A Fully Passive Approach for Real-Time Strain Sensing of $LiFePO_4$ Cells in EV Battery Packs

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***Abstract*— Monitoring mechanical strain in lithium-ion battery cells is critical for accurately assessing the state-of-charge (SoC) and state-of-health (SoH) in electric vehicle (EV) battery packs. This paper presents a novel, fully passive wireless strain sensing system that integrates a piezoresistive sensing element with ultrahigh-frequency (UHF) RFID technology. Utilizing the Magnus S3 RFID chip, the system operates without a dedicated power source, relying on energy harvested from the RFID reader. Changes in mechanical strain alter the impedance of the sensing element, which is encoded into a sensor code and transmitted wirelessly in real time. Experimental results from wired and wireless setups confirm the effectiveness of this approach for monitoring swelling-induced deformation in $LiFePO_4$ cells. The proposed solution significantly reduces wiring complexity and energy consumption, offering a scalable and cost-effective option for next-generation wireless battery management systems (wBMS).**

***Keywords*— electric vehicles, strain sensing, UHF RFID, Wireless BMS.**

I. INTRODUCTION

Electric vehicles (EVs) are key to reducing emissions and promoting sustainable transport [1]. Their performance relies heavily on the battery, which is managed by Battery Management Systems (BMS) to prevent faults like overheating or overcharging [2]. To reduce weight, cost, and wiring complexity, the industry is adopting wireless BMS (wBMS) [3].

Ultrahigh-frequency (UHF) RFID-based wireless strain sensing has gained attention in automotive applications due to its low power consumption and robustness [4]. In this work, we investigate strain in $LiFePO_4$ battery cells using passive piezoresistive sensors [5] mounted directly on the cell surface. While such sensors have seen use in various fields [6], their application in monitoring cell swelling and mechanical deformation in EV batteries remains underexplored.

We evaluate both wired and wireless approaches to quantify strain during charge–discharge cycles. The study begins with wired strain measurements and progresses to a fully passive RFID-based sensing system (see Fig. 1). Designed for use in metallic battery pack environments, the system eliminates the need for wiring and external power, making it well-suited for integration into next-generation wireless battery management systems.

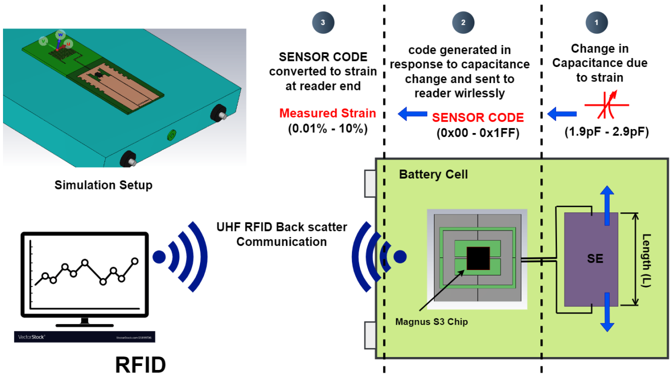


Fig. 1. Steps involved in measuring strain wirelessly using RFID

II. RFID PASSIVE WIRELESS STRAIN SENSING USING MAGNUS S3 CHIP

The integration of RFID technology in strain sensing systems provides a promising solution for wireless, battery-free monitoring of mechanical stresses, particularly in harsh environments such as those found in electric vehicle (EV) BMS [4]. The Magnus S3 RFID chip is used with a custom-designed RFID tag antenna suitable for performing in EV battery environment. A key advantage of the Magnus S3 chip lies in its self-tuning impedance matching, which ensures optimal tag performance even under dynamic and non-ideal conditions.

The core innovation lies in the coupling of the Magnus S3 chip with a flexible peizoresistive material, which serves as the sensing element (SE). This system shown in Fig. 1 eliminates the need for a dedicated power source by utilizing energy harvested from the RFID reader. The Magnus S3 chip's self-tuning capability dynamically adjusts its internal impedance to preserve optimal antenna matching, enabling reliable communication even as mechanical strain alters the SE's electrical characteristics.

The Axzon Magnus®-S3 M3D chip [7] operates within the EPC Class 1 Gen 2 v2.0.1 and ISO/IEC 18000-6C standards. Its core feature, the Chameleon™ engine, dynamically adjusts the tag's input impedance based on the sensor's varying impedance caused by strain-induced deformation (lenght L expantion). This change is encoded into a SENSOR CODE, transmitted wirelessly in real time. The SENSOR CODE reflects capacitance changes linked to the sensing element's length expansion due to cell swelling. A polynomial regression relates these capacitance variations to strain, enabling accurate, passive strain measurements. As illustrated in Fig. 1, the flexible design is well-suited for applications where conventional strain sensors are limited by power or connectivity constraints.

This RFID-based passive strain sensing system offers a sustainable, efficient, and scalable solution for real-time monitoring of mechanical stresses in environments that are traditionally challenging for conventional sensor systems. It paves the way for more reliable and cost-effective wireless sensing technologies in the automotive industry and beyond.

III. MEASUREMENT OF THE STRAIN OF A $LiFePO_4$ CELL

A. *Battery cell Inflammation*

The $LiFePO_4$ (lithium iron phosphate) battery consists of three principal components: a cathode composed of $LiFePO_4$, an anode typically made of graphite or other carbonaceous materials, and an electrolyte—commonly lithium salicylate—that enables the transport of lithium ions between electrodes.

Cell deformation arises from a combination of physical and chemical phenomena inherent to the battery's material structure. During charge and discharge cycles, lithium ions shuttle between the cathode and anode in a process known as lithiation and delithiation. This migration induces cyclic expansion and contraction in the crystal lattices of both electrodes. Notably, the graphite anode undergoes more pronounced volumetric expansion than the $LiFePO_4$ cathode. Such swelling behavior is of particular concern in high-demand applications like electric vehicle (EV) battery packs [8].

Additional contributors to battery swelling include the continuous formation and thickening of the solid electrolyte interphase (SEI) layer on the anode, electrolyte decomposition during cycling that leads to gas generation and increased internal pressure, and the mechanical degradation of active materials resulting from repeated cycling.

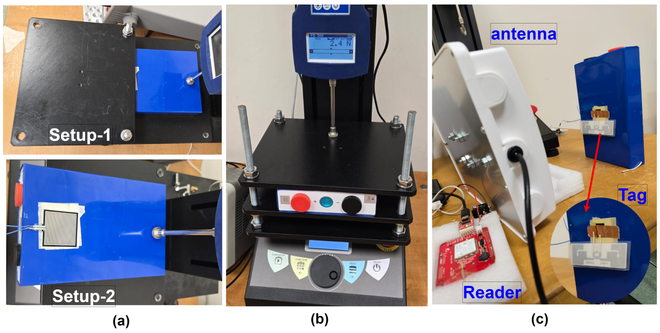


Fig. 2. Wireless strain measurement setup.

B. *Measurement methodologies*

The characterization of the strain in $LiFePO_4$ cells is of fundamental importance for developing monitoring systems for the state of charge (SoC) and state of health (SoH). This can be understood from the dimensional changes that occur as a result of the swelling phenomena that the cells undergo during the charge and discharge cycles. Current measurement methods rely on two approaches:

1) **Pressure measurement between the cell and the frame:** The cell is housed within a mechanical frame, and the RP-S40-ST pressure sensor is inserted between the cell and the frame. The pressure exerted by the expanding cell is recorded, as shown in Fig. 2 (a) setup-1.
2) **Direct strain measurement:** Strain gauges or piezoelectric sensors are affixed directly to the cell surface to monitor deformation during operation, as illustrated in Fig. 2 (a) setup-2.

The RP-S40-ST is a flexible thin-film pressure sensor with dimensions of 40 x 40 mm. Its electrical resistance decreases exponentially with increasing applied force. Under no load, the sensor exhibits a resistance of approximately 10 MΩ, with a response time of less than 10 ms [5]. The input/output characteristic of sensor were experimentally measured.

The purpose of these measurements is to analyze and measure the strain phenomena in $LiFePO_4$ cells, compare the methodologies, and then propose a monitoring framework that can be sensitive to these variations to accurately determine the SoC and SoH of individual cells, thereby improving the accuracy and reliability of SoC and SoH estimations in lithium-ion energy storage systems.

C. *Experimental setup*

Strain measurements were conducted on a prismatic $LiFePO_4$ battery cell with a rated capacity of 105 Ah during controlled charge and discharge cycles, structured as follows:

- **Charging phase:** Constant current of 20 A for approximately 6 hours.
- **Discharging phase:** Resistive load of 0.1 Ω with active dissipation, lasting around 5 hours.
- Charge phase: constant current of 20A, approximately 6 h.
- Discharge phase: with a resistive load of 0.1Ω with active dissipation, approximately 5 h.

Two experimental setups were implemented to assess the swelling force generated during these cycles:

1) Swelling Force Measurement via Pressure Sensor

A custom testing rig was constructed using two rigid steel plates, each 10 mm thick, to create a stable and constrained enclosure for the battery cell. The RP-S40-ST pressure sensor was positioned between one of the plates and the cell surface. A free-moving surface on the opposite side allowed for the application of external force via a dynamometer rod. The plates were tightly bolted together, as shown in Fig. 2 (b), ensuring consistent contact. The RP-S40-ST sensor's resistance, inversely related to applied pressure, was measured using a 12-bit analog-to-digital converter (ADC) to estimate deformation.

2) Swelling Force Measurement via Dynamometer

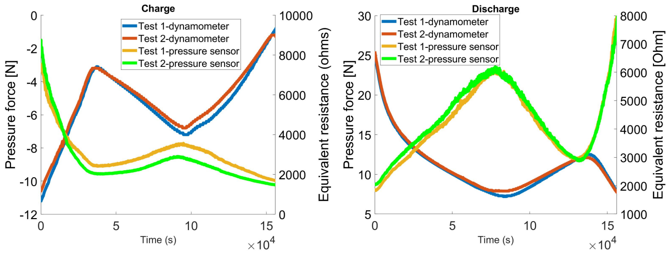
The same rig described above was used, with the addition of a dynamometer placed against the free-moving surface of the battery cell to directly measure the exerted force.

- During the **loading phase**, a preload of 10 N was applied to eliminate the air gap between the sensor and the plate.
- During the **unloading phase**, the offset was increased to 40 N to account for the reduction in force as the battery deflated.

Force data were recorded directly from the dynamometer and post-processed to generate time-based force profiles, enabling analysis of swelling behavior throughout the charge–discharge cycle.

D. Results and Discussion

Swelling force measurements obtained using the dynamometer yielded promising and repeatable results. As shown in Fig. 3, during the initial phase of the charging cycle, the pressure exerted on the cell face decreases significantly, likely due to internal electrochemical reconfiguration. This is followed by a stabilization phase, during which slight swelling and minor deflation are observed. In contrast, the discharge cycle exhibits a nearly symmetrical trend: the cell initially deflates, then stabilizes, experiences a brief swelling phase, and finally deflates again. Multiple charge-discharge cycles confirmed this trend, with consistent and repeatable behavior across trials.



(a) (b)

Fig. 3. Measured strain (a) charge cycle (b) discharge cycle

The pressure sensor-based measurements showed similar behavior. However, due to the RP-S40-ST sensor's exponential response to applied pressure, resistance changes were more prominent during the early charging phase. A substantial decrease in resistance—indicative of increased pressure—was followed by a moderate increase and a slight final decline. These observations are presented in Fig. 3. The agreement between both measurement methods confirms their validity and aligns with previous studies on $LiFePO_4$ cell swelling characteristics [9].

The Fig. 2 (c) shows the RFID based wirless strain measurement setup on a battery cell. The setup includes a ThingMagic M6e Nano RFID reader operating in the EU3 frequency band (865–868 MHz). The sensing element (SE) is connected in parallel to the RFID tag antenna, which transmits a dynamic SENSOR CODE based on the strain experienced by the SE. Data acquisition and plotting were performed using custom-developed software in Visual Studio Code. While the data collected through this RFID-based setup is not presented in this article for brevity, a comprehensive discussion of the results will be included in a forthcoming extended version of this work.

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