Application Note

Design to Achieve Both EIS Excitation and APB Functions on the Same Circuit in ESS

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ABSTRACT

ESS has new trend to use larger cell capacity (280Ah -> 314Ah -> 684Ah…) to save cost while with more challenges on safety and cell balancing. EIS is emerging requirements to monitor battery's temp and SOX to achieve higher safety by measuring cell's internal resistance at different freq. So, EIS excitation circuit is required to generate frequency-varying current on cell's internal resistance (micro-ohm) to make it measurable. Large cell capacity requires active balancing for faster cell balancing. Ti EI SEM propose total EIS solution to help customers realize active pack balancing and EIS excitation within one circuit.

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1 Introduction

With the rapid expansion of the global Energy Storage System (ESS) market, the industry is witnessing a significant shift toward larger lithium-ion battery cells. Cell capacities have escalated from the traditional 280Ah to 684Ah, and even beyond 1000Ah as shown in Figure 1 . While this trend increases energy density and reduces system footprint, it introduces a critical safety crisis. As of May 2025, over 167 major global ESS safety incidents have been recorded, placing immense pressure on Battery Management System (BMS) safety design.

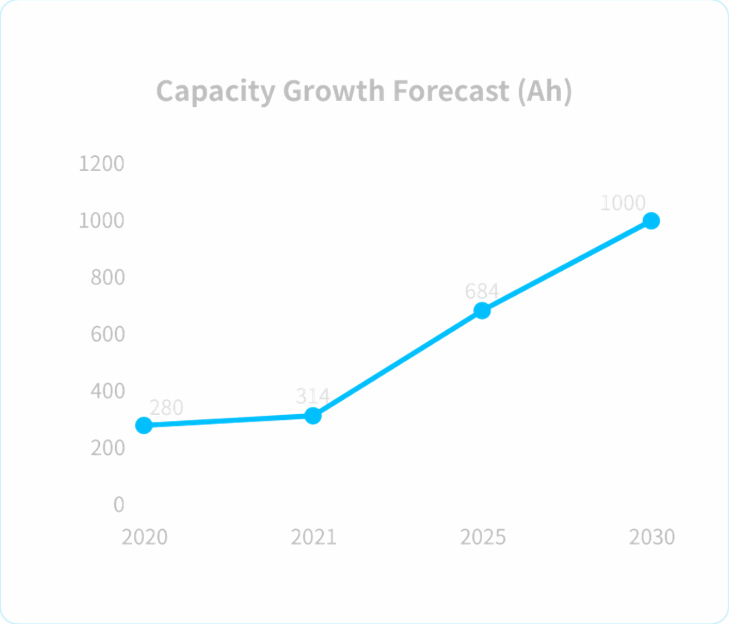

Figure 1-1. Energy Storage Cell Capacity Growth Trend

1.1 The Challenge of *Time Difference* in Heat Conduction

The core technical problem in high-capacity cells is the *time lag* between the core and surface temperatures. In large-format cells, internal thermal runaway propagates much faster than heat can reach the surface. Legacy BMS architectures, which rely solely on surface temperature sensors (NTCs), typically provide a warning window of less than five minutes. This is insufficient for the Power Conversion System (PCS) to safely de-energize or for fire suppression systems to activate before catastrophic failure.

1.2 Thermal Runaway: A Multi-Stage Failure Process

Thermal runaway is not an instantaneous event, but a multi-stage process as shown in Figure 1-2:

- **SEI Layer Decomposition (80°C–120°C):** The earliest stage where internal chemical changes begin.
- **Electrolyte Decomposition (150°C–200°C):** Accompanied by gas release and internal pressure buildup.
- **Cathode Material Breakdown (>200°C):** Leading to violent exothermic reactions and fire.

Traditional temperature sensors only trigger an alarm during the final breakdown stage, missing the critical window for preventive action.

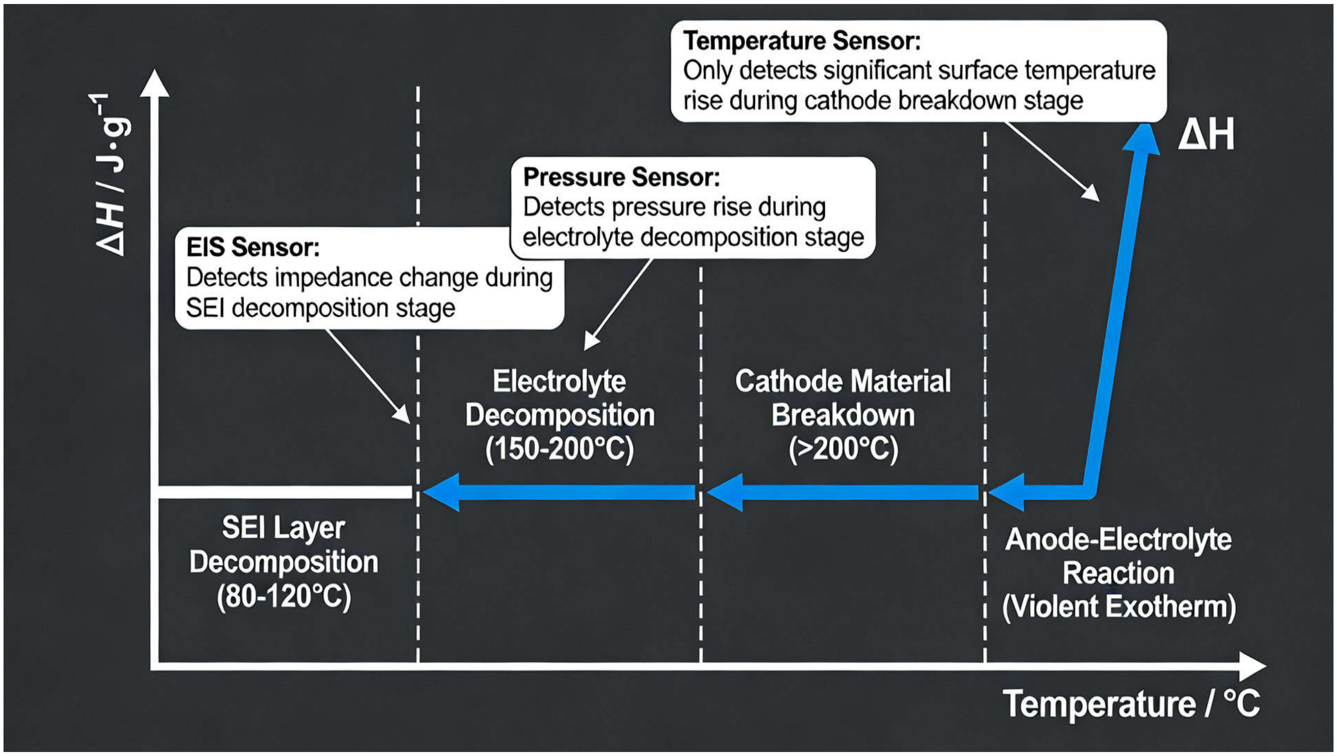

Figure 1-2. A Multi-Stage Failure Process

1.3 TI's Tiered Safety Design Hierarchy

To address these challenges, Texas Instruments proposes a multi-modal sensing framework that prioritizes detection speed. This hierarchy allows designers to balance cost and safety requirements across different architectures:

1. **Fastest (EIS)**: By monitoring internal impedance changes during the SEI decomposition stage, **Electrochemical Impedance Spectroscopy (EIS)** provides a **26-minute *head start*** over temperature sensors.
2. **Mid-tier (Pressure & Gas)**: Integrated sensors like the **TPR110x** (Pressure) and **HDC3020** (Humidity/Leakage) detect electrolyte off-gassing and coolant leaks, providing a 9.5-minute warning window.
3. **Baseline (Temperature)**: High-precision sensors such as the **TMP61** provide the mandatory final layer of thermal monitoring.

1.4 Comprehensive Reference Designs

This application note details TI's scalable designs for implementing this safety framework, featuring:

- **TIDA-010978 & TIDA-010990**: A combined design for online EIS measurement using the **C2000™ F28P55** and **BQ79826** AFE, leveraging Active Pack Balancing (APB) as the excitation source.
- **TIDA-010995**: A multi-modal *Safety Cell* design integrating pressure, humidity, and temperature sensing for comprehensive module-level protection.

By transition from reactive to proactive monitoring, these technologies enable next-generation ESS to meet the stringent safety demands of utility-scale and commercial energy storage.

This paper focuses on EIS designs.

2 Detailed Description

2.1 Electrochemical Impedance Spectroscopy (EIS) Theory

Electrochemical Impedance Spectroscopy (EIS) is a non-invasive diagnostic technique that characterizes the internal state of a battery by injecting a small-signal AC excitation and measuring the resulting voltage response across a range of frequencies, as shown in Figure 2-1.

- **Excitation Signal**: A sinusoidal current

  $$i(t) = I_m \sin(\omega t) \quad (1)$$

  is injected into the battery cell.
- **Response Signal**: The measured voltage response is

  $$v(t) = V_m \sin(\omega t + \theta) \quad (2)$$

  , where θ represents the phase shift.
- **Impedance Calculation**: According to Ohm's Law in the frequency domain, the complex impedance $Z(\omega)$ is calculated as:

$$Z(\omega) = \frac{v(t)}{i(t)} = |Z|e^{j\theta} = Z_{real} + jZ_{img} \quad (3)$$

Where $|Z|$ is the magnitude, and the real and imaginary parts represent the purely resistive and reactive components, respectively.

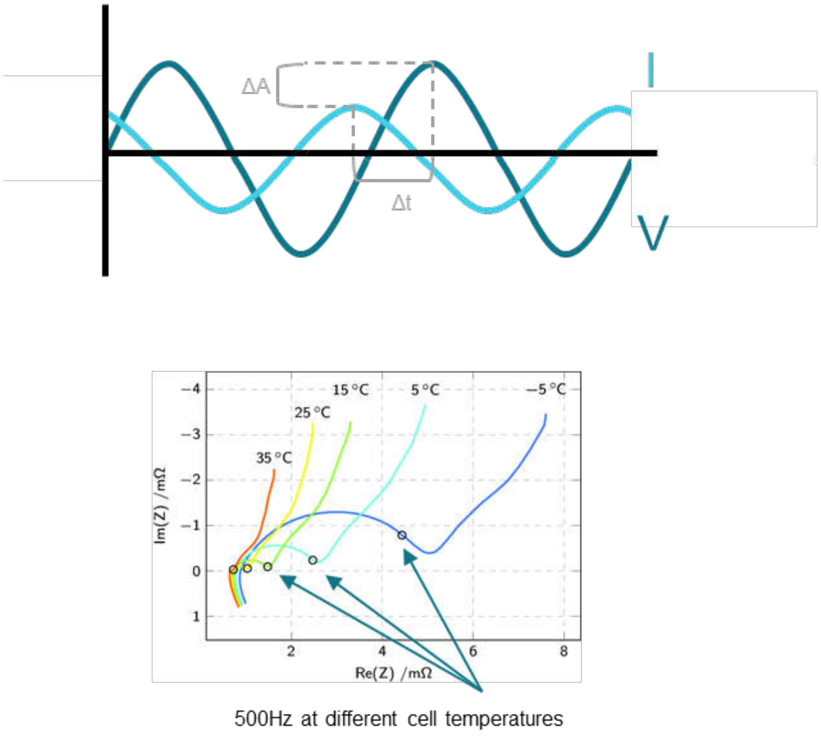

Figure 2-1. EIS Principle

By scanning frequencies from 0.01Hz to 3.5kHz, the system generates a Nyquist Plot. During the early stages of thermal runaway (SEI layer decomposition), the mid-to-high frequency impedance (Charge Transfer Rsistance, R_{ct}) exhibits a measurable shift long before any significant rise in surface temperature.

2.2 System Architecture Implementation

The implementation leverages a dual-board architecture combining the TIDA-010990 (Excitation) and TIDA-010978 (Measurement) reference designs, as shown in Figure 2-2.

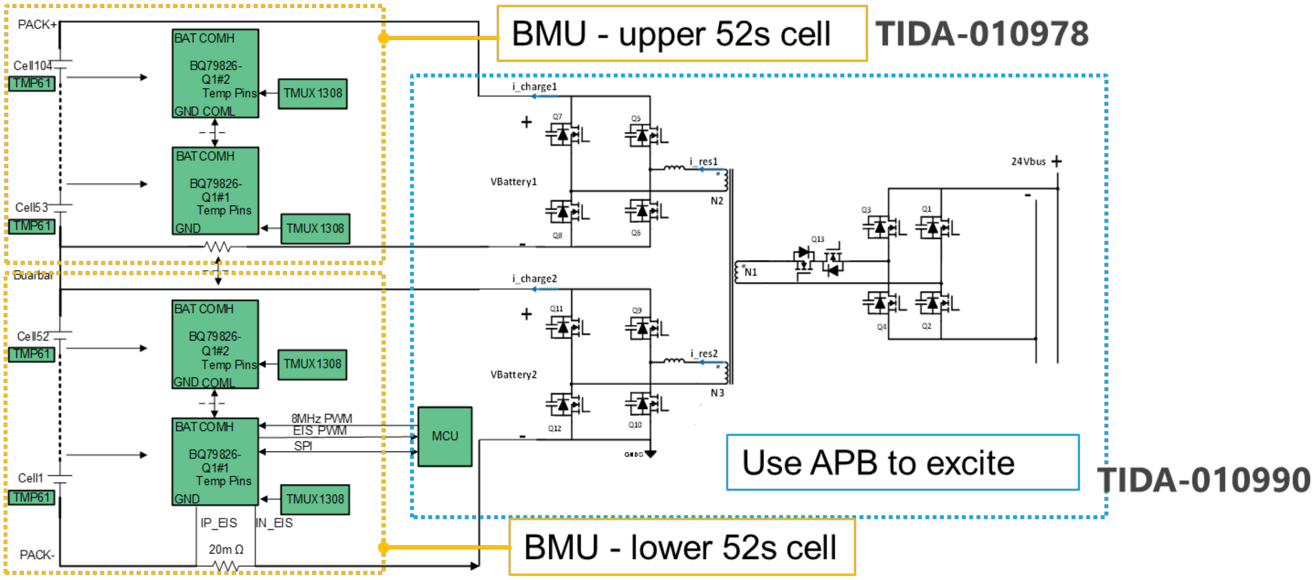

Figure 2-2. Pack EIS Combo Design

2.2.1 AC Excitation Generation (C2000™ F28P55 + DAB)

To generate the high-amplitude AC excitation (up to **5A**) required for low-ohmic ESS cells, the system reuses the **Active Pack Balancing (APB)** circuitry.

- **Topology**: A Dual Active Bridge (DAB) converter is controlled by the C2000™ F28P55.
- **Modulation**: The MCU utilizes the HRPWM (High-Resolution PWM) module to execute frequency and phase-shift modulation, verifying a high-purity sinusoidal current injection even at very low frequencies (<1Hz).
- **Feedback**: The TMCS1123 Hall-effect sensor provides precision current feedback to the C2000 control loop, maintaining the stability of the excitation amplitude.

2.2.2 Online Measurement Engine (BQ79826-Q1)

The **BQ79826-Q1** Battery Management Unit (BMU) features a dedicated integrated EIS engine.

- **Simultaneous Sampling**: The AFE performs synchronized high-speed sampling of both cell voltage and string current. This hardware-level synchronization eliminates phase errors typically caused by sequential ADC sampling.
- **On-chip DFT**: Unlike traditional solutions requiring heavy MCU computation, the BQ79826-Q1 integrates a hardware Discrete Fourier Transform (DFT) engine. It calculates Z_{real} and Z_{img} internally, allowing the MCU to retrieve processed impedance data via SPI, significantly reducing communication overhead and CPU utilization.

2.3 Software Architecture and Task Scheduling

The software on the F28P55 is organized into a multi-rate task framework to balance real-time control with data processing requirements.

Different tasks cycle in MCUs are listed in Table 2-1.

Table 2-1. Different Task Cycles in MCUs

Task Cycle	Module	Description
20us	Control Loop/PWM/ADC Trigger	Executes DAB control algorithms (PI regulation, phase shift angles) to maintain the AC excitation profile.Triggers ADC sampling of current and voltage for the instantaneous control feedback.
100ms	Cell Monitor	Reads standard cell voltages and temperatures from the BQ79826-Q1 stack.
5s	Diagnostics	Performs AFE diagnostic checks and monitors the nFault status for safety compliance.
300s	EIS Data Update	Retrieves the full-frequency DFT results from the AFE to update the Nyquist profile for thermal runaway analysis.

In high-voltage systems (for example, 104s configurations), synchronizing measurements across multiple AFEs is critical.

- **Global Clock**: The F28P55 provides an **8MHz synchronization clock** to the BQ79826 stack via the isolated daisy-chain interface.
- **Sync Trigger**: A hardware-timed sync pulse verifies all cells across the entire rack start ADC sampling and DFT calculations at the exact same microsecond, verifying the integrity of the multi-cell impedance data.

2.5 Experimental Results

The performance of the online EIS implementation is validated using high-capacity (314Ah) cells. To verify the reliability of the system, multiple measurement cycles are conducted to evaluate accuracy and repeatability.

The system uses the Mean$(\boldsymbol{\mu})$ and standard deviation $(\boldsymbol{\sigma})$ to quantify the consistency of the impedance data:

Mean value$(\boldsymbol{\mu})$:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{4}$$

Standard Deviation$(\boldsymbol{\sigma})$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (x_i - \mu)^2} \tag{5}$$

Based on the test results, as shown in Fig. 6, the Coefficient of Variation$(\boldsymbol{cv})$ remains significantly low across the target frequency spectrum:

$$cv = \frac{\sigma}{\mu} \times 100\backslash\% \tag{6}$$

- **Magnitude Performance**: The deviation is verified to be **less than 2%**, ensuring high fidelity in capturing the internal resistance changes.
- **Phase Performance**: The phase error is maintained **within 1°**, providing the precision required to distinguish complex electrochemical processes.

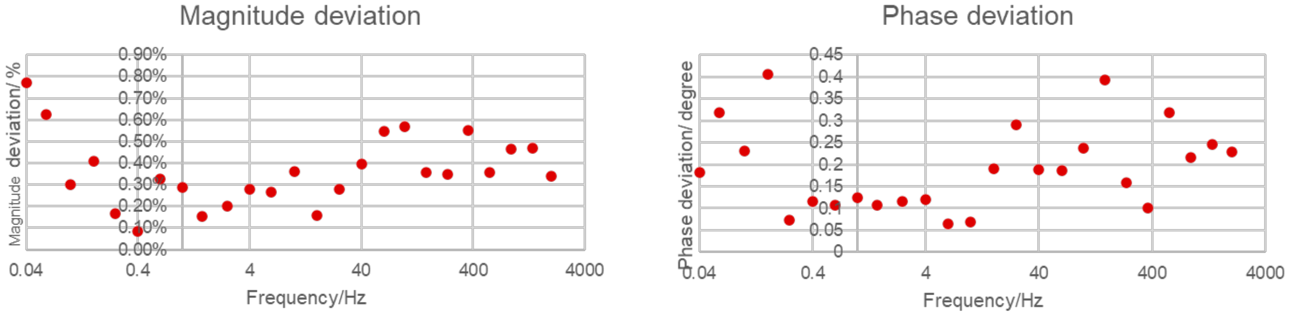

Figure 2-3. Deviation and Repeatability of Single Cell from Pack

The online EIS system successfully generated Nyquist plots for 314Ah cells, covering frequencies from 0.1Hz to 2kHz as shown in Figure 2-4.

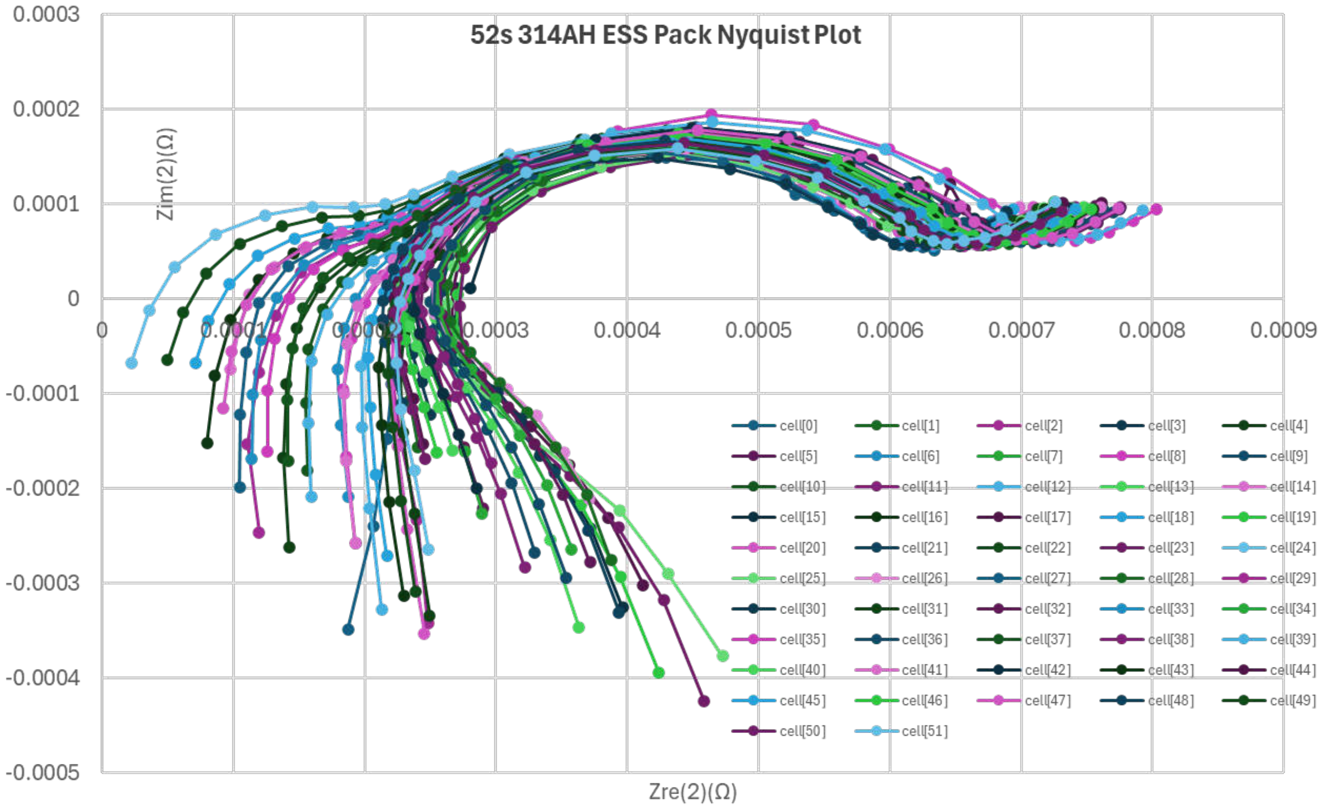

Figure 2-4. Nyquist Plot

3 Summary

This paper provides a cost-effective and high-precision method for online **Electrochemical Impedance Spectroscopy (EIS)** by reusing the **Active Pack Balancing (APB)** circuitry as the excitation source.

- **Integrated Excitation Architecture**: The system utilizes the **C2000™ F28P55** to control the APB (DAB topology), superimposing a precisely modulated AC current (up to **5A**) onto the battery string. This eliminates the need for dedicated external signal generators.
- **Hardware-Accelerated Sensing**: The **BQ79826-Q1** AFE performs simultaneous voltage and current sampling. By leveraging its on-chip **DFT engine**, the system calculates impedance magnitudes and phases internally, minimizing MCU overhead and SPI bus traffic.
- **Proven Measurement Precision**: Experimental validation on 314Ah cells demonstrates a **magnitude deviation of < 2%** and a **phase deviation of < 1°** across the critical frequency range (0.1Hz to 2kHz).

The APB+EIS synergy on the F28P55 platform offers a scalable, high-performance diagnostic tool that enhances ESS safety without significantly increasing system BOM cost.

4 References

1. Texas Instruments, *Bidirectional Isolated Dual-Bridge Series Resonant DC/DC Converter Reference Design for Pack Balance*, design guide.

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