a safe, quantitative surrogate for an internal short. As seen in the top graph of Figure 7, standard BMS cell voltage sensing data contains no indication of the presence of the internal short but, as shown in the bottom graph, the RDT system immediately detects the presence of the short even against a background of a complex waveform of rapidly changing charge and discharge currents.

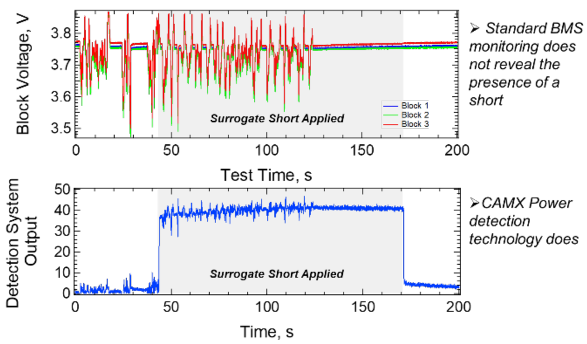

Figure 7. Test data showing successful detection by RDT of an internal short, invisible to the Battery Management System, under a demanding automotive drive cycle test protocol with rapid, high currents charge/discharge swings.

Figure 8 shows a recently implemented RDT-equipped 300-cell Full Battery Demonstrator. Figure 9 shows detection during discharge of a 100Ω internal short (load resistance as surrogate) with the battery actively cycling.

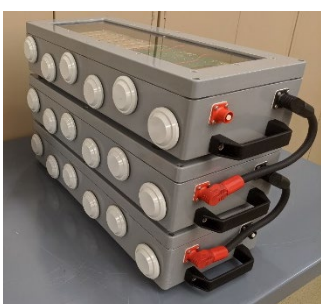

Figure 8. RDT-Equipped, 300-cell Full Battery Demonstrator.

Additional optional functions for RDT implementations include use of already-acquired RDT sensing data to provide detailed, cell-level battery state-of-health metrics, and with addition of an appropriate cut-off device comprehensive battery management functionality. RDT monitoring can also detect single-cell fail-open events within a battery.

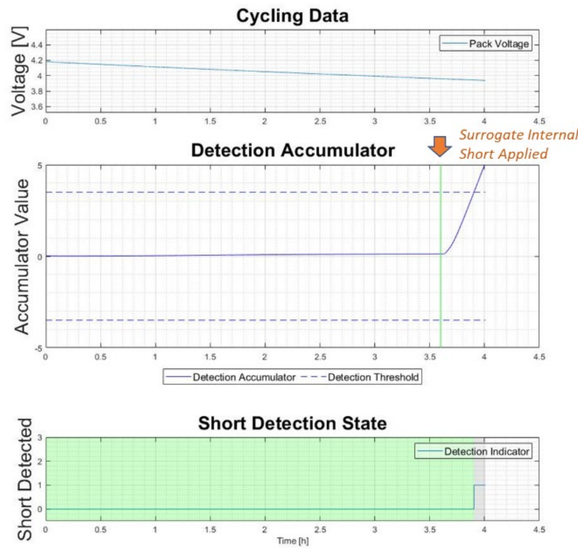

Figure 9. RDT detection of a 100-ohm internal short for one cell in the actively cycling 300-cell battery. A detection warning (level 1, 2 or 3) results when the associated detection threshold is crossed in the detection accumulator of the RDT algorithm system.

To support design and implementation of RDT, we have developed a small, surface-mount module that provides all RDT functions and components exclusive of the battery-specific RDT sensor network. This 1.2"x1.2" unit is shown in Figure 10.

Figure 10. (Left) RDT Core unit circuit board (1.2' x1.2"). (Right) With protective cover fitted.

In conclusion, we have significantly advanced the TRL of both UDT and RDT, with UDT nearing readiness for fielding in DoD battery systems. We have developed compact, small form-factor implementations of both technologies which can be made available in the form of evaluation kits to support the design process for integration into battery systems and can be made in quantity for incorporation into a wide range of Li-ion applications.

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