*38th International Electric Vehicle Symposium and Exhibition (EVS38)*
*Göteborg, Sweden, June 15-18, 2025*

# System architecture comparison for practicable onboard electrochemical impedance spectroscopy

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**Executive Summary**

Battery degradation and state estimation remain critical challenges in the electric vehicle (EV) industry, affecting battery lifespan, customer confidence, and market growth. Electrochemical Impedance Spectroscopy (EIS) is a promising technique for battery health assessment through cell impedance analysis. Although traditionally restricted to laboratory environments with disassembled cells, recent studies have explored its potential for onboard integration. This work investigates existing solutions and proposes original approaches for implementing onboard EIS in EVs, taking into account the technical and architectural constraints of current vehicle systems. Various integration strategies are analysed and compared qualitatively across different domains to identify the most practical and feasible configuration. The findings aim to support the development of reliable onboard EIS battery monitoring systems that enhance energy management and prolong battery life in electric vehicles.

*Keywords: Electric Vehicles, Batteries, Battery Management Systems, Power Electronics systems, Measuring Methods & Equipment.*

## 1 Introduction

Achieving carbon neutrality by 2050 and meeting the electrification targets by 2035 requires facing challenges from different heuristics including technological developments, social acceptance, reusability, and recycling methods [1].
Incrementing electric vehicle (EV) sales must be a result of increasing its social acceptance, which requires proving a high-reliability (technical improvements), while reducing the purchasing price and the Total Cost of Ownership (TCO). The TCO is related to the vehicle lifespan but also to battery repurposing and materials circularity, thus, reducing the carbon footprint of battery and vehicle manufacturing process.
The battery accounts for nearly 30% of an EV's cost [2], and manufacturers shall guarantee a lifespan of 8 years or 160,000 km — under optimal driving and environmental conditions — until it reaches 80-70% of State of Health (SoH) [3, 4], at which point the vehicle battery may no longer suitable for driving use. However, some studies suggest that battery lifespan can be extended [5]. Enhancing battery state (SoX) estimations, including State of Charge (SoC) and SoH, directly influences energy management, which in turn impacts the battery's Remaining Useful Life (RUL). Therefore, exploring new methods and technologies that can contribute to improve battery parametrization and SoX estimations is a foremost challenge.

SoXs are typically determined by the Battery Management System (BMS), the main battery controller. Existing algorithms for battery state monitoring, such as Coulomb Counting, Incremental Capacity Analysis, and Kalman Filters, often exhibit inaccuracies and performance limitations [6]. However, advancements in controller development and computational processing are enabling the integration of more complex algorithms into automotive controllers to enhance SoX estimation and energy management.
As a result, new data acquisition and measurement techniques that traditional methods cannot process are becoming increasingly relevant. A key example is internal cell impedance, which not only improves SoH estimation but also serves as an early indicator of abnormal cell degradation [7]. This can help prevent hazardous events such as thermal runaway, making it a critical safety parameter.
Internal cell impedance can be obtained via an Electrochemical Impedance Spectroscopy (EIS) analysis, enabling the development of dynamic battery models that correlate with electrochemical processes within a battery [8]. EIS characterizes a battery cell's dynamic response to a small-amplitude current or voltage signal, using either galvanostatic or potentiostatic approaches over a wide frequency range, under pseudo-linear behaviour, and in compliance with Kramers-Kronig (K-K) conditions: causality, linearity, and stability [9]. Traditionally, EIS has been analysed under laboratory conditions, either by disassembling batteries for forensic evaluation or assessing cell groups before second-life applications, typically covering a frequency range of 0.01 Hz to 10 kHz. However, industrial applications, including automotive systems, are constrained to a narrower frequency range, usually between 0.1 Hz and 1000 Hz. Moreover, galvanostatic EIS is preferred in industrial settings, as small voltage excitations in potentiostatic mode can induce large current perturbations, leading to abrupt internal temperature changes and SoC variations, thereby violating K-K conditions. Despite its potential, implementing EIS onboard EVs remains challenging due to system integration constraints, measurement limitations, result processing, and vehicle operational requirements.

## 1.1 EIS in EV architecture

Onboard EIS integration should be designed based on the EV powertrain architecture, considering all relevant interfaces that may impact EIS measurements. The EV powertrain consists of several systems, as shown in Fig. 1. These include the high-voltage (HV) battery and the battery junction box (BJB), which are typically integrated within the battery pack. The next stage in the energy path involves the DC-link, followed by the traction inverter and the electric motor (EM), which form the core of the power system. Connected to the HV bus is the low-voltage (LV) battery (12, 24, or 48V) via a LV converter, which supplies power to various vehicle auxiliary loads such as the infotainment and lighting systems. Finally, the charging interfaces consist of both DC charging and AC charging systems. The onboard charger (OBC), which is part of the AC interface, converts grid AC power to DC power for the vehicle.

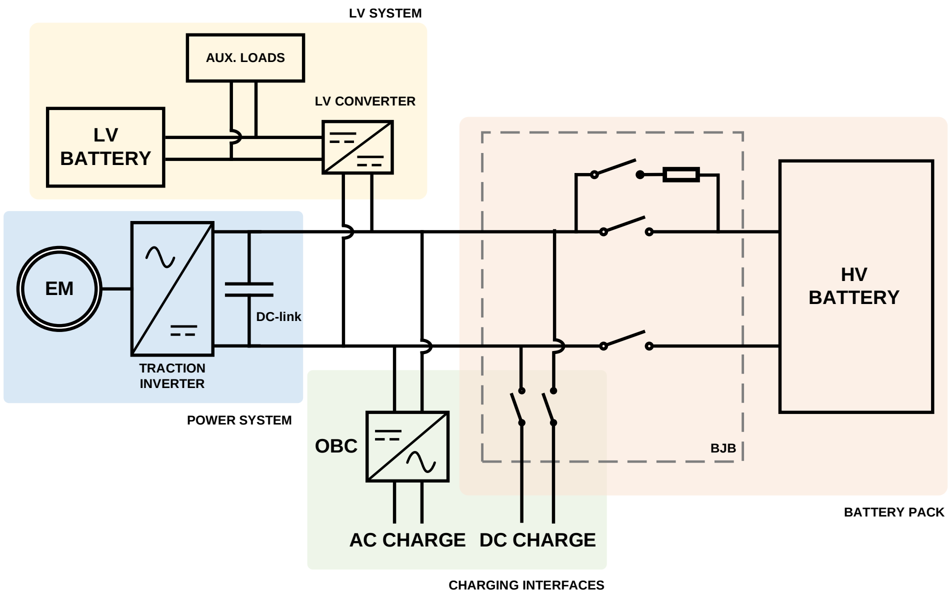



Figure 1: EV powertrain architecture where the battery pack includes the HV battery and the BJB; the power system contains the DC-link, the traction inverter and the EV; the LV system is composed by the LV converter, the LV battery and the EV auxiliary loads; and the DC and AC interfaces, including the OBC.

Each of these systems is critical for safety (ISO 26262), with risks classified according to Automotive Safety Integrity Levels (ASIL), from QM to D [10]. These levels are determined based on failure rates, redundancies, and interdependencies between systems.

Traditional vehicle architectures often use decentralized electric and electronic (E/E) systems with multiple Electronic Control Units (ECUs), but this increases cost and complexity [11]. To address this, centralized architectures (zonal or domain-based) have emerged. Advances in hardware and communication enable the same functions with fewer ECUs, improving scalability and reducing costs [11].
In decentralized systems, powertrain ECUs follow commands from a high-level controller in a hierarchical structure. Centralized systems, however, have a main controller (MC) with a lower ASIL level and smart actuators with higher ASIL levels for specific tasks. The MC manages the overall operations, while smart actuators handle communication, diagnostics, and interfaces with system components like power drivers of the inverter or BJB switches.
In centralized architectures, enhanced monitoring technologies and upgraded communication buses ensure higher precision and better data transfer. Centralizing computational tasks and data handling makes integrating techniques like EIS easier. The MC can now process impedance data in real-time, leading to better estimations of SoXs, which in turn improves energy management and vehicle performance.
Therefore, present cutting-edge technologies enable onboard EIS, remaining as challenge how it can be integrated into the existing vehicle architecture.

### 1.2 Study framework

The scope of this study is to analyse the feasibility of integrating onboard EIS considering the existing vehicle system architecture.
The EIS is considered to be operating under EV stationary state - stopped and parked - to ensure K-K specifications. As a result, this article reviews how the current excitation, in galvanostatic mode, is generated. Voltage and current monitoring, signal synchronization to determine phase difference and impedance calculation are beyond the scope of this study. However, high-level requirements are outlined in Sec. 2 to provide system context in the onboard EIS definition. As a result, the contributions of this study are:

1. System context in EIS current requirements and signal monitoring in Sec. 2.
2. Definition and differences between cell-level, module-level and centralised EIS integration in Sec. 2.
3. Analysis of the different EIS integration approaches considering vehicle architecture and the state-of-the-art research for battery EV in Sec. 2.
4. Comparative assessment to determine the most suitable EIS approach in Sec. 3.

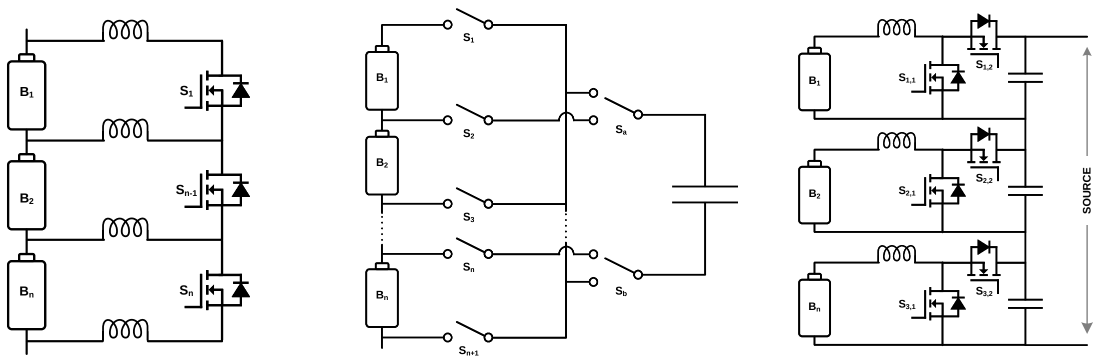
## 2 Onboard EIS analysis

EIS when operation in galvanostatic mode is constrained by the voltage drop across the cell, as it needs to be minimal to not surpass 10-15 mV amplitude in order to maintain pseudo-linear behaviour, which reflects the cell's internal impedance, typically ranging from 50 to 0.5 m$\Omega$ in automotive applications, according to the extracted values in [12].
The analogue-to-digital converter (ADC) resolution used with the sensors affects the minimum excitation current needed. In high-precision systems with a 24-bit ADC, this minimum current can be as low as 0.2 A. The existing automotive systems integrate 12 to 16-bit ADCs, which can lead to underperformance for EIS analysis with 0.2 A, appropriate ADCs shall be ranged in 18 to 20-bit to be compatible with EIS measurements, where the current would range from 2 to 30 A. This interplay highlights the importance of carefully managing the excitation current, resulting in two main approaches to integrating the EIS in the EV: cell-level and centralized EIS.
Cell voltage is similar in both centralized and cell-level methods. In automotive systems, this task is managed by the Cell Monitoring Controller (CMC), a sub-component of the BMS. The CMC contains an Analog Front-End (AFE), responsible for measuring the cell potential and other parameters such as temperature. Additionally, the CMC performs cell balancing operations to ensure voltage equilibrium and maintain a consistent charge/discharge status across battery cells. As part of the BMS, the CMC transmits the measured signals to the BMS controller. Typically, each CMC can monitor multiple cells connected in series - or groups of cells in a series-parallel configuration - resulting in one or more CMCs per battery pack. Modern battery designs prioritize modularity to facilitate disassembly and repurposing, and, accordingly, each battery module is equipped with its own CMC.
On the other hand, centralized and cell-level EIS present different approaches for current measurement. In standard EV implementation, current is typically measured at pack level to determine the total output current of the battery. For EIS applications, however, it is crucial to synchronize the current measurement with the corresponding cell voltage measurements. Cell-level EIS method addresses this challenge by applying a direct excitation current to individual cells, ensuring precise synchronization between cell voltage and current measurements. A variation of this method, known as module-level EIS, generates an excitation current for each battery module, leading to one current measurement per module. In contrast,

the centralized EIS method uses a single excitation current for the entire battery. This approach requires an external synchronization system to accurately align current and voltage measurements and obtain reliable impedance results.
This section reviews these EIS integration methods according to the EV architecture presented in Section 1.1 and evaluates their feasibility for application under automotive conditions.

## 2.1 Cell-level EIS

As introduced, the current excites each cell individually and measures the voltage response. This method can be realized in automotive systems throughout the CMC with active balancing systems.
In automotive applications, nowadays the balancing function is achieved with passive systems: resistors that dissipate the excess of energy from higher-charged cells to achieve the same charging levels. This system results in a loss of energy and capacity. Instead, active solutions redistribute charge from higher-charged cells to lower-charged ones, which improves efficiency and extends battery life.
The EIS application through active balancing systems is the predominant approach for cell-level EIS in the existing literature [13, 14, 15]. These solutions differ in the balancing topology implementation. As shown in Fig. 2a, the balancing is performed between adjacent cells using switched-capacitors, inductors or DC-DC converters. In Fig. 2b system transfers energy between arbitrary cells via flying capacitor, DC-AC-DC conversion stages or multi-winding converters. This topology can be implemented between cells of a solely battery module, between cells of different modules in the battery pack, or between modules. In contrast, Fig. 2c presents a balancing where the energy is charged/discharged from an external source.




(a) (b) (c)

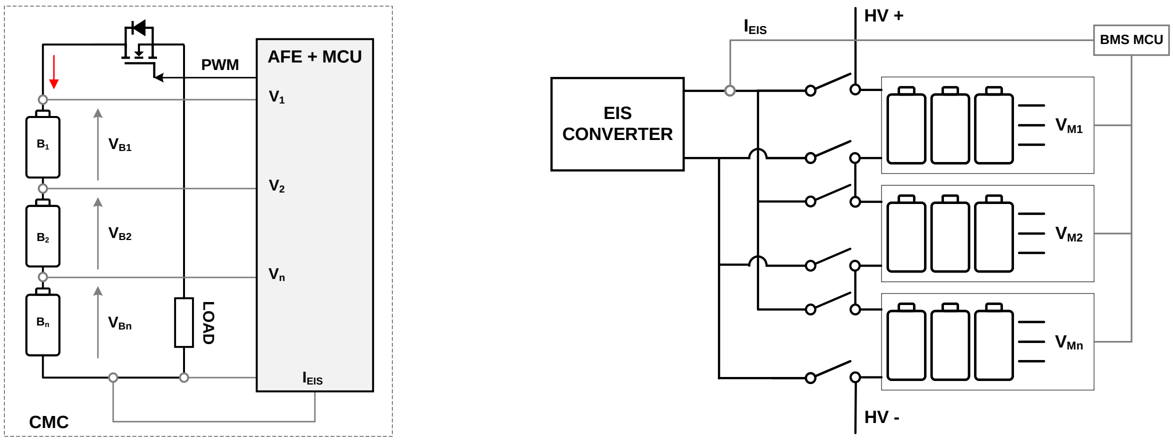
Figure 2: Active balancing topologies applied to EIS: (a) cell balancing between adjacent cells , (b) cell balancing between arbitrary cells, (c) cell balancing using an external source

The EIS integration into these systems requires controlling the semiconductors switching according to the implemented topology. In case of adjacent-cell or arbitrary-cell-balancing implementations, if the system cannot be conducted to different cells simultaneously, the analysis can be time-consuming. However, cell degradation is a gradual process in which EIS can be completed in different periods without impacting the SoH result.
Zhao [15] determine the feasible solution for small-scale batteries, such as consumer electronics, is the balancing between adjacent cells; for large battery packs, including EV applications, the appropriate active balancing strategy is the energy transfer between different modules; while to reduce components and control complexity, the use of an external source is presented as a feasible alternative. This study, however, does not take into account the essential requirements of automotive systems, such as low cost, low complexity, and high reliability, factors which explain why, to date, no vehicle manufacturer has implemented a functional active-balancing design.
All the presented topologies for active balancing require switching components resulting in designing extra electronics into the vehicle and increasing the complexity which increases the E/E safety risks. Inductors and capacitors can cause electromagnetic interfaces and they have a higher failure-rate compared to resistors, especially capacitors. In turn, EIS measurements reliability can be impacted by cross-talk effects, especially if the adjacent cells are being tested simultaneously [16].
Unlike active balancing, passive balancing only requires resistors controlled by the cell monitor AFE of the CMC, and its higher energy loss has little effects on the battery's end-of-life (EOL).
The integration constraints of active balancing in the EV and BMS is relevant to be analysed, especially for the case where an external source is used, as this approach is typically implemented using the LV battery. Referring to the diagram in Fig. 1, direct energy transfer between the LV and HV batteries is not possible when the main contactors of the BJB are open. This limitation affects the EIS and, more significantly, the balancing process, since insufficient energy accumulated in the LV battery could compromise the HV battery integrity.

EIS excitation signal waveform and data acquisition process are also key topics of focus.
The main advantage of cell-level EIS is the direct synchronization of voltage and current signals. As a result, several authors have proposed alternative excitation signals instead of a sinusoidal waveform [17]. Usage of square waves requires the controller to be fine-tuned to avoid inrush signals and involves complex data processing with Fourier transforms. Alternatively, more complex wideband signals, such as multi-sine or pseudo-random binary sequences, have shown notable results in theoretical and laboratory studies. However, their implementation is impractical for existing automotive systems, as the required sampling frequency, along with the resolution and accuracy of ADCs for this type of signal, is not currently available on the market for automotive applications, and its implementation cost is only feasible for laboratory equipment.

## 2.2 Module-level EIS

The module-level EIS can be integrated into the CMC without requiring an active balancing circuit, where two approaches are identified. In Fig. 3a, the CMC directly controls the current by isolating the battery module from the rest of the pack. In contrast, Fig. 3b shows a unique converter that switches to connect to one module at a time [18].




(a) (b)

Figure 3: Module-level EIS integration where (a) using each CMC independently with its own excitation current, while (b) is performed using a switched converter for all battery modules.

To perform EIS tests using the CMC as a stand-alone component, it is also necessary to integrate a small microcontroller unit (MCU) for generating the current excitation signal, enabling the seamless calculation of impedance parameters within the MCU. This solution does not require external sources but increases the complexity of the CMC. As described, ADC specifications of the CMC determine the excitation current amplitude needed, which affects the design of EIS circuit.
The multiplexed single converter simplifies design complexity compared to the CMC alternative but requires integrating an additional system into the battery where the switcher may pose a risk to the E/E battery architecture. A unique current measurement can used at the converter output to simplify the integration, but external synchronization with the voltage is required.
The converter must be operated based on high-level commands from another ECU, to change switch position and adapt current signal waveform, introducing redundancies, increasing communications complexity and risk of failure.

## 2.3 Centralized EIS

Centralized EIS employs an external source from the HV battery to inject the excitation current. A direct integration of centralized EIS can be achieved with the existing system of the EV powertrain introduced in Fig. 1, as Fig. 4 presents.
The equivalent circuit using the powertrain for figures 4a–4d solutions resembles to a current source with a parallel load: the DC-link $C$ [F] and the battery impedance $Z_b$ [Ω]. Therefore, the sourced current $i_t$ [A] is

$$i_t = i_c + i_b \,, \tag{1}$$

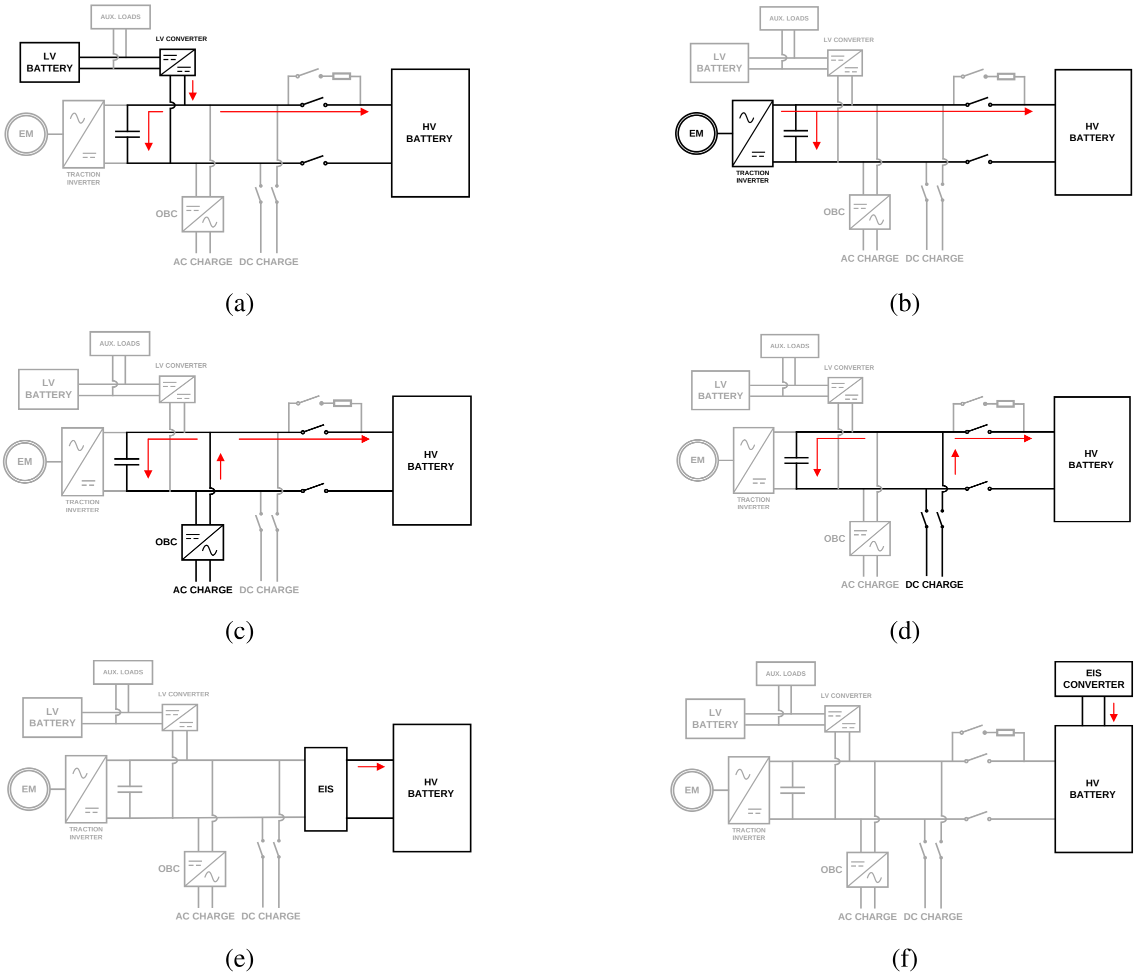



Figure 4: Centralized EIS integration using the EV powertrain elements to generate the excitation current: (a) LV battery, (b) Traction Inverter, (c) AC Charger (OBC), (d) DC Charger, (e) BJB, (f) Dedicated converter.

where $i_c$ is the current that goes through the capacitor and $i_b$ is the current through the battery, which is equivalent to $i_{EIS}$. Then, the the voltage in the battery $v_b$ [V] is described as

$$v_b = v_{DC} + i_{EIS} \cdot Z_b \,, \tag{2}$$

where $v_{DC}$ is the DC output voltage of the HV battery. The factor $i_{EIS} \cdot Z_b$ generates the EIS voltage perturbation at battery level. Due to the HV bus connection the capacitor voltage $v_c$

$$v_c = v_{DC} + \frac{1}{C} \int i_c \, dt \tag{3}$$

must be the same as $v_b$, where $C$ is the DC-link capacitor value. As a result, $i_t$ must be controlled according to the equivalence

$$\frac{1}{C} \int i_c = i_{EIS} \cdot Z_b \,. \tag{4}$$

The type of current waveform and its frequency affects the total current to be injected. Therefore, for a sinusoidal EIS current, the peak value of $i_c$ is

$$\hat{i}_c = \hat{i}_{EIS} \cdot 2\pi f \cdot Z_b \cdot C \,, \tag{5}$$

where $\hat{i}_{EIS}$ is the EIS current peak value and $f$ [Hz] is the signal frequency. Thus, $i_t$ is

$$i_t = \hat{i}_{EIS} \cdot (1 + 2\pi f \cdot Z_b \cdot C) \cdot \sin(2\pi f t) \,. \tag{6}$$

Alternatively, Fig. 4e and 4f are equivalent to a voltage source and the DC-link capacitor does not affect the excitation current amplitude due to the proposed integration approached described in sections 2.3.5 and 2.3.6.

### 2.3.1 LV converter

The LV converter can be presented as a fully integrated solution in the vehicle [19]. All vehicles include LV batteries, traditionally of 12 V, but new vehicle architecture presents 24 and 48 V batteries to source more energy-consuming loads. Generally, according to the LV battery and LV auxiliary loads, the converter is designed in a range of 2 to 6 kW, with the possibility to be slightly increased up to 8 kW according to centralized architectures [20].
The use of the LV battery, and consequently the LV converter, to perform onboard EIS tests is presented in Fig. 4a. In terms of design requirements, the converter must first incorporate HV-to-LV isolation following the architecture configuration and safety specifications. Second, it must be bidirectional to satisfy K-K conditions. However, most standard LV converters are not bidirectional, future designs are expected to incorporate this feature.
Generally, the selected topologies for bidirectional LV converters in the automotive industry are dual half-bridge, dual full-bridge, and resonant converters are preferred for their reliability, moderate complexity, and component efficiency [20].
The LV converter operates with fixed-reference current control based on system consumption, but for EIS, the current control loop must adapt to inject the required waveform, where both controller firmware and hardware must be optimized for EIS operation conditions. The output current should not only match the expected amplitude required by the battery but also account for the current absorbed by the capacitor, as shown in Eq. 6. Depending on the battery pack design and the internal cell impedance, meeting EIS demands may require the LV-converter's nominal power to be significantly increased.
External current and voltage synchronization can be simplified by using the converter's output reference for control while monitoring the EIS current with a sensor near the battery and BMS, with a control loop between the BMS and LV converter potentially required to regulate total output current, enable EIS operation, and define the signal references.

### 2.3.2 Traction Inverter

The traction inverter converts the DC current from the HV bus to AC current for the vehicle motors, allowing the inverter to generate the required EIS excitation current without any power limitations.
As shown in Fig. 4b, EIS current generation can be performed with the traction inverter with motor torque control, as Permanent Magnet Synchronous Motors which commonly used in EV applications due to their advantages in power density and power factor, with Field-Oriented Control being the most widely used control technique.
Existing studies are subjected to online measurements when the vehicle is in driving operation mode [21, 22]. However, as mentioned in Sec. 1, the K-K conditions must be satisfied to properly measure the impedance values, and thus, EIS should be performed with the rotor blocked, as the EV has to be stopped to ensure steady-state conditions in the battery.
The inverter can meet the required switching frequency to generate and control the EIS excitation current. Similar to the LV battery approach, the current drawn from the DC-link must be considered when defining the current amplitude reference and closing the control loop. Therefore, a high-level control strategy must be implemented to regulate the current measured at both the battery and the inverter output.

### 2.3.3 AC Charger (OBC)

EIS integration into the OBC is illustrated in Fig. 4c. The OBC consists of a power factor corrector (PFC) inverter, a DC-link, and an isolated DC-DC converter to convert AC current from the grid to vehicle DC. Alternatively, some approaches employ one-stage OBCs with an AC-DC isolated inverter.
In the charging system architecture, the OBC communicates with the EV Charge Controller (EVCC), responsible of managing communication and operational conditions with the charging station; the BMS that monitors battery status and regulates the charging process; and the MC that manages energy schedulers and vehicle interfaces.
The OBC's power rating, which typically ranges from 1.44 to 22 kW when designed for low-to-medium power levels, is regionally determined due to the lack of a global charge inlet standard [23].
Since the OBC controller and the grid connection may generate the EIS current and be the energy source respectively, several studies have considered the approach of implementing EIS measurements when charging [24]. However, IEC 61851 standard limits the maximum power of single-phase chargers to 7.4 kW, and higher power requires a three-phase connection, where not all EVs include three-phase OBCs. Consequently, depending on the battery characteristics, the OBC may not generate the required current.
From a constructive perspective, the converter must be bidirectional to ensure stability conditions and EIS current signal generation at the DC output, although most of the existing OBCs are unidirectional, the trend is to move forward bidirectional systems compatible with vehicle-to-grid (V2G) operation.
Connectivity with the grid requires compliance with the specific charging communication protocol. In Europe, this is ISO 15118; in China, GB/T 27930; in North America, SAE J2847; and in Japan, CHAdeMO.

In Europe, ISO 15118-20 covers charging communication for bidirectional energy flow defining specific services, including AC, DC, wireless, and bidirectional power transfer [25]. Its generic operations include schedulers and sequences for charging references, but the EIS operation is not explicitly defined. Nonetheless, ISO 15118 includes a range of undefined services, generally known as Value-Added Services (VAS) [26], where EIS can potentially be integrated.
Up to this point, the use of OBCs within the charging infrastructure — and, by extension, to generate the EIS current — may remain a topic of discussion in the coming years. Some trends suggest that future vehicles may only include DC charging interfaces, considering the potential full deployment of DC charging stations and the possibility of domestic DC chargers while ensuring power quality and V2G management.

### 2.3.4 DC Charger

The DC charger operates independently from the vehicle, requiring only monitoring of battery current and cell voltages, as shown in Fig. 4d, with the main advantage being minimal modifications to existing EV systems, enhancing only the monitoring capabilities. Advancements in semiconductor technology and converter control allow charging stations to supply the required EIS current with only a minimal cost increase.
Charging system is the widely studied approach for onboard EIS, although most of the studies do not differentiate between OBC or DC charger when defining the current excitation interface [24, 27], yet none of the reviewed studies address the effects of the DC-link on the system. In consequence, a feedback path between the charger output current and the battery-measured current, accounting for the current absorbed by the capacitor, must be defined to the DC charger to adjust both frequency and amplitude accordingly.
Similar to the OBC, DC charge requires a compatible communication protocol between vehicle and charger. Defining a VAS for performing EIS via DC charging could facilitate battery testing and characterization, i.e., the VAS could include a lookup table where current amplitude and frequency references are sent to the charger. Following this, once the BMS measures the voltage and current values, it commands the charger to update the output current to the next set of amplitude and frequency values.
EIS execution when DC-charging can enable dedicated test stations where EVs can assess battery status under secure and authorized conditions, with oversight from a certified third-party

### 2.3.5 Battery Junction Box (BJB)

The BJB functions as a safety system for the HV battery by incorporating protective elements such as fuses, including newer, advanced pyro-fuses, and contactors, which disconnect the battery from the powertrain when the vehicle is turned off or when an error or hazardous event is detected. BJB contactors are mainly electromechanical systems controlled by the BMS, although recent advancements in semiconductor manufacturing offer opportunities to transition to solid-state relays.
Additionally, BJB includes a pre-charge circuit to control the inrush current when connecting the HV bus and charging the DC-link. Currently, this is accomplished using a contactor and dissipation resistor, forming an RC circuit with the DC-link; albeit, an active pre-charge circuit, employing a switching semiconductor in a chopper configuration, could offer a more efficient alternative by further limiting the initial current surge.
Bidirectional LV converter can be utilized to boost the DC-link voltage, eliminating the need for controlling transient current. This approach encourages the integration of a power converter into the BJB to generate the excitation current as Fig. 4e illustrates. This alternative appears feasible, although with technical complexity mainly associated with E/E safety risks to ensure battery disconnection, power converter operation and controller communications, while modifying the powertrain architecture, which might be challenging for vehicle manufacturers to adopt it.

### 2.3.6 Dedicated Converter

The dedicated converter can be directly connected to the battery to avoid DC-link and system interconnection as described in Fig. 4f. However, the system requires a primary energy source. Some studies propose using the LV battery, which requires galvanic isolation between the LV and HV sides, increasing both system complexity and E/E safety risks according to the powertrain architecture definition. Alternatively, an energy accumulator, such as a capacitor, can be integrated to enable full stand-alone operation without isolation.
The converter shall not present operative limitations to generate the excitation current as it is specifically designed for EIS applications, being only limited by its mechanical integration into the battery pack, as it is subedited to spacing availability and cooling requirements. Consequently, this solution must present high energy density and efficiency, while presenting a low cost to be attractive for the automotive industry or present remarkable advantageous results compared to the rest of the alternatives already explained.

# 3 Comparison Review

The previous section reviewed various alternatives for integrating onboard EIS measurements into EVs, highlighting the pros and cons of each approach. This section compares and analyses these alternatives to define the most suitable one.
The analysis is primarily qualitative, considering existing proposals in literature and EV architecture constraints. The comparison focuses on three main areas presented in table 1.

Table 1: Qualitative description from 1 to 5 rating for Adaptability, Controllability and Acceptability criteria.

| Rate | Adaptability | Controllability | Acceptability |
|---|---|---|---|
| **1** | • Incompatible with existing EV architecture.<br>• Requires significant redesigns and system modifications. | • System operation control and synchronization not possible.<br>• Complex controllers needed. | • High operational and safety risks.<br>• Applicable only for EIS.<br>• Large-scale production challenges. |
| **2** | • Limited power rating and converter topology modifications.<br>• Major system redesigns. | • Complex control loops.<br>• Communication channels needed between multiple vehicle controllers.<br>• EIS not performed on multiple cells simultaneously. | • Increased safety risks.<br>• System modifications only enable only EIS. |
| **3** | • Modifications needed in architecture.<br>• No changes to power rating or converter topology. | • Changes to controller operation needed.<br>• EIS on multiple cells simultaneously.<br>• External synchronization required. | • Uses an existing architecture element with few changes.<br>• Component use under discussion. |
| **4** | • Largely compatible with current EV architecture.<br>• Minor changes needed with limited hardware components and minor mechanical impact. | • Minimal modifications required for controllers communications.<br>• EIS on multiple cells simultaneously.<br>• External/direct synchronization. | • High safety and operational reliability.<br>• Regulatory adjustments required. |
| **5** | • Seamlessly integrates with current EV design.<br>• No modifications needed. | • Integrates with existing control loops.<br>• Synchronization is directly managed within the same element. | • Fully compatible with standards.<br>• Proven safe and applicable for wide-scale use, including beyond EIS. |

Accordingly, the different EIS approaches described in this document are rated as shows table 2.

Table 2: EIS approach comparison based on adaptability, controllability, and acceptability criteria.

| EIS Approach | Adaptability | Controllability | Acceptability | Total |
|---|---|---|---|---|
| **Cell-level (Adjacent)** | 1 | 3 | 1 | 5 |
| **Module-level (CMC)** | 3 | 5 | 2 | 10 |
| **LV Converter** | 2 | 2 | 3 | 7 |
| **Traction Inverter** | 4 | 3 | 2 | 9 |
| **OBC** | 2 | 3 | 3 | 8 |
| **DC Charger** | 4 | 4 | 4 | 12 |
| **BJB** | 2 | 3 | 1 | 6 |
| **Dedicated Converter** | 1 | 4 | 1 | 6 |

The analysis identifies the use of the DC vehicle's charging infrastructure as the most suitable approach for onboard EIS, achieving a total of 12 points. This method requires minimal modifications to the EV powertrain, as the excitation signal is generated by the external battery charger. Necessary control and operational adaptations can be managed through a dedicated VAS, paving the way for the development of third-party certified battery test stations following regulatory updates. A close second is the module-level EIS implementation using an independent system integrated into the CMC. This approach entails

some modifications to the CMC for EIS signal generation. However, voltage and current measurements are directly synchronized at the CMC, reducing control and operational complexity. Despite this, the CMC-based system is limited to EIS functionality, and its increased circuit complexity poses safety risks to battery performance and integrity. Additionally, the added development costs for integrating EIS into the CMC may only be justifiable in premium vehicles or transport applications, such as trucks or buses, where real-time cell degradation monitoring significantly benefits energy management strategies. Finally, in third place, the traction inverter offers relatively easy adaptability and a familiar control approach, but its complex operation and associated safety risks result in a lower overall rating for this solution.
Nonetheless, this analysis has primarily focused on systems and technical characteristics. Further studies are needed to evaluate the industrialization costs and the cost-benefit results of each solution once integrated into the vehicle.

# 4 Conclusions

This study analyzes the integration of EIS as an onboard diagnostic method for EV batteries, with a focus on the vehicle's powertrain architecture. First, the different systems that constitute the EV powertrain are presented to assess the technical feasibility of implementing galvanostatic onboard EIS through them. The system constraints are then contrasted with existing literature, considering each of the proposed alternatives for onboard EIS. Recent studies have not sufficiently considered the power systems' control, including different communication loops and the effects of other powertrain elements, such as the DC-link. However, the findings of this document suggest that the onboard integration of EIS is both possible and technically viable. The presented approaches are compared through a qualitative study, based on three criteria: adaptability, referring to the ease with which the proposed system can be integrated into existing EV architecture; controllability, focusing on the extent to which existing control loops can be adapted to integrate the system; and acceptability, considering operational risks and compatibility in adopting the system. Among the evaluated approaches, leveraging the DC charging interface emerges as the most favorable option. It enables direct integration with minimal modifications to existing battery monitoring systems, while supporting a secure and efficient communication protocol between the vehicle and the charger. Alternatively, the use of Module-level EIS via a system generator in the CMC requires limited system modifications, resulting in direct integration and synchronized measurements for accurate impedance analysis.

# Acknowledgements

This work is the result of a collaboration between FICOSA Automotive and CITCEA-UPC, with the support of the Industrial Doctorates Plan of the Department of Research and Universities of the Generalitat de Catalunya (DI-021/2022).

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## Presenter Biography

Roger Bautista Florensa was born in Tàrrega, Spain, in 1997. He received the M.Eng. degree from Universitat Politècnica de Catalunya (UPC) in 2022. Since 2021, he has been working at FICOSA Automotive, where he is pursuing an industrial Ph.D. degree in electrical engineering focused on EIS on-board systems for electromobility applications in collaboration with the Centre d'Innovació Tecnològica de Convertidors Estàtics i Accionaments (CITCEA), UPC.

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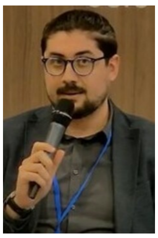

Alberto Gómez Núñez is graduated in Physics from the University of Barcelona in 2012, with a Master's in Energy Engineering from the Polytechnic University of Catalonia in 2013, and a PhD in Nanoscience and Nanotechnology from the University of Barcelona in 2018. He has experience in the automotive industry, first as part of the R&D Department at Francisco Albero (FAE) until joining Eurecat in 2019, where he was in charge of the e-Mobility & Energy Storage (MobES) line, and later leading the advanced engineering of e-Mobility at FICOSA. Over the past decade, he has led and worked on R&D projects focused on future mobility and energy storage (including H2020 MARBEL, for which he was the technical coordinator), hydrogen, electric mobility in European and South American regions, energy efficiency and optimization, printed electronics, chemical simulations in materials, and gas sensors for the automotive industry, among others.

Carlos Abomailek is a PhD graduate in Electrical Engineering from the Universitat Politècnica de Catalunya (UPC), with a specialization in high-voltage systems, awarded Excellent Cum Laude. He conducted part of his research as a visiting researcher at Kinectrics Inc. His academic background also includes a degree in Industrial Engineering from UPC, with a focus on heat transfer. Professionally, Dr. Abomailek has experience in power electronics and grid technologies, recently contributing to the Syensqo's ADL Electrification Initiative leading the specialty polymers strategy for Power Electronics and Power Grids applications. From 2019 to 2023, he worked on eMobility solutions with FICOSA's Advanced Engineering team, and previously as a research engineer in high-voltage systems at UPC.