

Next-Generation Battery Monitoring With Electrochemical Impedance Spectroscopy



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ABSTRACT

Battery adoption in high-power applications such as electric vehicles (EVs), energy storage systems (ESS), and industrial robotics continues to drive innovation in battery management monitoring and control. Next-generation battery management systems (BMSs) must extend battery life, ensure the highest reliability, and enable the utmost safety for users and passengers.

Incidents such as recalls for failing batteries, overused cells, and rapid battery pack failures that result in fires and property damage, have harmed the reputation of several battery vendors and original equipment manufacturers. Industry leaders and government regulators are making detection methods and safety top priorities for the next generation of battery products.

To meet these safety and reliability challenges, designers are turning to electrochemical impedance spectroscopy (EIS), a technique applied to batteries for decades. EIS is a method designed to excite a battery cell and monitor the reaction of the battery, which gives insight into the condition and state of the cell. This process allows designers to monitor different aspects of a battery cell using noninvasive electrical signals to provide critical information on battery temperature, battery charge (state of charge), battery fade (state of health), thermal runaway detection, and much more.

This white paper highlights some of the challenges facing battery system designers today, and how EIS can help enable a much more reliable and long-lasting battery design.

Table of Contents

1 Introduction	2
2 Analyzing Batteries With EIS	2
2.1 What Has Changed? Regulation Driving Earlier Detection.....	2
2.2 What is EIS?.....	2
2.3 How Does a Battery EIS Work?.....	3
2.4 How to Use Impedance Data.....	3
2.5 What Other Insights Does EIS Provide?.....	4
3 Impact of EIS: Three Use Cases	5
3.1 Thermal Runaway Detection.....	5
3.2 Faster Charging.....	6
3.3 Charge and Availability.....	7
4 Measuring EIS	8
4.1 EIS System Architecture.....	8
4.2 Parameters for EIS Measurement.....	9
4.3 TI's EIS Chipset.....	10
4.4 Reference Designs.....	10
5 Conclusion	11

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1 Introduction

The EV sector has grown dramatically over the past decade. The transition required significant engineering advances to overcome early limitations in range, charging speed, and battery reliability. Still, while skeptics point to range anxiety and the gradual loss of capacity that can occur over time with batteries, breakthroughs have addressed those concerns, including:

- **Increased battery density** from 100Wh/kg to 300Wh/kg through advances in cell chemistry and manufacturing.
- **Improved charging infrastructure** enabling faster charging, reducing charge times from eight or more hours to under 30 minutes for an 80% charge.
- **More accurate battery monitoring** using advanced, high-voltage, application-specific semiconductors, enabling the ability to manage packs with >200 cells in series across 400V and 800V architectures.

Despite all of these improvements, battery system designers still face three core challenges:

- **Life-cycle management:** Designers must improve the reliability and longevity of higher-density lithium cells, including lithium iron phosphate (LFP) and nickel manganese cobalt (NMC). These cells are sensitive to temperature swings, overcharging, undercharging, and high charge rates such as fast charging, requiring a delicate balance of monitoring and control to ensure reliability and stability.
- **Aging and capacity fade:** Cell capacity fade, or how much the battery can hold as the battery ages, is often modeled but not measurable today, making predictions difficult. Consumers have similar experiences with new smartphones: a full battery charge lasts multiple days at the beginning but slowly loses capacity until the battery holds only a fraction of the original charge.
- **Safety and thermal runaway:** Detecting the cell stress and damage that triggers catastrophic thermal runaway remains the most urgent challenge of the industry, driven by both industry pressure and government regulation.

The adoption of new tools to address these challenges is making battery systems safer and more reliable for demanding applications. One of the most promising technologies is EIS, which gives designers real-time insights into the state and condition of the battery, allowing designers to effectively see inside the cell.

2 Analyzing Batteries With EIS

2.1 What Has Changed? Regulation Driving Earlier Detection

Thermal runaway—defined as a chain reaction in which a cell starts to self-heat, pressurize, and eventually combust—can spread rapidly to other cells and cause the entire pack to catch fire. The event is nearly impossible to stop, and can only be contained.

For this reason, battery industry experts and government regulators are taking steps to enable earlier detection to provide drivers with a longer warning time.

In 2020, the Chinese Guobiao (GB) 38031 national standard required at least a five-minute egress period after a thermal runaway warning. A GB 38031-2025 revision taking effect in July 2026 extends that window to at least two hours once a single cell enters thermal runaway before a fire or explosion is visible outside the pack.

These standards put extreme pressure on automakers to detect thermal runaway at the individual cell level and capture every possible minute of warning time. Unfortunately, few solutions today can meet this requirement with confidence. EIS offers a way to deliver measurable, cell-level insights integrated into next-generation BMS devices from Texas Instruments (TI).

2.2 What is EIS?

Let us start by breaking down EIS. Spectroscopy is a technique used in many systems to detect characteristics of the system by exciting across a frequency range and measuring the response. For example, in biospectroscopy, a smart scale estimates body composition by sending current signals of various frequencies through the body to measure muscle, fat, and water.

The electrochemical portion of EIS applies the same principle to batteries. Electrical signals measure the chemical reaction of a battery. Measurements such as tracking the lithium location in the cell or determining whether the anode or cathode remains intact are useful chemical properties to monitor ([Figure 2-1](#)). The goal

of spectroscopy is to gain deeper insights into the internal, frequency-dependent behavior of the cell in a nonintrusive way.

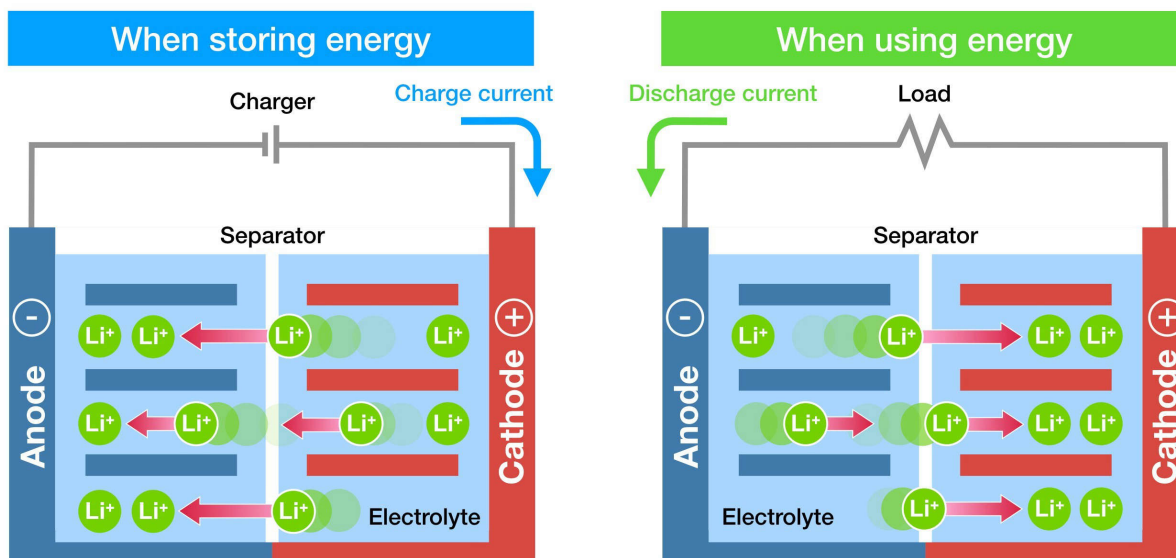


Figure 2-1. Battery Lithium-ion Flow During Charging and Discharging

2.3 How Does a Battery EIS Work?

TI's [BQ79826Z-Q1 battery monitor](#) and [BQ79881-Q1 battery junction box pack monitor](#) apply current excitation to a battery cell, module, or pack and measure the responding voltage. Figure 2-2 shows the current and voltage inside a battery. Comparing the amplitude difference (impedance magnitude) and time difference (impedance phase) across frequencies and monitoring the changes over time, temperature, charge, or other battery parameters offers insight into what is happening inside the cell.

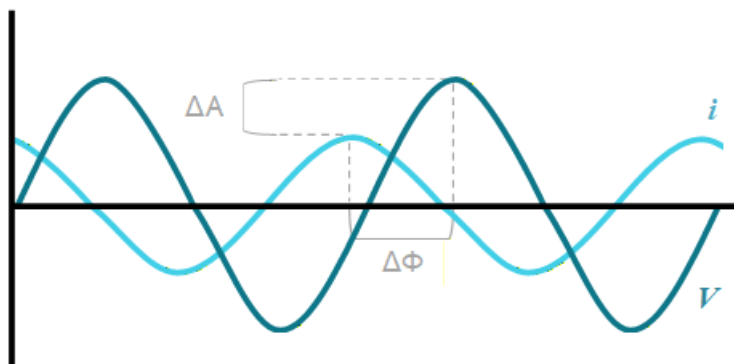


Figure 2-2. EIS Measurement Using Current and Voltage

2.4 How to Use Impedance Data

Once a BMS is enabled with impedance measurement capability, identifying the battery parameters that correlate with the impedance becomes the focus.

A Nyquist plot is a common technique to visualize impedance over frequency. Figure 2-3 shows the real impedance on the x-axis and the imaginary impedance on the y-axis. Each line comprises a sweep of frequencies from 0.1Hz to 1kHz, with the lowest frequency on the right and the highest on the left. The line color in Figure 2-3 indicates the temperature of the battery during the sweep.

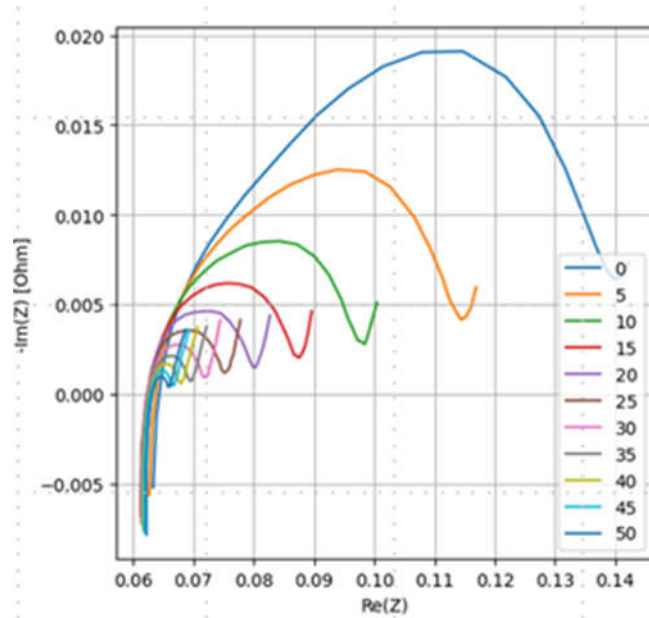


Figure 2-3. Temperature Versus Impedance Nyquist Plot

In the plot, the impedance curves change shape versus temperature. Furthermore, the black circle, which represents a single impedance at 500Hz, moves as the temperature changes. Designers can use this EIS-based temperature data to identify the core temperature of the battery, monitor spikes in temperature during charging, and reduce the number of temperature sensors needed in the system.

2.5 What Other Insights Does EIS Provide?

Beyond simple temperature measurements, EIS provides insights into specific battery components such as anode, cathode, lithium diffusion, solid electrolyte interphase (SEI) layer integrity, and other components important to battery operation. These parameters become clear when breaking down the Nyquist plot by shape and frequency. Figure 2-4 shows the frequency regions and equivalent circuit models used in EIS analysis.

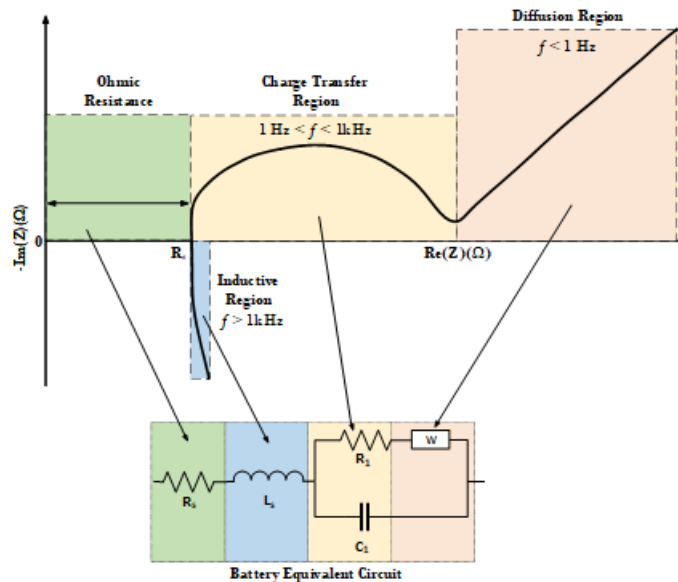


Figure 2-4. Identifying Battery Components in a Nyquist Plot

The regions or Nyquist shapes outlined by the colored boxes highlight specific areas to monitor in the battery cell:

- **Ohmic resistance (green box, horizontal line):** This region shows the DC resistance of the electrolyte, indicating if there are any shorts in the battery potentially caused by manufacturing defects, assembly errors, or damage from events such as a vehicle crash or storm.
- **Charge transfer region (yellow box, semicircle):** This region often indicates the health of the electrode-electrolyte interface where the ions and electrons meet in the electrodes. One of the most important physical components in the cell monitored in this region is the SEI layer that allows the combining and separating of the ions and electronics. If the SEI layer starts to deteriorate, this deterioration often indicates the age of the cell and can be a reasonable predictor of cell failure.
- **Diffusion region (red box, 45 degree line):** Correlating to the lithium diffusion process in the anode and cathode, this region helps assess state of charge, state of health, and the ability of the cell to charge or discharge at any one time.

Combining physical modeling of the battery cell with in-vehicle EIS measurements lets the BMS assess health, aging, and possible damage to the battery in real time.

3 Impact of EIS: Three Use Cases

Let us look at three use cases for EIS based on data and market requirements.

3.1 Thermal Runaway Detection

Thermal runaway is the catastrophic failure of cells and packs that leads to hazardous conditions for people and can cause substantial collateral damage. [Figure 3-1](#) shows multiple cells in an EV battery pack.



Figure 3-1. Lithium Cells in an EV Battery Pack

Previous BMS generations relied on slow-reacting temperature sensors that typically provided detection only after multiple cells had already entered thermal runaway. Most BMS designs in the market today add expensive pressure and gas sensors that detect the venting of a cell, which can occur only a few minutes before a fire. Both approaches fail at the individual cell level.

EIS detects the core temperature and impedance changes of each and every cell. EIS can flag earlier stages of thermal runaway by monitoring the core temperature of the cell based on electrical impedance measurements, which is not possible with traditional temperature sensors.

Additionally, EIS detects anomalies or irregularities in the battery. One primary cause of thermal runaway is dendrite growth, or a buildup of lithium on the anode, which causes a short inside the cell (Figure 3-2). Monitoring the impedance of each cell enables individual cell monitoring for issues that develop gradually over time. This cell-level visibility directly supports the two-hour warning window required by GB 38031-2025.

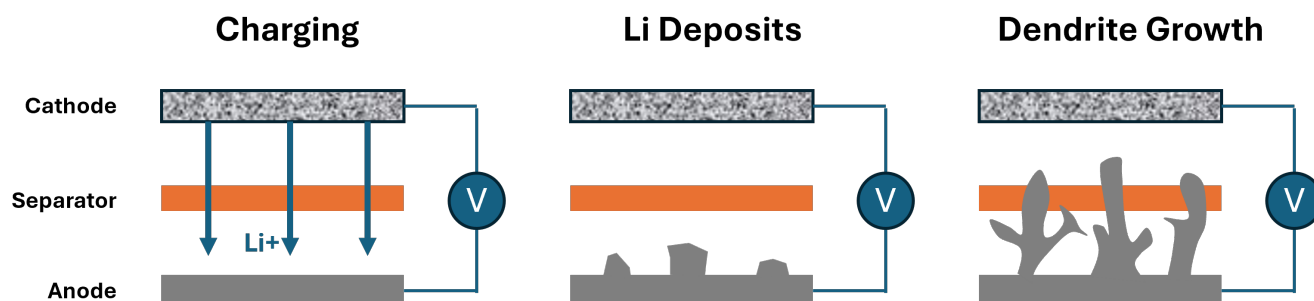


Figure 3-2. Dendrite Growth Leading to Thermal Runaway.

3.2 Faster Charging

The topic of EV charging has overshadowed many of the inherent benefits of EVs, because consumers do not want to wait to charge an EV vehicle. The convenience of filling a gas tank over charging an EV battery has pushed the industry to target faster and faster charging capabilities, and rightfully so.

Consumers need fast charging when away from home or on a road trip. Commercial vehicles, including trucks and buses, rely on fast charging by necessity because these vehicles operate continuously.

Unfortunately, frequent fast charging can accelerate battery aging, shortening battery pack lifetime by 10% to 20%. High-current charging stresses battery components and can lead to an irreversible condition called lithium plating. Lithium plating is the buildup of lithium on the anode caused by poor lithium diffusion, meaning that the cell is not ready to accept additional electrons. Temperature, charge level, and aging of the thin SEI layer all influence when plating begins. These stresses and the lithium diffusion of the cell are why device manufacturers recommend against charging a battery to 100%.

EIS helps designers manage fast charging in two ways:

- **Temperature monitoring** keeps environmental and core battery temperatures within an acceptable range during fast charging. Low temperatures restrict diffusion while fast charging can raise battery temperatures, so constant monitoring is essential.
- **Diffusion monitoring** provides insight into the diffusion region (the *tail* of the Nyquist plot) in real time. If the impedance becomes too high, for example, the charge current must be lowered.

While monitoring lithium diffusion provides warning signs of battery aging, these monitors let system designers increase charging currents. Instead of relying on static, modeled parameters of lithium diffusion that require extra built-in margin and effectively limit the maximum charge rate, a direct measurement tells the system when to reduce the current. Keeping the impedance low enables even faster charging.

The EIS engine in TI's BQ79826Z-Q1 enables diffusion sensing with ultra-low-frequency detection $\leq 0.01\text{Hz}$ and reduces measurement time by exciting up to five impedance frequencies simultaneously (Figure 3-3).

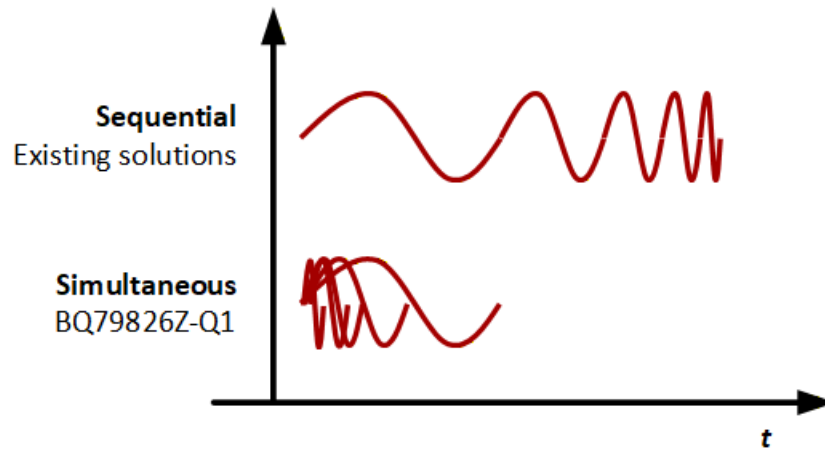


Figure 3-3. Short Measurement Time With Simultaneous Frequency

3.3 Charge and Availability

Battery state of charge and state of health are important parameters for every battery system. EIS does not replace traditional DC-voltage measurements, but enhances the availability of meaningful data to make decisions and improves existing systems in two ways:

- **DC voltage accuracy:** LFP cells show a very flat voltage versus state-of-charge curve between 30% and 90% (as shown in [Figure 3-4](#)), which makes traditional open-circuit voltage measurements inaccurate. EIS improves accuracy by providing a direct state-of-charge measurement, reducing worst-case errors from 5% or 10% to <2% and delivering a more usable charge.
- **Detecting battery health while idle:** Many ESS systems remain idle for extended periods of time, so knowing whether a cell can deliver the charge when necessary is difficult. Unfortunately, DC voltage alone cannot measure lithium diffusion or impedance. EIS lets system designers periodically check the health of the battery, verifying that the system is ready to deliver power when required.

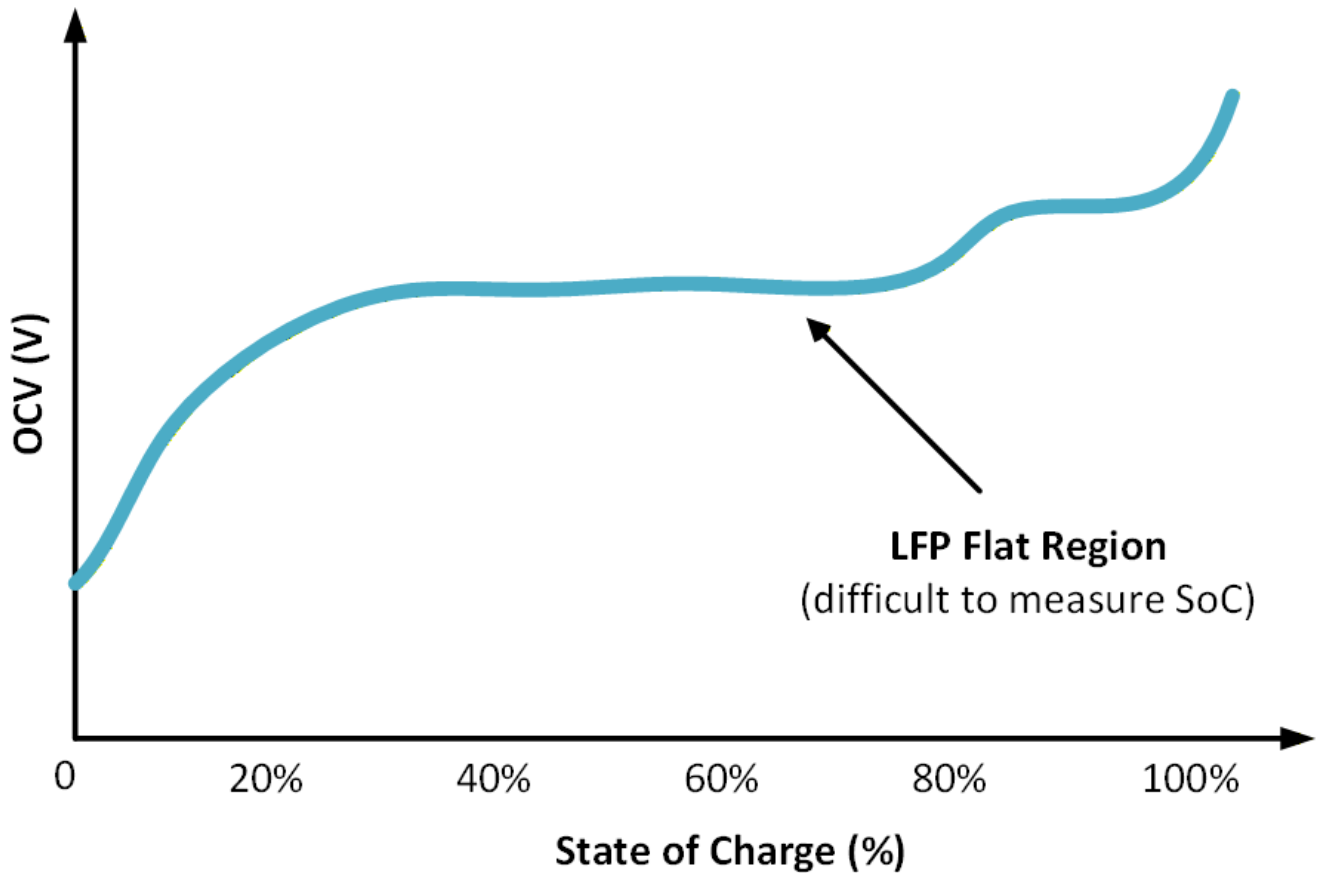


Figure 3-4. LFP Open Circuit Voltage Versus State-of-Charge Curve Showing Flat Region

EIS offers additional insights when traditional BMS methods are complex or impossible to measure, providing more accurate state of charge and maintaining power availability.

4 Measuring EIS

4.1 EIS System Architecture

An EIS-enabled BMS builds on a traditional architecture, including multiple, stacked battery monitors for voltage sensing and a pack monitor for current sensing, plus these two components (Figure 4-1):

- **A current excitation source** creates a sine, square, or other shaped waveform to excite the cells.
- **Synchronous voltage and current sampling** synchronizes the oscillator between the current- and voltage-measurement devices to reduce impedance phase errors.

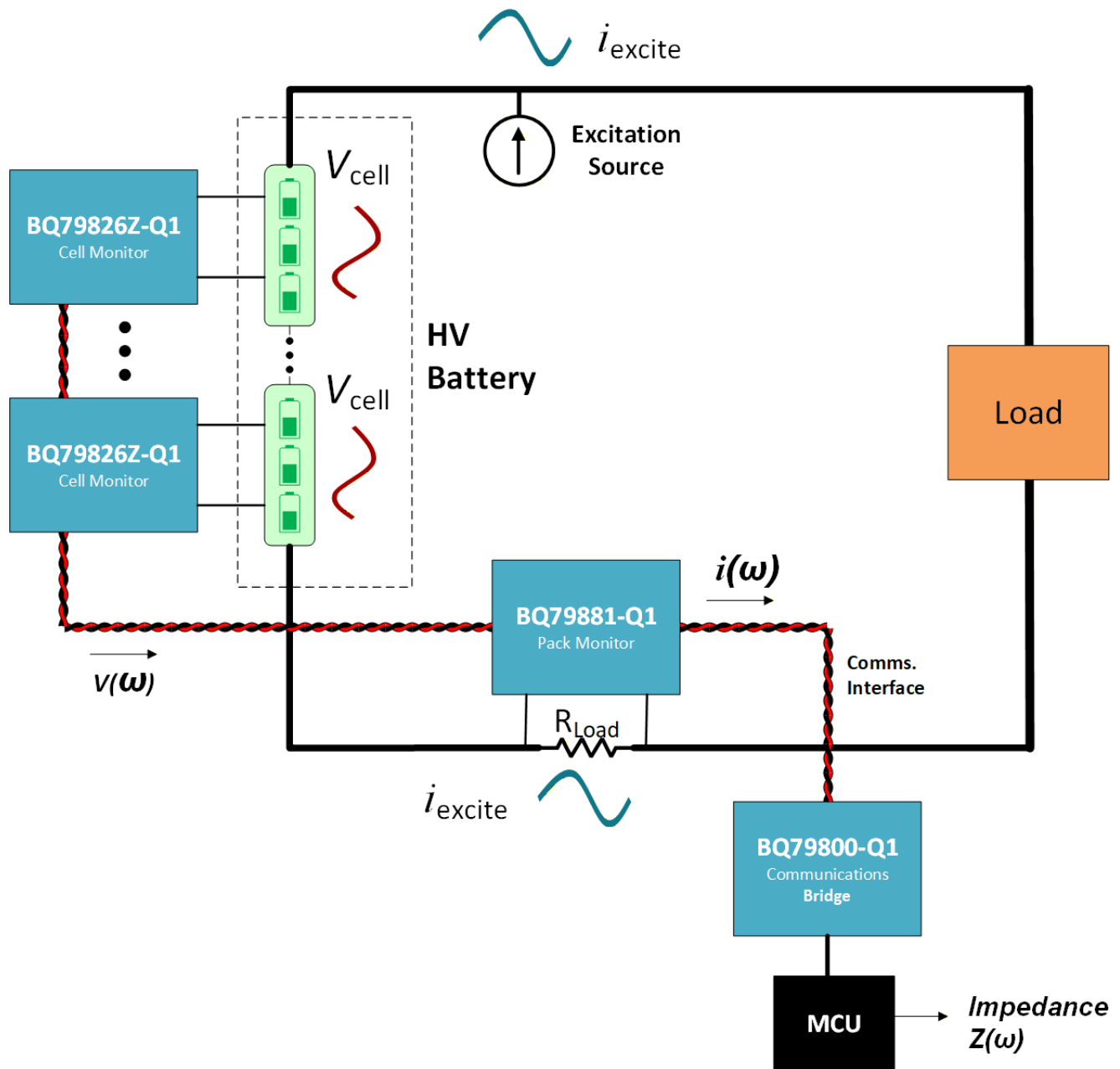


Figure 4-1. Pack EIS System Block Diagram

Figure 4-1 shows a typical battery pack configuration, including two BQ79826Z-Q1 cell voltage monitors and one BQ79881-Q1 pack monitor for current. The BQ798xx monitors include an integrated synchronization protocol that keeps current and voltage measurements tightly aligned, minimizing impedance phase error. The excitation source can be directly controlled by the BQ798xx devices or generated by an existing source in the end equipment such as a DC/DC converter, charger, balancer, precharge circuit or inverter.

4.2 Parameters for EIS Measurement

Optimizing an EIS system requires attention to three electrical design parameters:

- **Cell impedance:** A battery has a range of impedances over the operating life of the battery, which designers can capture in a Nyquist plot. The impedance directly dictates the amount of current required to excite the cell. For example, a 100Ah cell typically shows an impedance of $500\mu\Omega$ to $750\mu\Omega$ and can require a peak of 1Ap to 2Ap for the analog-to-digital converter (ADC) measurement.

- **Excitation current amplitude:** The current amplitude affects the battery linearity requirements and the optimal measurement range of the ADC. Linearity ensures that the battery responds with a sine wave when excited with a sine wave. The goal is to keep the current excitation amplitude as low as possible to limit power consumption.
- **ADC noise:** Low ADC input-referred noise is essential for a high signal-to-noise (SNR) ratio, as voltage and current signals can be in the microvolt range. Selecting a low-noise ADC improves SNR and reduces the required excitation current.

4.3 TI's EIS Chipset

The BQ79826Z-Q1 and BQ79881-Q1 battery monitors enable designers to measure the impedance of every cell with TI's integrated EIS engine. Capturing impedance across all EIS frequency bands is possible down to 0.01Hz, detecting nuanced impedance linked to temperature, state of charge, and thermal runaway.

Together, the BQ798xx chipset forms a complete BMS (as shown in Figure 4-2), offering a stackable 26-channel battery monitor for large battery-cell-count configurations and a high-precision pack monitor for measuring current and pack voltages.

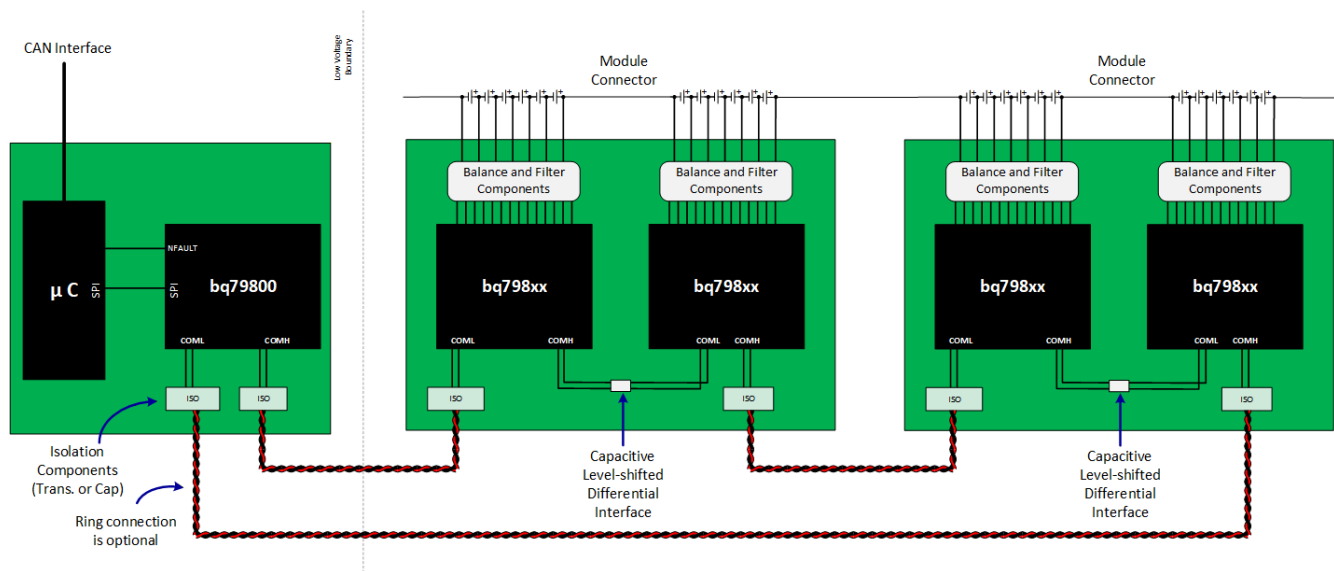


Figure 4-2. BQ798xx BMS Block Diagram

The devices meet the demanding requirements of growing battery capacities, enabling measurement of very small impedances with the EIS-optimized design. Very low-noise ADCs for voltage and current sensing improve the SNR; a wide frequency range from 0.01Hz to 3.5kHz covers vital impedance regions; and stack synchronization minimizes the time between current and voltage measurements, reducing phase error.

4.4 Reference Designs

To evaluate EIS quickly with BQ79826Z-Q1 and BQ79881-Q1, TI provides reference designs that include hardware, software, and system-level support. Designers can perform most EIS evaluations with standard BQ79826 and BQ79881 [evaluation modules](#) by connecting the evaluation modules directly to the battery cell, modules, or pack. TI also supplies a software solution for EIS performance testing, data collection for algorithm development, and in-vehicle integration. Additionally, several [reference designs](#), including TI's EV BMS 3.0 reference design, help designers speed planning, testing, and development time of BMS and EIS systems.

Other reference designs available from TI by request include:

- 52 cells in series to 104 cells in series ESS systems: A pack or rack reference design for ESS systems.
- Stacked active bridge: A patented EIS excitation source with >99% efficiency.
- Active pack balancing: An excitation source based on a dual-active-bridge topology that uses existing pack balancing circuits to excite the cells.

5 Conclusion

The growing need for safer, more reliable, and longer-lasting batteries used in EVs, energy storage, and industrial robotics has influenced how BMS systems are designed, built, and what the systems can achieve. EIS makes BMS systems smarter, enabling faster detection of temperature spikes, more accurate state-of-charge estimates, and earlier warning of cell degradation. Such insights help designers extend battery life, increase charging speed, and improve safety.

TI's next-generation chipset with integrated EIS engine helps accelerate these capabilities to meet the future electrification goals of the industry.

About the author

Brian Burk is a systems engineer on Texas Instruments' Battery-Management Solutions team. Since joining TI in 2009, he has led R&D and product management for audio DSPs, amplifiers, motor-drive control, power electronics, and battery-management systems. As product manager and systems engineer for the automotive BMS line, he drives innovations such as electrochemical-impedance spectroscopy that keep TI's offerings at the forefront of automotive, industrial, and consumer electronics. He has championed forward-thinking solutions that earned more than 10 patents. Burk holds a B.S. in electrical engineering from the University of Texas at Austin and serves on TI's technical-leadership council.

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