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# Grid compliance and advanced control features of Volvo Cars' V2G system

Ali Fotouhi[1]

[1] *Volvo Car Corporation, ali.fotouhi@volvocars.com*

**Executive Summary**

This paper explores Volvo Cars' AC Vehicle-to-Grid (V2G) system, focusing on how it fulfills grid codes while enhancing grid support and integrating seamlessly with Home Energy Management System (HEMS). By aligning with key standards such as RfG 2016, EN50549-1, and VDE-AR-N 4105, the system ensures full compatibility with European low-voltage distribution networks. In addition to meeting core compliance criteria, the V2G system offers advanced control capabilities that enable it to adapt to varying Distribution System Operator (DSO) requirements while maintaining an optimal user charging experience. The system is designed as part of a complete ecosystem, supporting secure, flexible, and intelligent interaction with the grid and the home. The paper includes selected test results that demonstrate the system's performance in areas such as frequency response, reactive power control, and ride-through, confirming its readiness for real-world deployment and its contribution to future energy flexibility.

*Keywords: AC & DC Charging technology, Electric vehicles, Smart grid integration and grid management, Standardization, V2H & V2G*

## 1 Introduction

Sweden has set an ambitious target to achieve net-zero greenhouse gas emissions by 2045, driving a nationwide shift toward sustainable energy through the adoption of innovative technologies, integration of renewable energy sources, and more efficient energy management practices [1]. To help achieve this vision, Volvo Cars has committed to becoming climate neutral by 2040, reinforcing its leadership in sustainable mobility.

One of the key technologies supporting this transition is Vehicle-to-Grid (V2G), which enables bidirectional power transfer between electric vehicles (EVs) and the grid. V2G systems allow EVs to not only draw energy for charging but also return power to the grid when needed. This capability transforms EVs from passive loads into active grid assets, improving grid flexibility, supporting renewable energy integration, and enhancing the resilience of local energy systems.

To support these objectives, Volvo Cars has developed a robust AC V2G ecosystem, comprising a bidirectional onboard charger (OBC), bidirectional electric vehicle supply equipment (EVSE), and a Home Energy Management System (HEMS). These components together can enable seamless interaction between the vehicle, home, and grid. It allows efficient operation within standard voltage and frequency limits, requiring minimal need for additional infrastructure.

A critical aspect of enabling V2G functionality is compliance with grid codes and standards, which ensures safe and reliable grid operation. Volvo Cars' AC V2G solution has been designed in accordance with key European grid requirements, including RfG 2016, EN 50549-1, and VDE-AR-N

4105. In addition to satisfying baseline regulatory needs, the system includes advanced control capabilities that allow it to adapt to specific Distribution System Operator (DSO) requirements, enabling dynamic configurations to meet local grid conditions or policy goals.

This paper presents the general system architecture, control strategies, and grid interaction capabilities of the Volvo Cars AC V2G solution. The goal is to demonstrate how the system fulfills standard grid codes while offering customizable support for DSOs and ensuring a positive user charging experience.

The paper also includes a selection of preliminary lab test results from early-stage V2G system prototypes. While these tests are not formal compliance certification tests, they provide evidence of functional alignment with critical grid support features, such as fault-ride through (FRT), frequency response and voltage-reactive power control. They highlight the potential of the system to contribute meaningfully to the stability and flexibility of the grid.

# 2 Background and Technical Framework

## 2.1 AC V2G Technology Overview

In an AC V2G system, the EV is transformed into a flexible energy asset capable of both consuming and supplying power to the grid. The core of this functionality lies in the bidirectional OBC integrated within the vehicle. Unlike conventional unidirectional chargers, the bidirectional OBC can convert AC power from the grid into DC for charging the battery and invert DC power from the battery back into AC to export electricity to the grid when needed.

The EVSE, commonly known as the charging station, serves as the interface between the vehicle and the grid. In AC V2G, the EVSE primarily acts as a smart, controllable switch, ensuring safety, communication, and coordination, while the actual AC/DC conversion and grid interaction is handled inside the vehicle. The grid interface occurs at the low-voltage distribution level, where the vehicle connects to the grid via the EVSE and interacts with grid voltage and frequency conditions.

In contrast to DC V2G systems, where power conversion occurs within the EVSE, the AC V2G solution eliminates the need for costly upgrades or specialized charging equipment, reducing investment, installation, and maintenance costs for users. While DC V2G offers rapid charging and high-power capabilities, these often exceed residential requirements, making AC V2G a more practical, cost-effective, and scalable solution for widespread home deployment, facilitating efficient integration into smart grid ecosystems.

## 2.2 Benefits of V2G EVs for the Power System

V2G systems enhance power system stability by enabling EVs to function as distributed energy resources (DERs). With the increasing integration of inverter-based renewables and EVs, the ability of V2G to provide flexible, bidirectional power flow becomes essential for balancing supply and demand locally.

At the distribution network level, the V2G systems can contribute to services such as peak shaving, voltage support, and frequency response, reducing reliance on centralized generation. These capabilities help mitigate grid imbalances and enable a more resilient and responsive power system. When managed properly, V2G operation does not significantly shorten battery life, especially for EVs designed to handle several charge and discharge cycles per day within safe limits [2].

V2G technology enables a range of use cases for both residential users and larger aggregators. At the residential level, users can leverage V2G for energy arbitrage, charging their vehicle when electricity prices are low and discharging back to the home or grid when prices are high. In addition, residential EVs can contribute to grid stability by participating in local flexibility markets, offering services such as voltage support and congestion management. These services become more impactful when V2G systems are managed at the fleet level by an aggregator, who can coordinate large numbers of vehicles to deliver ancillary services like frequency regulation and flexibility for the distribution grid. Aggregators play a key role in enabling these advanced services by pooling V2G resources and interfacing with grid operators and market platforms. Through this coordinated approach, EVs can actively support grid operations and enhance overall energy system flexibility.

### 2.3 Grid Codes for V2G Systems

Grid codes are technical specifications that define how generators and grid-connected devices must behave to ensure reliable and secure power system operation. Compliance with them is essential for enabling technologies like V2G for grid connection. The Volvo Cars AC V2G system is designed to meet European grid requirements as specified by the EU Commission Regulation Requirements for Generators (RfG) 2016/631 [3] targeting Type A generator standards, EN50549-1 [4], VDE-AR-N 4105 [5] and other national standards and regulations.

Grid codes applicable to low voltage connected generators, including AC V2G systems, can be broadly categorized into the following core areas: operational compatibility, protection and disconnection mechanisms, and power control capabilities. These categories encompass the essential technical requirements that ensure safe and stable integration of DERs into the grid.

- **Operational compatibility**: This category defines the conditions under which the system must operate reliably both under normal and disturbed grid conditions. It includes voltage and frequency operating ranges, ride-through capabilities during short-term disturbances, and immunity to high rates of change of frequency (ROCOF). The goal is to keep the system stability and continuity of operation during grid events, avoiding unnecessary disconnections unless explicitly required by protection thresholds.
- **Protection and anti-islanding:** Grid codes require the implementation of interface protection to disconnect the system in the event of grid faults, out-of-range operating conditions, or unsafe conditions. A key aspect is anti-islanding protection, which prevents the unit from continuing to energize a disconnected section of the grid, thus ensuring safety for maintenance personnel and equipment. These protections are typically coordinated with local grid regulations and can include passive and active detection methods.
- **Power control capabilities:** This includes the system's ability to modulate active and reactive power in response to grid signals. For active power, the system must support frequency-sensitive responses, such as Limited Frequency Sensitive Mode (LFSM), to contribute to system frequency stability. For reactive power, the system should implement voltage-dependent control strategies like Q(U) mode, enabling support for local voltage regulation. Grid codes often specify a range of acceptable power factor values or predefined reactive power characteristics, which may be static or dynamic depending on the local DSO requirements.

Three key grid code capabilities are explained in more details here: FRT as an aspect of operational compatibility, LFSM and Reactive Power Control (Q(U) mode) as representative power control functionalities.

#### 2.3.1 Fault-Ride Through (FRT) Capability

FRT capability ensures that the unit remains connected and operational during short-term grid voltage disturbances. This capability prevents unnecessary disconnections that could lead to further instability. European grid codes, including EN 50549-1 [4], specify both Under Voltage Ride-Through (UVRT) and Over Voltage Ride-Through (OVRT) requirements, defining precise voltage and time limits within which the connected devices must remain operational.

- UVRT: During voltage dips, systems must withstand voltages down to 0.15 p.u. without disconnecting, provided these dips are within specified durations.
- OVRT: Systems must also tolerate temporary overvoltages, typically up to 1.25 p.u., within the required time limits.

Figure 1 illustrates the required voltage-time envelopes for both UVRT and OVRT, indicating the permissible voltage conditions and durations.

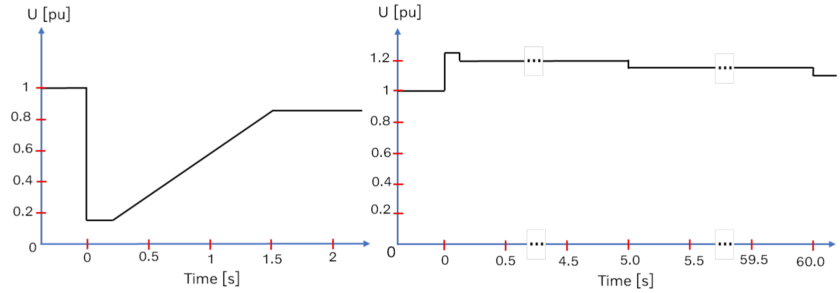


Figure 1: FRT voltage-time envelope showing the required UVRT and OVRT capabilities [4]

### 2.3.2 Limited Frequency Sensitive Mode (LFSM)

LFSM is a key feature required by European grid codes, especially under ENTSO-E standards and national regulations [3]. LFSM defines how grid-connected units must respond to frequency deviations outside nominal values (50 Hz in Europe) to help stabilize system frequency. There are two options:

- **LFSM-O (Overfrequency)**: The system must reduce active power output when the frequency exceeds a defined threshold.
- **LFSM-U (Underfrequency)**: The system must increase active power output (if capable) when the frequency drops below a threshold.

In the context of V2G, LFSM functionality enables EVs to behave like traditional frequency-sensitive generation units. The collective contribution of EVs connected at different points to frequency control can support grid stability, especially during disturbances or imbalances caused by renewable intermittency or sudden load changes.

The rapid and decentralized frequency support of V2G EVs enhances grid stability and reduces reliance on central generation. Figure 2 depicts a typical frequency-sensitive power response curve as required by LFSM, indicating the frequency thresholds at which power output modulation begins and the associated droop response.

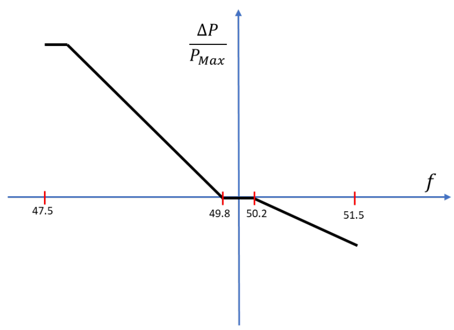


Figure 2: Active power response under LFSM-O/U frequency conditions [3]

### 2.3.3 Reactive Power Control – Q(U) Mode

Voltage-dependent reactive power control, commonly known as Q(U) mode, is another fundamental requirement specified by grid codes such as EN 50549-1 [4]. In Q(U) mode, the V2G system adjusts reactive power (Q) output in response to measured local grid voltage (U), providing localized voltage support and helping stabilize grid voltages under various operational conditions.

Under Q(U) mode, the V2G system injects reactive power into the grid during undervoltage events (voltage below nominal) to help restore voltage levels. During overvoltage events, the system absorbs reactive power to reduce the voltage magnitude. The required behavior is defined by a standardized Q(U) characteristic curve, which defines the relationship between reactive power output and local voltage conditions. Figure 3 presents the reactive power capabilities required at different voltage levels in European grid codes.

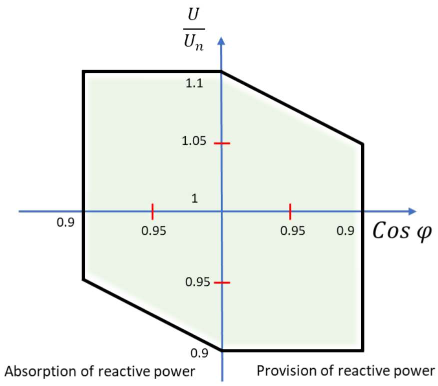

Figure 3: Reactive power support capabilities across different voltage conditions.

## 3 Volvo Cars AC V2G System Description

Volvo Cars' AC V2G system includes a bidirectional OBC within the EV, paired with EVSE at each installation site, allowing it to support AC V2G operations effectively. This configuration leverages existing electrical infrastructures, enhancing scalability and accessibility for users. The hardware and control mechanisms ensure that power flows can be managed dynamically to provide frequency and voltage support, required in grid codes and for grid support services. These requirements support improved grid operation and stability. Figure 4 shows the Volvo Cars AC V2G setup.

The HEMS considers the unit within the user's premises, adjusting power based on household consumption to prevent fuse limit violations and complying with national regulations governing power exchange for larger loads and generators.

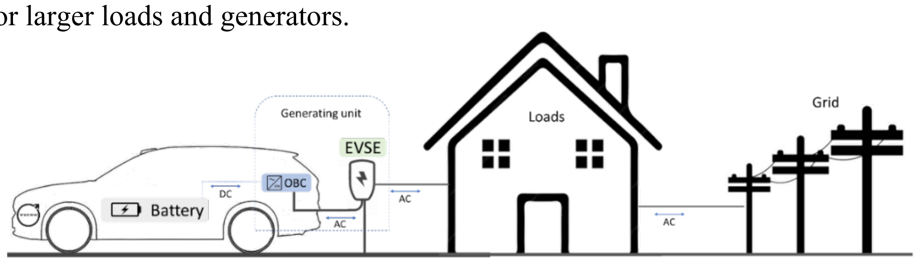

Figure 4: Volvo Cars AC V2G setup

The control architecture of Volvo Cars' AC V2G system combines centralized energy management through a HEMS with real-time local control at the charger level. This layered design allows for both optimized household energy use and reliable grid interaction.

Figure 5 illustrates the integrated control framework of the Volvo Cars AC V2G solution. The HEMS manages charging and discharging based on electricity prices, grid tariffs, and peak load constraints, enabling cost-effective and grid-responsive operation.

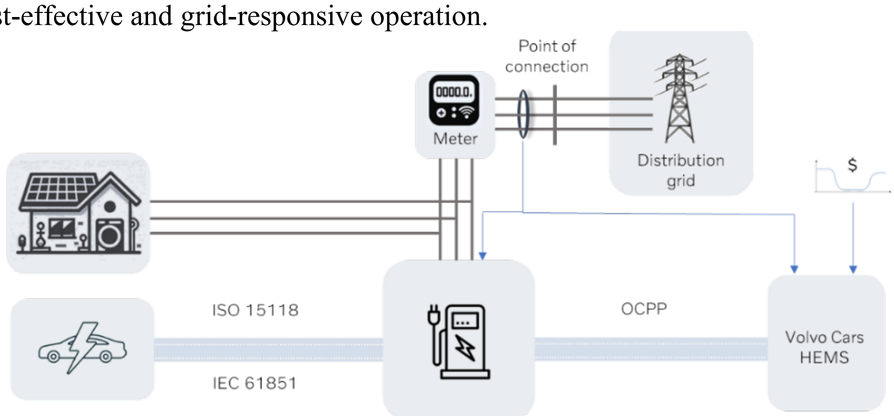

Figure 5: V2G solution with integrated Home Energy Management System (HEMS)

A core function of the HEMS is to optimize energy flow based on energy prices and grid tariffs, considering the physical limitations of the installation, such as user-defined current limits and fuse limits. It dynamically adjusts power flows to ensure safe operation without exceeding the household's capacity. In parallel, local control functionalities embedded within the charger ensure fast response to local events. Local control functionalities ensure adherence to phase-specific current export and import limits, in compliance with DSO requirements. The DSO-defined parameters specify allowable power thresholds and define whether temporary deviations from these limits are permitted. Together, the HEMS and the local charger controls provide a robust and adaptive control scheme that supports user preferences and ensures full compliance with regulatory and technical requirements.

# 4 Grid Code Performance Validation

To assess the grid code performance of the Volvo Cars' AC V2G system, a set of tests was carried out using a hardware-in-the-loop (HIL) setup. The test environment included both the OBC, rated at 11 kW for bidirectional operation, and a 22-kW bidirectional EVSE. Together, these components represent a complete AC V2G configuration, designed to operate within standard grid codes. Control commands were sent from the Volvo Cars cloud platform to the EVSE through OCPP, simulating realistic communication and control conditions.

A grid simulator was used to create various voltage and frequency scenarios, allowing detailed observation of how the system reacts to changes in grid conditions. To ensure accurate analysis, the setup included real-time monitoring and high-precision measurement tools. This methodology enabled the evaluation of key functionalities such as UVRT, LFSM-U, and reactive power control (Q(U)), all under representative operating conditions.

## 4.1 UVRT Performance Demonstration

To assess the UVRT performance of the Volvo Cars AC V2G system, a series of voltage dip scenarios were emulated using a grid simulator in a HIL testbed. The system was operating in discharge mode at 10 kW. During each test, the grid voltage was ramped down at a rate of 9 V/ms, reaching a specific voltage dip level in per unit (p.u.), and maintained for a predefined duration. Following this, the voltage was restored to nominal levels (1.0 p.u.) for 30 seconds before the next dip was applied.

Throughout the test, the V2G system (i.e., OBC and the EVSE) was expected to remain connected to the grid during the voltage disturbance, although active power output could temporarily decrease or drop to zero. The key compliance requirement was that the system must resume normal power delivery immediately after the voltage recovered, without manual intervention or disconnection. Table 1 summarizes the voltage dip levels and their corresponding durations based on the UVRT test profile.

Table 1: Voltage dip levels and their corresponding durations for UVRT performance test

| Voltage (p.u.) | Duration (s) |
|---|---|
| 0.2 | 0.415 |
| 0.3 | 0.846 |
| 0.4 | 1.277 |
| 0.5 | 1.708 |
| 0.6 | 2.138 |
| 0.7 | 2.569 |
| 0.8 | 3.000 |

Each dip scenario was executed sequentially, with recovery periods between events. This setup enabled detailed observation of the EV/EVSE voltage disturbance handling and its ability to meet UVRT requirements, particularly the ability to ride through temporary faults without tripping. As shown in Figure 6-Figure 8, the voltage dips were precisely simulated by the grid simulator. In these figures, the top row shows the grid voltage profile, and the bottom row shows the corresponding active power output response of the V2G system.

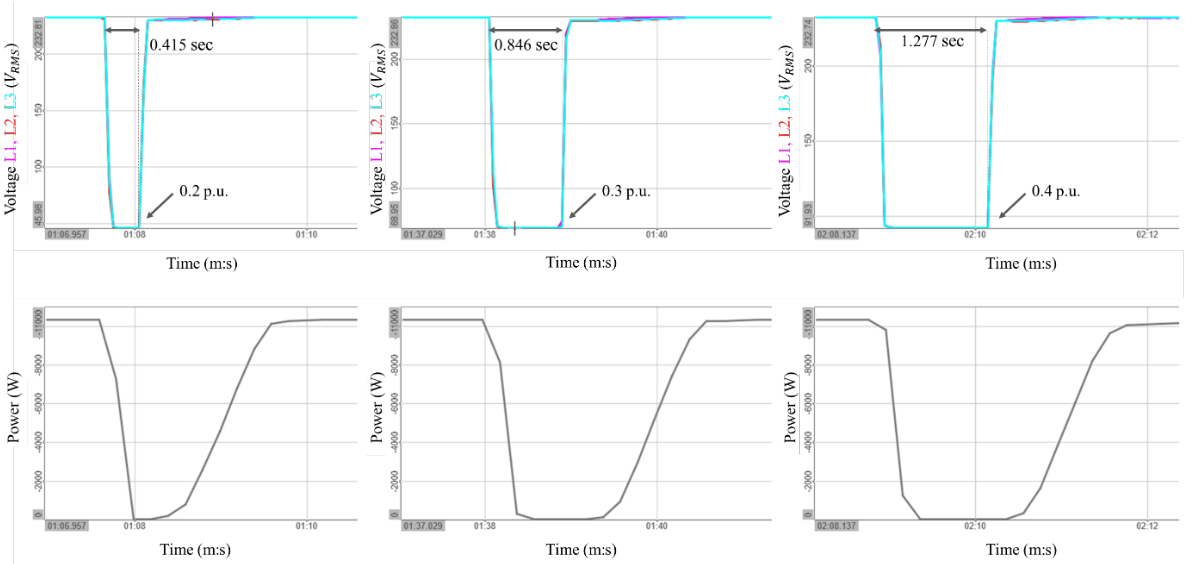

Figure 6: UVRT test results for voltage dips at 0.2, 0.3, and 0.4 p.u.

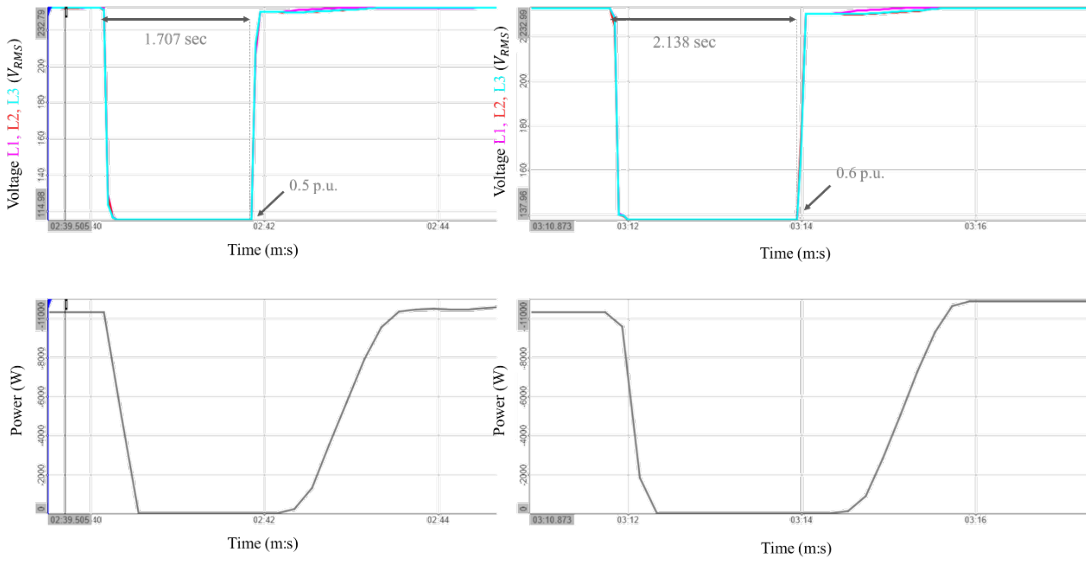

Figure 7: UVRT test results for voltage dips at 0.5 and 0.6 p.u.

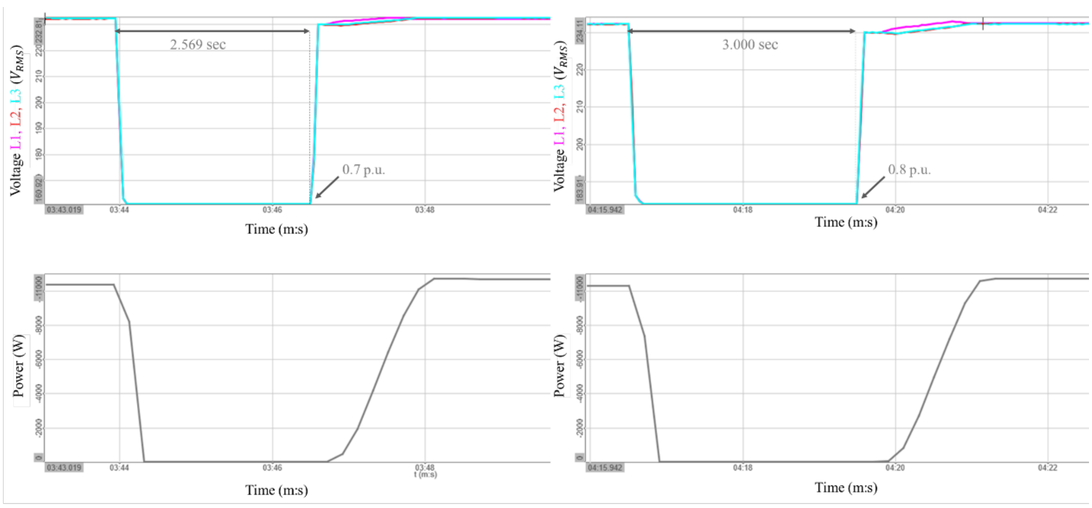

Figure 8: UVRT test results for voltage dips at 0.7 and 0.8 p.u.

The V2G system was initially operating in a discharging mode at approximately 10 kW prior to each dip. During each event, the system significantly reduced active power output, demonstrating effective control and protective response. The V2G system remained connected to the grid throughout the entire duration of each dip event, avoiding disconnection as required by grid codes.

Following the restoration of nominal voltage conditions, the system rapidly resumed its normal power output within the specified recovery time, confirming both the robustness of the control system and compliance with UVRT requirements. The swift restoration to pre-disturbance levels of active power highlights the capability of the V2G solution to maintain grid stability and continuity of operation following grid disturbances.

## 4.2 LFSM-U Performance Demonstration

A controlled test was performed under simulated frequency conditions to verify the LFSM-U functionality of V2G system. The goal was to observe whether the system could correctly modulate its charging power in response to frequency values below the nominal 50 Hz, as required by underfrequency response mechanisms defined in various European grid codes. The test was designed for functional evaluation and does not represent a formal compliance test. Instead, it serves to demonstrate the system's readiness and responsiveness to LFSM-U conditions.

The objective is to demonstrate that the V2G system reduces the active power (charging load) proportionally as the grid frequency decreases below 50 Hz, following a droop characteristic of 2%, and goes to the discharging mode. This behavior is shown when the EV is charging at the bidirectional power transfer mode. Test setup and the parameters are shows in Table 2.

Table 2: LFSM-U test setup and parameters

| Parameter | Value / Description |
|---|---|
| **Mode of operation** | Bidirectional power transfer (Charging) |
| **Maximum charging/discharging power** | 11 kW at nominal 50 Hz |
| **Frequency setpoints** | 50.0, 49.5, 49.0, 48.5, 48.0, 47.5, 47.0 Hz |
| **Frequency step duration** | 10 seconds per setpoint |
| **Test environment** | Controlled lab setup with frequency injection capability |
| **Measurement parameters** | Grid frequency (Hz), Charging Power (W), Time (s) |

The frequency variations are shown in Figure 9. As shown in Figure 10, the system decreases its charging power in steps as the frequency is reduced and goes to discharge mode. A consistent response, without instability and overshoot was observed. This confirms the system's ability to support frequency control services in grid-connected charging applications.

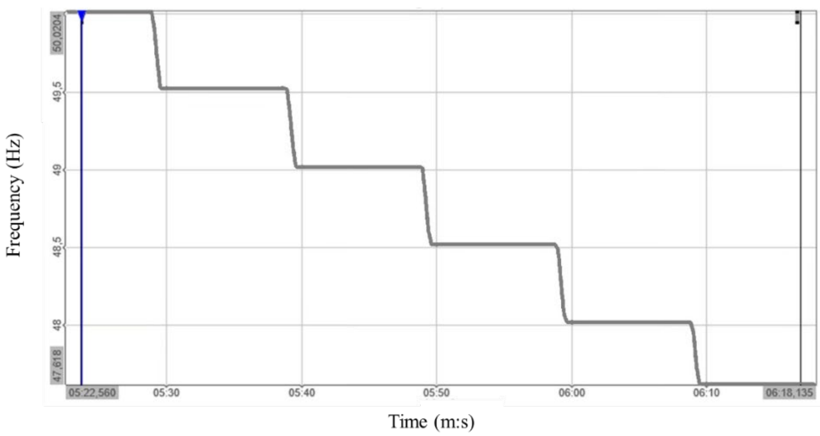


Figure 9: Input frequency over time (LFSM-U test)

The initial active power is positive, indicating the vehicle is charging (importing power from the grid) and as time progresses and frequency decreases, the active power decreases in steps, eventually reaches zero and then becomes negative, indicating that the system starts exporting power to the grid (discharging). The V2G system transitions from power import (load) to power export (source) as frequency continues to drop.

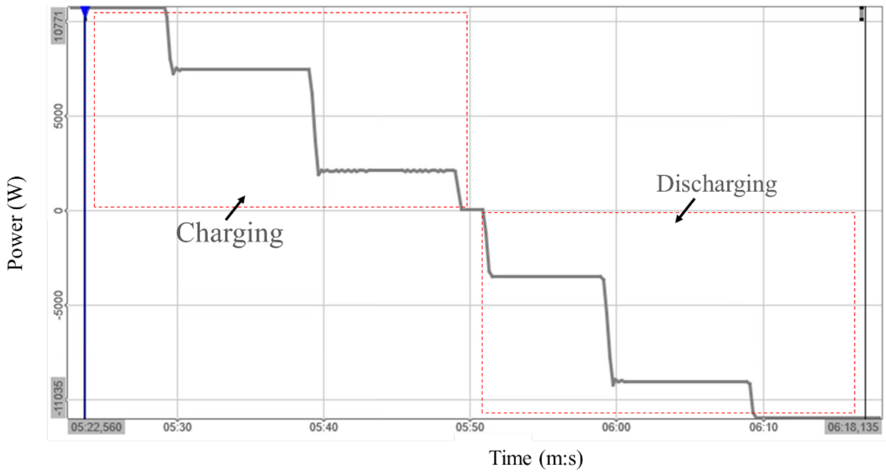


Figure 10: Corresponding active power (charging) response

## 4.3 Reactive Power Control (Q(U)) Functionality Demonstration

Reactive power control is a critical aspect of grid code compliance for grid-connected inverters, including EV chargers. The Q(U) functionality, or voltage-dependent reactive power response, enables the system to inject or absorb reactive power based on local voltage measurements. This function helps stabilizing grid voltage during overvoltage or undervoltage conditions. To evaluate this capability, several tests according to Table 3 were conducted using the Volvo Cars' AC V2G system to demonstrate dynamic and steady-state Q(U) behavior under voltage variation scenarios.

Table 3: Q(U) test setup overview

| Parameters | Value / Description |
|---|---|
| **Rated apparent power ($S_{max}$)** | 11 kVA |
| **Max active power ($P_{max}$)** | 11 kW |
| **Test power mode** | Discharging (V2G) |
| **Max reactive power ($Q_{max}$)** | $\pm 0.44 \cdot S_{max}$ |
| **Control strategy** | Q(U) – Reactive power as a function of voltage |
| **Target voltage range ($V_n$)** | ~0.92 to ~1.08 p.u. (in steps) |
| **Voltage ramp rate** | 0.7-0.9 V/ms |
| **Holding time per setpoint** | 60 seconds |

The plot in Figure 11 shows the applied voltage levels as per-unit (p.u.) values relative to nominal voltage (230 V). Step changes include 0.97 p.u., 0.92 p.u., 1.03 p.u., and 1.08 p.u., each held for approximately 60 seconds.

The upper plot in Figure 12 shows active power (P), while the lower plot displays reactive power (Q). As the voltage varies from 0.92 to 1.08 p.u., the V2G system injects reactive power at undervoltage and absorbs reactive power at overvoltage. Reactive power remains near zero within the deadband (0.97–1.03 p.u.) and ramps outside this range. During high Q demand, the system reduces active power to respect the 11 kVA apparent power limit, demonstrating coordinated control of P and Q under grid voltage variations.

A V2G system operating with current lagging the voltage injects reactive power into the grid, which tends to raise the local voltage under normal conditions. This behavior corresponds to over-excited operation. A V2G system with current leading the voltage absorbs reactive power from the grid, which tends to lower the local voltage under normal operating conditions. This behavior is referred to as under-excited operation [6].

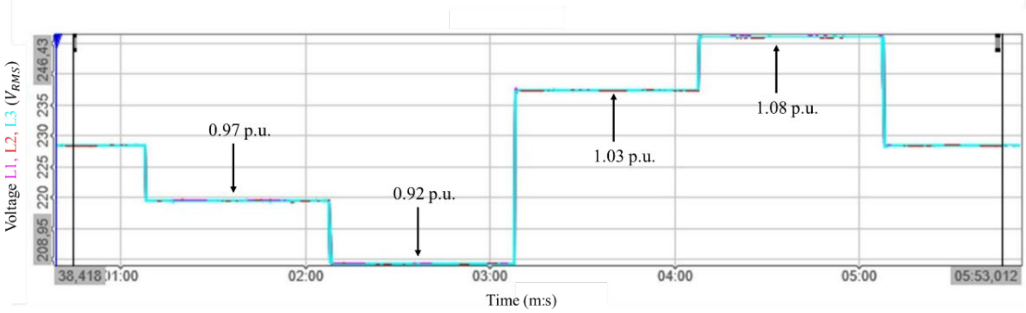


Figure 11: Voltage step profile applied during Q(U) testing

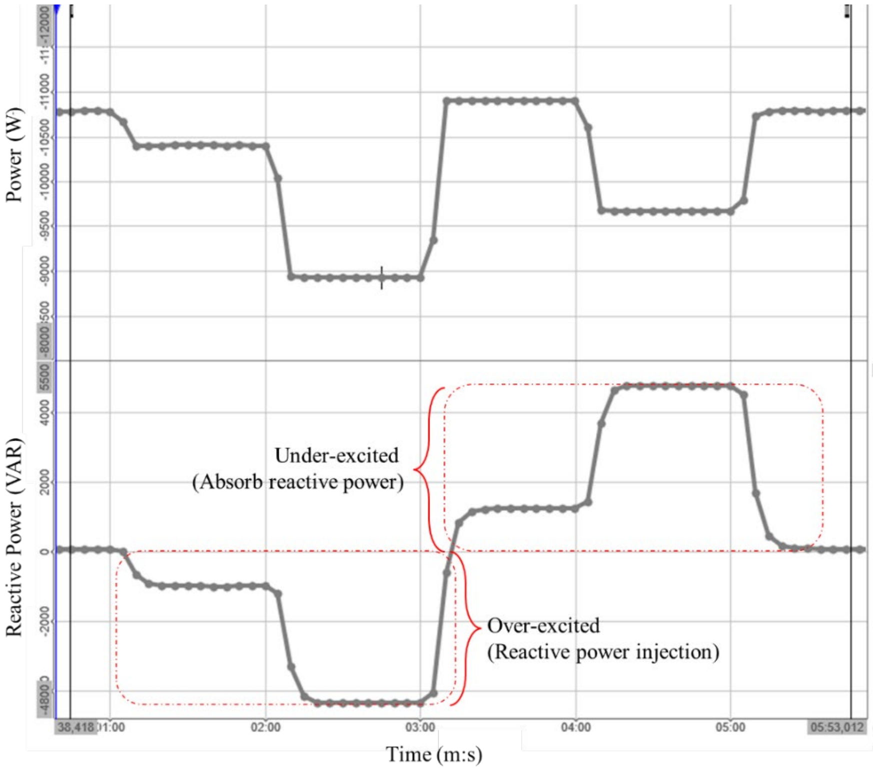


Figure 12: Active and reactive power response of the AC V2G system during Q(U) voltage step test

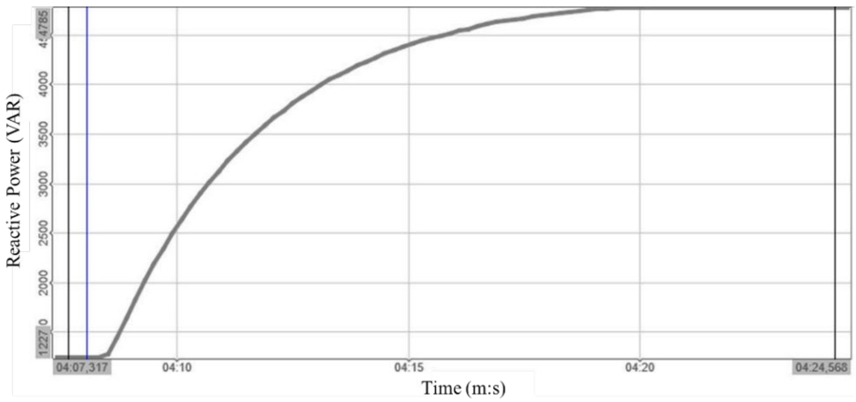


Figure 13: Reactive power injection following a voltage step from 1.03 to 1.08 p.u.

The plot in Figure 13 shows the dynamic response of the AC V2G system as it transitions from the deadband region into the overvoltage range defined in the Q(U) curve. The V2G system begins absorbing reactive power, ramping smoothly to approximately 4.8 kVAr at 1.08 p.u. The continuous and stable increase confirms the system's ability to deliver accurate over-excited and under-excited reactive power support with no overshoot or oscillation, demonstrating control stability.

# 5 Local Control Requirements and Compliance

In addition to general grid code functionalities such as frequency and voltage support, AC V2G systems must also comply with local control requirements defined by national regulations and DSOs. These requirements are essential to ensure the safe integration of DERs at the household and neighborhood levels, particularly within LV distribution networks.

## 5.1 Regulatory Requirements in Key Markets

In Germany, the VDE-AR-N 4105 standard mandates the implementation of $P_{AV,E}$ monitoring, which limits the active power fed into the grid to a pre-defined threshold specified by the DSO. The V2G system, like any other generator in the low voltage grid, must monitor the total feed-in at the connection point using the real-time meter and dynamically reduce its output when the threshold is exceeded. The response must follow a time-dependent curve to prevent network overloading [5].

Additionally, §14a of the Energy Industry Act (EnWG) [7] introduces mandatory controllability for flexible electrical devices, including EV chargers in both charging and discharging modes. Under this regulation, DSOs are authorized to remotely reduce power flows to alleviate local congestion, while ensuring a minimum supply is preserved for the end user. This capability is expected to become a foundational element in future decentralized grid management strategies.

In the United Kingdom, the Engineering Recommendation G100 [8] requires systems to limit both active and reactive power exchange as well as current at the grid connection point. This ensures local grid hosting capacity is not exceeded and helps avoid voltage or thermal violations within distribution networks.

## 5.2 Distributed Control in the Volvo Cars AC V2G System

The Volvo Cars AC V2G system is designed to meet these regulatory demands through a layered control architecture combining:

- HEMS: Provides higher-level supervisory control based on grid tariffs, user-defined fuse constraints and EV constraints and specifications. The HEMS plans charging and discharging to optimize costs and avoid triggering local limits.
- Charger-Level (EVSE) Local Control: Implements real-time functionalities such as phase-specific current limitation, overshoot protection, and fast response to grid disturbances. These controls operate autonomously to maintain compliance with grid requirements and physical installation constraints.

This distributed control structure enables compliance with current and evolving national regulations while supporting grid reliability and preserving user flexibility.

### 5.2.1 Remote Curtailment via Digital Input Port

In line with EN 50549-1 [4], Clause 4.11, the EVSE is equipped with a digital input port to support direct curtailment by the DSO. Upon receiving a signal from a locally installed control device, the EVSE must cease or reduce active power within five seconds. This input also supports remote configuration and adjustment of active power setpoints across the full operating range, fulfilling DSO requirements for both emergency disconnection and gradual load control.

# 6 Conclusion

This paper presented a comprehensive evaluation of the Volvo Cars AC V2G system, highlighting its compliance with essential European grid codes and its advanced capabilities for supporting power system stability. Through detailed explanations and laboratory validations, key functionalities including FRT, LFSM, and reactive power control (Q(U) mode) were demonstrated.

Test results from HIL evaluations confirmed that the V2G system robustly handles voltage dips (UVRT), frequency deviations, and reactive power requirements without compromising connection stability. Moreover, the integration of a HEMS was shown to effectively optimize energy management, accommodating dynamic grid tariffs, user preferences, and local DSO constraints, such as those outlined in VDE-AR-N 4105, §14a EnWG, and EN50549-1.

In conclusion, the Volvo Cars AC V2G system not only meets current regulatory demands but also demonstrates significant flexibility and adaptability for emerging and evolving grid requirements. Such technology can significantly accelerate the integration of renewable energy sources and DERs, reinforcing grid stability and enabling proactive energy management for both residential users and DSOs.


## Acknowledgments

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## 8 Presenter Biography

Ali Fotouhi is a Technical Expert in Vehicle-Grid Integration at Volvo Cars. He holds a Ph.D. in Electrical and Computer Engineering from the University of Lisbon, awarded in 2018. Following his doctoral studies, he joined Chalmers University of Technology, Sweden, as a researcher, where he specialized in energy management, active distribution grids, and power system analysis. Since March 2022, Ali has been a member of the Energy Products and Grid Team at Volvo Cars, contributing to the development of innovative solutions at the intersection of automotive electrification and grid integration. His work focuses on advancing sustainable energy solutions within the automotive industry, driving the transition toward a more resilient and intelligent energy ecosystem.