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Lithium-ion Battery Tab Welding Diagnosis using Electrical Reflectometry

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Abstract—This paper investigates the use of electrical reflectometry as a non-destructive testing technique to monitor the health status of battery tab welding in a parallel pack configuration. 3D models consisting of cylindrical lithium-ion cells connected by a tab at each extremity through copper welding were developed. Current surface distribution analyses were performed to understand reflectometry signal propagation and to select the optimal setup for increasing reflectometry sensitivity. Then, several defect models with varying severities and locations were created to simulate the progressive loss of material in the welding layer. This work demonstrates the ability of reflectometry-based systems to detect welding degradation in a parallel battery pack configuration, which, to our knowledge, has never been done in the literature.

Index Terms—Electrical Reflectometry; Lithium-ion Battery Tab Welding; Defect Diagnosis

I. INTRODUCTION

The transportation sector, responsible for 25% of global greenhouse gases (GHG), has considered Electric Vehicles (EVs) as key solution for climate neutrality. Within the automotive industry, which accounts for 72% of GHG emissions in this sector, mounting societal pressure and environmental emergencies necessitate a shift away from fossil fuel vehicles. However, EVs breakthroughs require innovative storage power systems, smart embedded sensors, and onboard computing power. In this context, electrical connections play a crucial role in the performance and reliability of battery cells and Energy Storage Systems (ESS). In these systems, individual battery cells are interconnected through soldered connections, forming series and parallel configurations to achieve desired voltage and capacity levels. Promising joining methods for interconnecting battery cells include laser welding, ultrasonic welding, resistance spot welding, induction soldering, and solid-state press-fit connections. Electrical resistance, mechanical strength, and manufacturing considerations for each of these joining methods are critical for optimizing the interconnections in high-performance battery packs.

The integrity of these soldered connections is absolutely critical, as any defect or degradation can lead to localized heating, increased internal resistance, and ultimately, reduced efficiency and lifespan of the overall system. Moreover,

ensuring the quality and consistency of these connections is a critical aspect in the manufacturing and maintenance of battery cells and ESS. Various non-destructive testing (NDT) methods are employed to detect defects or discontinuities in welded or soldered interconnections. Some of the most commonly used techniques include visual inspection, X-ray imaging, ultrasonic testing [1], and eddy current testing [2]. The choice of the most appropriate technique depends on material properties, component geometry, accessibility, and the nature of defects. These methods can be used in quality control during the soldering process, ensuring the integrity of the soldered connections, preventing potential failures in the final product, or for predictive maintenance purposes to assess the condition of the battery cells and interconnections without disassembling the pack. Among these methods, electrical reflectometry, a well-know method for electrical wiring diagnosis, has shown interesting results for monitoring the degradation of solder joints on printed circuit boards by sensing changes in high-frequency impedance caused by small cracks [3].

In this paper, electrical reflectometry is used to monitor the health status of battery tab welding across a pack of parallel cells. For proof of concept, 3D-based models consisting of cylindrical lithium-ion cells and tab weldings have been developed. Several configurations of injection and acquisition of reflectometry signals have been tested to study the performance of reflectometry in terms of sensitivity. Several defects with different severities and localization have been modeled to simulate a progressive loss of copper material in the welding layer. The analysis of surface current distribution fields performed permitted understanding of reflectometry signal propagation and assessing signal attenuation or distortion effects. Such observations are necessary to optimize the calibration and integration of the measurement system (frequency bandwidth, signal energy, sensor positions, etc.). The obtained results demonstrate the capability of reflectometry-based systems to detect the degradation of the welding state.

This paper is organized as follows. Section II presents battery tab welding methods and most common diagnosis

techniques. Section III introduces the principle of electrical reflectometry and its challenges related to defect detection and localization. Section IV and V describe the developed work based on 3D-models and electromagnetic simulations. A conclusion is introduced in Section VI to summarize the obtained results and address perspectives of the current work.

II. BATTERY TAB WELDING

Batteries in electric vehicles and energy storage systems, rely on robust interconnections between individual cells to form modules and packs. A battery pack is composed of multiple battery modules, each containing a number of battery cells. The joints that establish these critical connections between the battery tabs and tabs are made from thin materials and are typically lap, fillet, or spot welded. This assembly process is a critical aspect of battery pack manufacturing that may impact the overall performance and reliability of the battery system.

Various welding types are employed for battery interconnections. Among them, laser beam welding utilizes a high-intensity laser beam to fuse the metallic materials, such as copper or aluminum, offering high precision, deep penetration, and minimal heat-affected zones, although it requires precise positioning and can be sensitive to surface conditions [4]. Ultrasonic welding, widely used for pouch cell interconnections, relies on high-frequency vibrations to create friction-based solid-state welds, providing advantages like low heat input, fast cycle times, and good electrical conductivity, but may face challenges with limited weld depth and strict material compatibility requirements [5]. Resistance spot welding passes an electric current through the work-pieces, generating localized heat and fusion at the interface, suitable for thin-gauge materials and offering a simple setup, but can cause material expulsion and may require post-weld operations for improved electrical properties [3]. Soldering, while not strictly a welding process, is sometimes used for battery interconnections, particularly in smaller applications, offering ease of use and low-temperature processing, but can be limited in mechanical strength and long-term reliability.

During manufacturing and the life cycle of batteries, it is essential to inspect the integrity of these welded interconnections to ensure product quality, safety, and reliability. Visual inspection involves examining welds for surface defects, discoloration, or irregularities but may miss internal defects and is subjective. Radiographic testing, using X-ray or gamma-ray imaging, can reveal internal weld defects, such as porosity, cracks, or lack of fusion, but involves radiation safety concerns and is typically used for critical applications. Ultrasonic testing, utilizing high-frequency sound waves, can detect internal flaws, cracks, or discontinuities in welds in a non-destructive manner and can be automated, but may require specialized equipment and skilled operators. Electrical resistance or conductivity alteration of welded joints can indicate their degradation. These methods are simple to implement but

may lack the sensitivity to detect small defects. The choice of weld inspection method often depends on factors such as the application's criticality, cost considerations, accessibility, and required sensitivity. A combination of techniques may be necessary for comprehensive quality control and condition monitoring of battery interconnections throughout their lifecycle.

In this work, we propose to use electrical reflectometry as a non-destructive diagnostic tool to monitor the health state of welded battery tab connections. To the best of our knowledge, this is the first work exploring the use of reflectometry for diagnosing degradation in battery tab welds.

III. ELECTRICAL REFLECTOMETRY'S PRINCIPLE AND CHALLENGES

Electrical reflectometry is a non-destructive testing technique that uses high-frequency electrical signals to detect and locate discontinuities or changes in the characteristic impedance of an electrical system. The underlying principle is based on analyzing the reflections of electrical pulses or signals propagating along a transmission line or waveguide. When an electrical signal encounters an impedance discontinuity in the system under test, a portion of the signal is reflected back towards the source, while the remaining portion is transmitted past the discontinuity. The analysis of the reflection coefficient, given in (1), provide information about the nature and the severity of the impedance discontinuity, while the measurement of the time-of-flight between the incident and reflected signals, along with knowledge of the propagation velocity v , enables the localization of the impedance discontinuity:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad (1)$$

where Z_0 is the characteristic impedance of the transmission line and Z_L is the impedance discontinuity.

Recently, electrical reflectometry has been used in the inspection and monitoring of solder joints and interconnects in electronic assemblies [3]. The researchers subjected surface-mount solder joints to fatigue testing while continuously monitoring the RF impedance via reflection coefficient measurements. The authors demonstrated the reflectometry's capability to detect the preliminary stages of solder joint degradation and the formation of initial cracks, which manifested as an increase in the measured RF impedance values. Due to the skin effect at high frequencies, signals propagate primarily along the surface of the interconnects. Thus, even small surface cracks in solder joints can induce detectable changes in the RF impedance and reflection coefficient measured by electrical reflectometry.

In the literature, reflectometry methods can be classified into two main categories - Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR). The TDR method periodically injects a specific probe signal and analyzes the time-domain characteristics of the reflected signals obtained

at each impedance discontinuity, while FDR measures the frequency, magnitude, and phase of the injected sine waves. An advantage of TDR over FDR lies in its ability to provide precise spatial resolution and accurate localization of discontinuities within the transmission medium. Most basic TDR systems use a Gaussian pulse as probe signals that is described as follows:

$$V(t) = V_0 \exp\left(-\frac{t^2}{2\sigma_t^2}\right), \quad (2)$$

where, $V(t)$ represents the amplitude of the Gaussian pulse as a function of time t , V_0 is the peak amplitude of the pulse and σ_t is the standard deviation of the pulse in the time domain, which affects the width of the pulse. In a transmission line, the propagation velocity v is given by:

$$v = \frac{c}{\sqrt{\epsilon_r}}, \quad (3)$$

where, c is the speed velocity of light in vacuum (310^8 m/s), and ϵ_r is the relative permittivity.

The spatial resolution Δ_z is the ability of a measurement system to distinguish two closely spaced points. In other words, it defines the smallest distance between two distinct discontinuities that the system can identify as separate and, is determined as follows:

$$\Delta_z = v \cdot \Delta t, \quad (4)$$

where, Δt is the full width at half maximum of the temporal pulse.

The localization precision is the ability of the system to determine the exact location of an impedance discontinuity (i.e. defect) with high accuracy. It depends on the spatial resolution Δz but also may include some factors such as noise, interference, and systematic measurement errors, encountered in real environment. For example, for a reflectometry system with Δt is 1 ns and $v=2 \times 10^8$ (m/s), the spatial resolution is 20 cm. Hence, in time domain reflectometry, the choice of the pulse width and the knowledge of the speed velocity v are crucial for diagnosis accuracy. However, in the case of a heterogeneous propagation medium (different material properties), the problem becomes more complex since the propagation velocity v is not the same at all points.

Moreover, since the spatial resolution depends on the full width at half maximum of the Gaussian pulse Δt and hence its bandwidth since $f_{max} \approx 0.44/\Delta t$, a Gaussian pulse with a higher maximum frequency f_{max} will typically have a shorter Δt , which can lead to better spatial resolution Δz suitable for soft faults detection and localization. In fact, soft faults, which can be localized or spread over a certain distance, refer to minor abnormalities or deviations in the propagation medium that cause partial signal reflections rather than complete signal loss (i.e. open/short circuit). Usually, they introduce two reflection coefficients on the reflectogram (1) related to the impedance discontinuity at the entry and the output of the soft fault, and their trace on the reflectogram has a weak signature that could be masked out by noise. Hence, the

detection and localization of such faults requires the increase of the signal bandwidth f_{max} . In [4], authors demonstrated that if a cable is tested over a bandwidth f_{max} , then only those faults whose length roughly exceeds

$$w \gtrsim \frac{v}{4f_{max}} \quad (5)$$

can have their severity estimated, as the region around the peak of would otherwise not be accessible. They conclude that the way to address soft faults using electrical reflectometry is either by conducting tests at sufficiently high frequencies or by ensuring that only sufficiently long faults are identifiable. However, the increase of f_{max} will increase also the signal attenuation and dispersion limiting the diagnosis coverage and localization accuracy [5].

In this study, the diagnostic of welding faults in battery tabs using electrical reflectometry presents several major challenges. As previously introduced, electrical reflectometry relies on analyzing reflected signals to identify anomalies, but detecting small welding faults requires high precision and the use of sufficiently high frequencies to ensure adequate spatial resolution. Welding faults, often very small and localized, produce weak signatures that can be rapidly masked by noise, making their identification difficult. Additionally, the high frequencies necessary to improve spatial resolution can introduce additional losses and distortions in the signal, complicating data interpretation. These combined factors make faults detection a complex process that requires careful optimization of measurement parameters f_{max} and advanced post-processing methods to ensure the reliability and safety of battery systems.

IV. 3D MODELING AND EM SIMULATION

A. 3D Modeling of a single cell

A lithium-ion battery, or Li-ion accumulator, consists of two electrodes (cathode and anode) and an electrolyte that facilitates the ionic exchange within the system. During the discharge (use) of the battery, ions move from the anode to the cathode. During charging, the reverse occurs. These two electrodes are separated by a separator, which prevents a short circuit. Fig.1 and Fig.2 show the model 3D of the cylindrical cell: external and internal view, respectively, designed using CST Studio Suite. It is composed by an outer layer (aluminium material) and then, the anode (Graphite material) and the Cathode (Magnesium material) are separated by a layer composed in Polytetrafluoroethylene (PTFE) material. The external view demonstrates the outer button of the cylindrical cell composed of Aluminium material.

B. 3D Modeling of parallel cells

A pack of 4 parallel cells has been considered for this study as shown in Fig.3 relied by a copper tab (or tab) at the top and down of the cylindrical cells.

For reflectometry application (need for an isolation between the conductors), a ground plane with the same characteristic of those tabs has been introduced. In this case, three configurations are possible for injection/receiving reflectometry

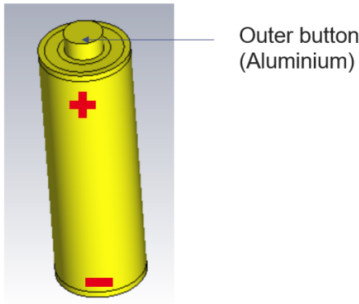


Fig. 1. Model 3D of the cylindrical cell: external view

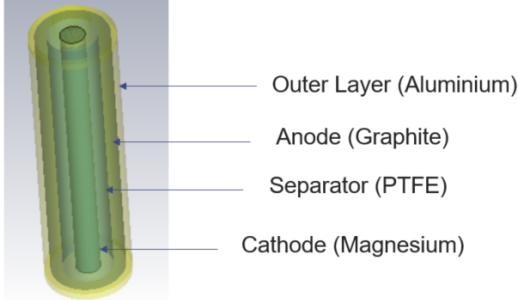


Fig. 2. Model 3D of the cylindrical cell: internal view

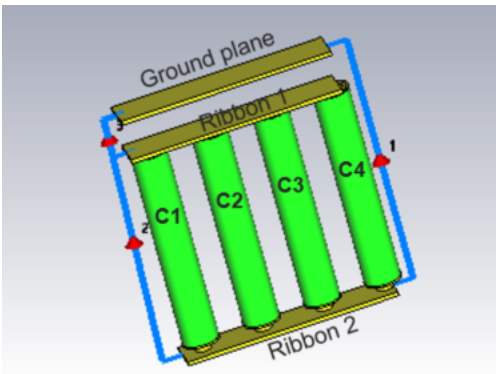


Fig. 3. Model 3D of a 4 parallel cell pack

methods. The port 1, is relating the ground plane to the tab 2 (named Ribbon2 in Fig.3). The port 2, is relating the ground plane to the tab 2 on the other extremity. Finally, the port 3 is relating the tab 1 (named Ribbon1 in Fig.3) to the ground plane. In order to select the best configuration for signals propagation down the conductors, the current surface propagation have been studied for the three configurations. Fig.4 and Fig.5 show the current surface distribution down the battery pack and the ground plane (added for reflectometry application), using port 3 and port 2, respectively. It is obvious that using port 3 for reflectometry signal propagation is more advantageous than using port 2 or port 1, as the maximum surface current for port 3 is 5.11 A/m, compared to 2.07 A/m for port 2, at a maximum frequency of 5 GHz. For the remaining of the paper, only the port 3 configuration will be considered for diagnosis purpose. In fact, the distance between

the two conductors seem to be important for reflectometry application using port 1 and 2.

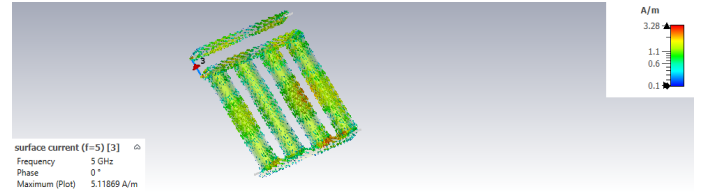


Fig. 4. Surface Current propagation (port 3)

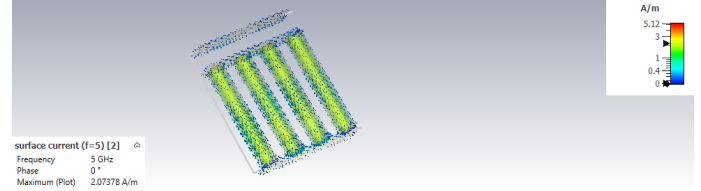


Fig. 5. Surface Current propagation (port 2)

V. DIAGNOSIS OF BATTERY TAB WELDING

After the choice of the best configuration for reflectometry application in the previous section, we propose to simulate the battery tab welding, a layer with a cylindrical form with dimension 2mm of radius and 2mm of thickness is added between the tabs and the cells. Several soft defects have been simulated on the welding of the top of the cell 2 as shown in Fig. 6, where a part of the welding in contact with the outer button of the cylindrical cell 2 has been removed. For the soft defect noted $DNF1$, the opening angle is about 3.46 mm against 3.97 mm for angle $DNF2$. The models of the defects shown in Fig.6 have been also introduced at the bottom of the cell C_2 making them closer to the injection port $P3$.

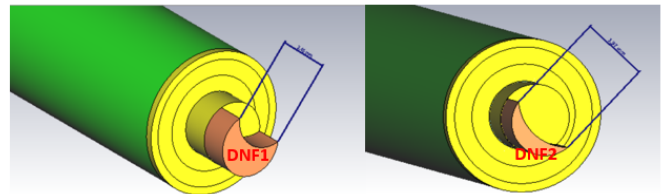


Fig. 6. Tab welding defects on the top of cell 2

A test signal with a frequency band from DC to 2 GHz has been injected on port 3 in the case of the healthy case and faulty one for base-lining performing. Hence, only the peaks related to the presence of the soft defect will be conserved on the reflectogram (echoes related to the native discontinuities in the propagation medium should be removed). In fact, the detection of the variation directly on the obtained reflectogram seems to be very difficult due to the dimension of the welding tab (5mmx2mm) and the spatial resolution of the test signal used for simulation (5cm).

Fig. 7 presents the differential reflectograms (after base-lining performing) in presence of soft defects as shown in Fig.6 in the tab welding present at the top and bottom of the cell C_2

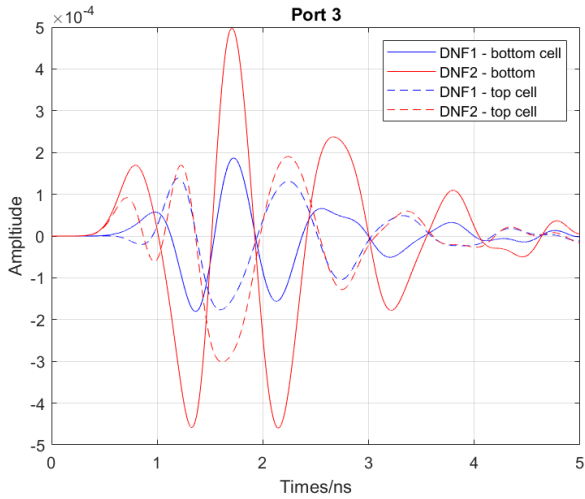


Fig. 7. Differential reflectograms using P3 in presence of two welding defects in the top and bottom of C_2

(not at the same time for comparison purpose). The evolution of the amplitudes of the peaks present on the reflectogram corresponds with the severity of the defect (percentage of section load on the welding). Moreover, when the tab welding defects are present at the bottom of the cell C_2 , closer to the injection port, the amplitude of the peaks seems to be higher than those obtained when those defects are localized at the top of the cell. Hence, the position of the injection port influences on the fault signature characteristics. However, it is very difficult to pinpoint an exact location of the fault. Based on these observations, a new configuration of the setup is proposed with the integration of an additional ground plane in parallel with tab 2 (closer to the top of the cell) as shown in Fig.8. Here, a port named P4 is added relating the tab 2 to a second ground plane.

Fig.9 shows the obtained reflectograms for the defect $DNF2$ with two injection points P3 and P4. The peak amplitude is more important when this defect is monitored using P4 than P3. The findings permit to conclude that in a pack of battery with two tabs at the bottom and the top of the cells, the diagnosis of the corresponding welding will be more accurate using two injection points (distributed reflectometry). This solution permits to avoid the test signal attenuation and dispersion introduced by the propagation of the cell medium (considered as a complex transmission line due its non conventional conductors materials (Graphite, Magnesium). Moreover, for localization purpose, it will be interesting to increase the signal bandwidth (about 10 GHz), and hence increase the spatial resolution (around 5mm). However, this may also increase the signal attenuation and dispersion as explained previously.

VI. CONCLUSION

This paper investigates the use of electrical reflectometry for monitoring the health status of battery tab welding through electromagnetic simulations, aiming to decouple the presence

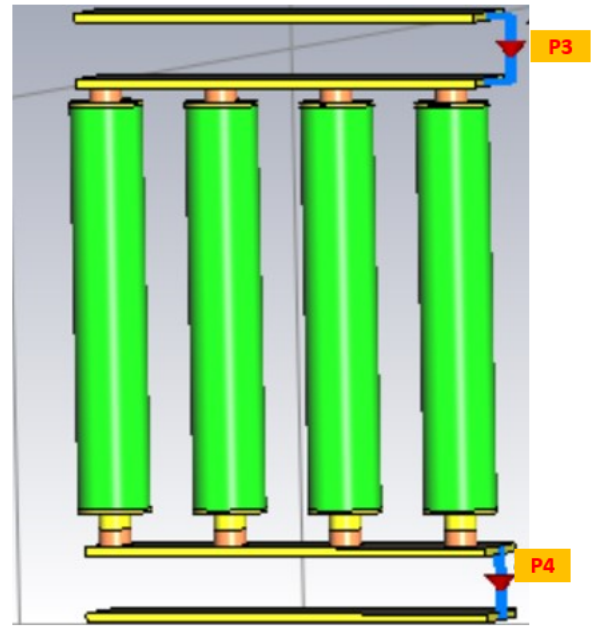


Fig. 8. Model 3D of a 4 parallel cell pack with two ground planes

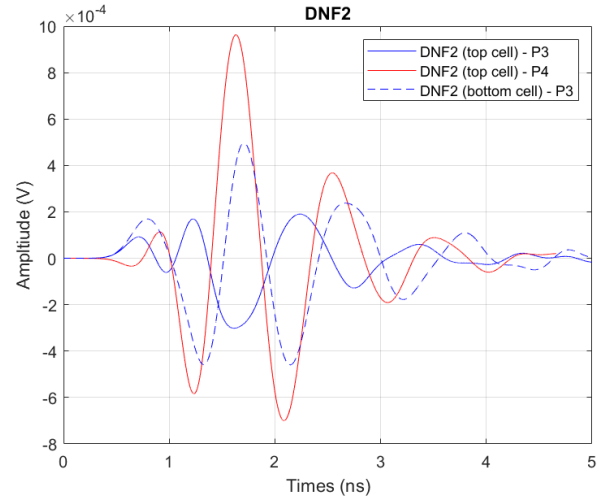


Fig. 9. Differential reflectograms using P3 and P4 for $DNF 2$ in the top and bottom of C_2

of other phenomena typically encountered in laboratory experimentation. To achieve this, 3D models comprising cylindrical lithium-ion cells and tab weldings were developed. Multiple defect models with different severities and locations were also simulated to represent the progressive loss of material in the welding layer. The obtained results demonstrate the capability of reflectometry-based systems to detect welding degradation using at least one ground plane, with two ground planes yielding better results. However, fault localization requires an increase in signal bandwidth to enhance spatial resolution. Additionally, the weak amplitudes of the peaks may be masked by native noise in real environments. In conclusion, reflectometry methods appear to be promising for tab welding diagnosis, but

more advanced post-processing methods should be introduced to improve de-noising and accuracy.

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