V2G potential for grid services provision and the relevance of a technical characterization

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***Abstract*—International CO_2 reduction commitments are pushing increasing penetration levels of renewable energy sources and electrification of the transports sector. The expected growth for electric vehicles (EVs) will surely have a tremendous impact on the electricity distribution system. Despite the challenges ahead, EVs are able to make bidirectional energy transactions in what is designated as a Vehicle-to-grid (V2G) framework. Thus, EVs, when aggregated, have the potential to offer system management opportunities to the power grid, more specifically as providers of grid ancillary services. These services are considerably time critical and, therefore, is of utmost importance to understand the V2G characteristics and performance, particularly when remotely controlled by Aggregators. Currently, only DC charging through CHAdeMO and CCS/Combo standards enables V2G. This work presents an overview of V2G challenges and opportunities while introducing the relevance of a robust technical characterization. A set of tests focusing on V2G system accuracy, efficiency and response time were performed on remote operation and real environment. The presented results complement and support the current literature and contributes for the comprehension of V2G systems capabilities and suitability to provide flexibility grid services.**

Keywords—electric vehicle, vehicle-to-grid, electric vehicle supply equipment, EV charger, CHAdeMO

I. Introduction

The decarbonization of electricity generation complemented by the ongoing electrification of the transportation system are expected to play a determinant role in achieving CO_2 reduction international commitments [1], [2].

Nevertheless, the substantial growth observed for grid-connected small-scale distributed energy resources (DERs) poses new challenges in distribution planning and operation, due to its dispersed and variable nature. Furthermore, electric vehicles (EVs), with a globally-increasing penetration [3] will constitute a relevant share of the electricity demand and will have a tremendous impact on the power system [4], [5]. As an additional load, EVs will require a larger generation capacity [1]. Increased peak-load, energy losses and grid equipment overload have been listed as some operational challenges caused by EV integration in the distribution system, contributing for a lower power quality and grid reliability [6]. Thus, the expected penetration of large fleets of EVs jointly with the abovementioned increasing penetration of DERs, such as solar and wind, will require additional distribution system ancillary services to maintain high quality power provision to the end consumers [7].

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On the other hand, EVs can also be characterized as distributed energy storage elements with considerable storage capacity [8], which can behave either as controllable loads or energy sources. Thus, there is a remarkable potential for the use of EVs to maintain power system balance by tackling DERs variability [9], [10].

The interaction between the power system and EVs, with bidirectional power flow, is designated as vehicle-to-grid (V2G) or vehicle-grid integration, and is already the study object of multiple R&D projects worldwide [11].

II. Ancillary services through V2G

From the power grid perspective, the V2G concept enables EVs to play a relevant role in the power grid operation, providing services at different spatial (household level, local grid level or regional level) and temporal scales. In [12] the authors list and describe six categories of services provided by EVs in the Parker Project [13]. Because of their ability to respond to dynamic situations, be it to vary the power output or even to switch from being load to a source, several works suggest that EVs are more suitable for primary (frequency containment reserve) and secondary reserve, where they can maximize their revenue [14], [15].

Thus, EV smart charging and the provision of ancillary services through V2G offers several opportunities: *i)* integration of renewable energy into the transportation sector [16]; *ii)* EVs as an alternative to other types of generators that currently provide primary frequency control [8]; *iii)* delay some investment costs associated with the expansion of the grid infrastructure [1]; *iv)* reduce the costs for electricity [17]; and *v)* promote full participation of innovative power end-users in the energy transition, as aimed by the European Commission [18].

It should be taken into account that ancillary services are time critical and that different services require different response times from milliseconds up to tens of seconds [19]. As so, knowledge of the performance of EVs and the electric vehicle supply equipment (EVSE) is of major importance to determine the suitability of EVs and EVSE to provide different types of grid services.

The work of [19] and [20] (related to Nikola project [21]) addresses the most time critical services (primary frequency and synthetic inertia) and focuses on response time of EVs during AC charging process, providing a real analysis of several EVs readiness to provide grid services. Regarding DC charging, the authors in [12] state that one of the main developments of vehicle-grid interaction is the support of V2G through DC chargers utilizing CHAdeMO protocol [22].

In [23] the authors test and model a commercial V2G system to assess its suitability for ancillary services.

In a V2G system providing grid services, the bidirectional power flow between the EV, the EVSE and the grid is controlled by a control software often called Aggregator. The aggregator calculates and dispatches power requests in both directions and can by-wire or remotely operate a fleet of EVs [24]–[26]. In [19] the authors point incomplete communications protocols and lack of information regarding hardware response times as barriers for commercial ancillary service provision using AC charging or V2G systems[19]. They add that, despite the capability of the majority of EVs for time critical grid services provision, harmonization in communication and regulatory areas of current commercial applications are still needed.

Thus, the capabilities and readiness of V2G technology to provide commercial grid services are deeply dependent on performance attributes of the EVSE, such as efficiency, accuracy, and response time for both remote communication and hardware activation.

III. Charging Infrastructure

A charging infrastructure comprises a set of standards and hardware required for EVs to transfer electric energy from the distribution grid to the vehicle battery.

A. Charging Standards

Charging of EVs can currently be done through AC or DC charging. Regarding fast charging (above 22 kW) three fast standard connectors prevail in Europe: CHAdeMO, Combined Charging System (CCS) Combo2, and AC43kW (Fig. 1). Tesla EVs are able to fast charge using CHAdeMO via adapter for Tesla [27].

The presence of an on-board AC/DC converter is mandatory when using AC charging, while in DC charging, a dedicated off-board AC/DC converter allows for direct DC power supply to the EV battery. IEC61851-1 establishes 3 modes (Mode 1, Mode 2 and Mode 3) for AC charging [28]. In public charging stations and commercial buildings Mode 3 is widely adopted since it assumes a dedicated EVSE with built in protection and control components.

For high charging power levels (Level 3 [29]) DC charging (defined in IEC61851-1 as Mode 4) is preferred. Three types of DC charging systems are currently available in the market: type 4 CHAdeMO, type 4 CCS/Combo, and Tesla (AC and DC single phase).

B. Dynamic Charging

An EV charging process using variable power is often called dynamic charging. As aforementioned, if the interaction between the EV and the grid allows for dynamic charging and dynamic discharging the V2G terminology is applied.

Despite AC charging and DC charging via CHAdeMO or CCS/Combo allow for dynamic charging, only the last two enable V2G. The absence of EVs equipped with on-board bidirectional chargers that allow for battery discharging and the inability of the communication protocol for AC charging to initiate V2G, makes V2G not possible when using AC charging.

C. V2G via CHAdeMO and via CCS/COMBO

As opposed to previous version, CHAdeMO v2.0 enabled the EVSE to be the master and allowed for V2G operation. The share of information between the EVSE and the EV rely on CAN communication [30]. According to [31], during the charging (or discharging) process and based on the state-of-charge (SOC) and temperature of EVs' battery, the EV continuously (each 200ms) sets charging and discharging current limits. The authors state that CHAdeMO v2.0 facilitates V2G operation with high flexibility.

CCS/COMBO makes use of Power-Line-Carrier (PLC) communication to enable V2G operation. Compared to Pulse-Width-Modulation (used in AC charging communication) PLC provides higher level communication.

Nonetheless, when using CCS/COMBO standard, a continuous negotiation between the EVSE and the EV needs to take place to set a new charging/discharging current set point. This means that for each intended change in charging/discharging current the EVSE is able to request for a change in current but the EV needs to accept the request, which result in a lower flexibility when compared with CHAdeMO. This continuous negotiation of current set points increases the response time and entail a larger grid buffer capacity when sudden changes need to take place [32].

Further, the results presented in [32], where dynamic charging of two different CCS compatible EV was implemented, showed significant differences in response time from EV to EV, enhancing the importance of technically characterize different EVSE/EV combinations.

Fig. 1. Fast charging connectors: CHAdeMO (left), CCS/Combo for Europe (middle) and European Type 2 Mennekes (right). Adapted from [33].

The present work aims to extend and complement the existing literature by characterizing a V2G system (comprising a commercial CHAdeMO charger and a commercial EV) in remote operation. The DC and AC power are measured in both charging and discharging modes and a set of equations describing the equipment's operation is presented.

The following V2G system parameters were assessed:

- Accuracy—agreement between a requested power set-point and the effective AC/DC power output.
- Efficiency—AC/DC conversion efficiency.
- Response time—time needed to deliver a requested AC/DC power.
- Ramping ability—maximum rate allowed for AC/DC power output ramping.

IV. Experimental setup and case study discription

The various elements of the V2G system tested in this work are presented in Fig. 2. The EV was a Nissan Leaf (2015 model) with a default 24 kWh lithium-ion battery. The EVSE is a V2G bidirectional outdoor charger commercial model, based on CHAdeMO fast charging protocol [22], [30]. According to the standard IEC 61851-1 [28], this charger can be classified as Mode 4 (i.e. the EV is indirectly connected to the AC supply network, through an off-board charger which is responsible for the AC/DC conversion) and the connection between the EVSE and the EV is case C (i.e. the power supply cable is permanently attached to the EVSE). The EVSE can be directly connected to an electrical grid or to an existing customer power distribution board (as in this case study) and requires three phases (16 A), neutral and protective earth connections.

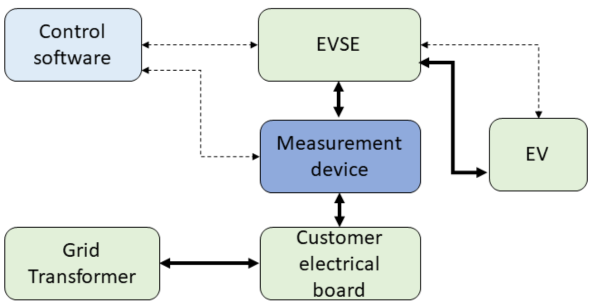

Fig. 2. Experimental setup of the V2G system under analysis, indicating both power flows (continuous arrows) and communication links (dashed arrows).

The charger has five operation modes: *i)* "stop mode", where the equipment is in a stand-by state; *ii)* "simple charge", for EV's which do not support V2G technology and, thus, only accepts power flows in one direction; *iii)* "V2G pause mode", where the equipment is paused but ready for V2G operations; *iv)* "charge mode" and *v)* "discharge mode", where power flows from the grid to the EV, or vice-versa, respectively. It is worth noting that the EVSE initiates at its rated power (10 kW) and varies upon receiving power set-points from the V2G charger operator.

The communication protocol between the EVSE and the control software application was implemented in Python for a remote wireless operation. It allows the V2G charger operator to send new power set-points or stop/standby its operation as well as request its status (retrieving variables such as DC power, AC active power, SOC, among others) at any given moment. For a continuous, real time data acquisition (frequency, active power, reactive power, apparent power, power factor) a *Chauvin Arnoux*® PEL 103 power and energy logger [34] was installed between EVSE and the grid. For 1--10 kW set-points, the AC active power measurements from the EVSE internal sensors and the PEL 103 were highly correlated ($R^2 = 1$), with a 30 W mean absolute deviation. The DC side parameters were measured with the internal DC current and DC voltage sensors of the EVSE since the installation of external probes is not suitable in the field (site with public access).

A V2G system analysis was performed regarding its accuracy, efficiency and response time, for both charging and discharging modes. To explore the delay between the requested power set-points and the changes in AC power flow, i.e. the response time, as well as quantify the EVSE's accuracy and conversion efficiency, a different batch of power set-points were requested. With a starting 1 kW power set-point, the EVSE was requested to perform positive and negative power ramps with an absolute value ranging from 1 kW to 9 kW, in both discharging and charging modes (Fig. 3). Each set-point was separated by a 30 s interval to ensure stable measurements. Regarding sign convention, positive power denotes charging and negative power denotes discharging.

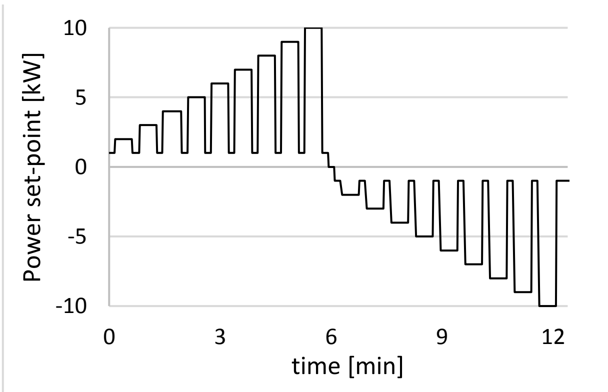

Fig. 3. Tested sequence of power set-points, both for charging and discharging modes,

V. Results

A. EVSE accuracy of response

From the performed tests, when the EVSE effective power flow is compared to the requested set-point, it is possible to conclude that the set-points are implemented by the equipment in terms of its measured DC power (Fig. 4). In charging mode, the AC input is systematically higher than the requested set-point, presumably to compensate for the equipment's energy needs and the inverter's conversion efficiency. However, in the discharging mode since the DC power is, in fact, the EVSE input, the converted AC power is substantially lower than requested. It is also possible to observe that the EVSE in charge mode saturates for set-points higher than 9 kW. In this case, the current saturates at 23 A, and not the supposed rated 25 A, possibly to ensure that the EVSE AC power does not surpass its rated value (10 kW) [35].

Disregarding these two outlier cases (one for each operation mode), the deviation between the requested and effective power flow ranged, randomly, from -0.2 kW to 0.2 kW when operating in charging mode; whereas a systematic undersupply between -0.69 kW down to -1.46 kW, the worse the higher the requested set-point, occurs when operating in discharging mode. Additionally, it was possible to obtain linear expressions (R^2 charge and R^2 discharge = 0.99) to estimate the EVSE output based on the requested power set-point (P_{set}),as shown in (1) and (2).

$$AC_{charge} = 1.011 \times P_{set} + 0.578\ [kW], P_{set}\ \epsilon[1,9]kW \qquad (1)$$

$$AC_{discharge} = 0.926 \times P_{set} - 0.578\ [kW], P_{set}\ \epsilon[2,10]kW \qquad (2)$$

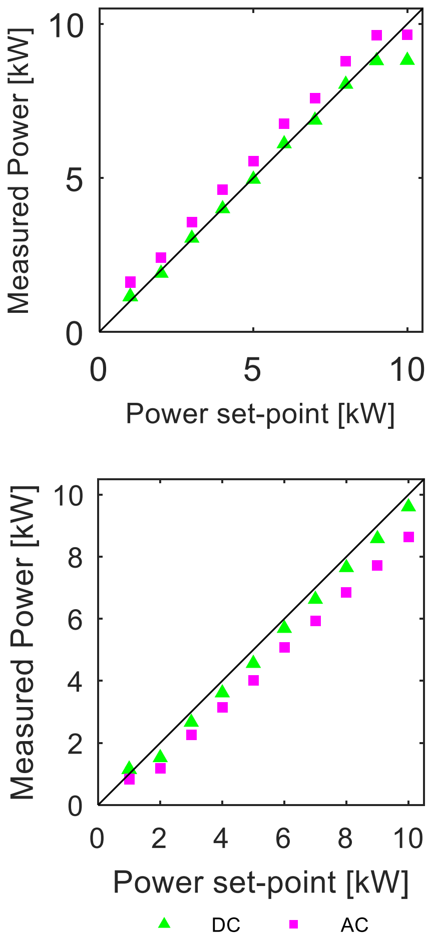

Fig. 4. DC and AC power measurements for the requested power set-points in charging (up) and discharging (down) modes. Each value represents the average of four identical tests.

B. EVSE efficiency

The EVSE efficiency was tested in both charging, when it acts as a converter, and discharging modes, when it acts as an inverter. When operating close to the EVSE's rated power (10 kW) the conversion efficiency is around 91.4 % and 90 % for charging and discharging modes. However, for lower set-points these efficiencies decrease to 71.4 % and 73.4 % (Fig. 5), respectively.

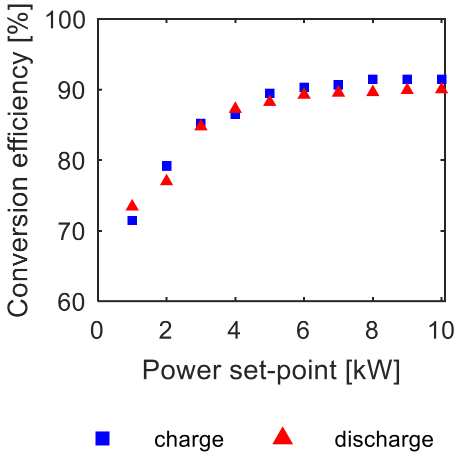

Fig. 5. EVSE conversion efficiency for the requested power set-points for charging and discharging modes.

C. Response time

For both charging and discharging modes, different power-set points, leading to specific power ramps (ΔP) from 1 kW up to 9 kW, were requested. The time needed for the V2G system to change its power flow and stabilize was quantified through visual analysis of the EVSE power input/output. The recorded values were then disaggregated into a communication response time (i.e. the time needed for the EVSE to remotely receive the new power set-point) and an EVSE/EV response time (i.e. the time needed, after receiving the new set-point, to change the power flow). Being in the range of seconds, the response times showed some dispersion due to the data logger's acquisition rate (1 Hz). Thus, each power set-point was repeated four times, and clearer patterns could be observed after averaging (Fig. 6).

The results were quite similar for the two modes. The total response time showed to depend on ΔP and can be estimated using a single linear regression ((3), $R^2 = 0.81$), ranging between 4 and 6.5 s for the tested ΔP values.

$$Total\ response\ time = 0.26 \times \Delta P + 3.99[s], \Delta P \in [1,9]kW \qquad (3)$$

For the disaggregated components (c.f. Fig. 6), it was possible to conclude that only the EVSE/EV response time, is highly correlated with ΔP. From a linear regression ($R^2 = 0.95$), the EVSE response time showed to increase at a 0.26 s/kW rate (i.e. its maximum power output variation is of 3.85 kW/s), added to a 1.67 s fixed expense (this constant may be explained by an insufficient data acquisition rate). On the other hand, the communication time was on average 2.37 s with a 0.33 s (14 %) standard deviation, independently of the ΔP.

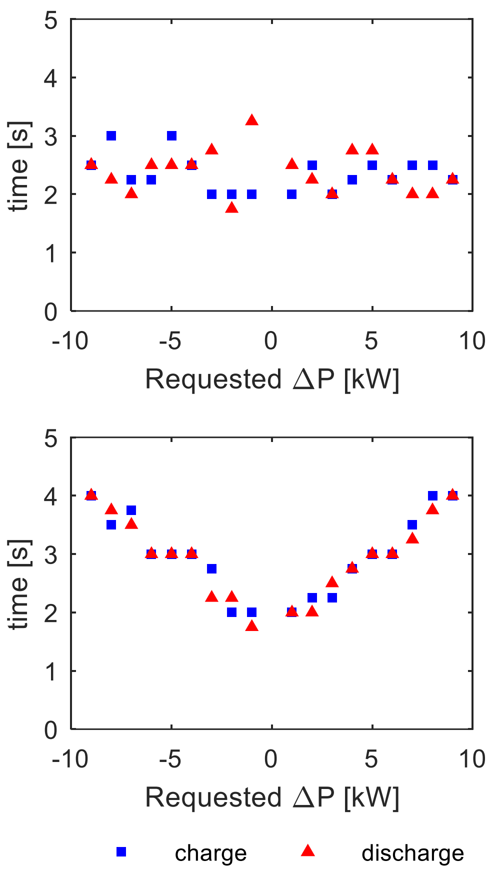

Fig. 6. Communication (up) and EVSE/EV (down) response times as a function of the requested ΔP for charging and discharging modes. Each value represents the average of four identical tests.

VI. Conclusion

This work provides an overview on the provision of ancillary services by EVs in a V2G framework, while raising awareness for the need of characterizing these systems (justified by field measurements on a commercially available V2G system).

The power set-points showed to correspond to DC power, making the EVSE underperform when in discharging mode, since its self-consumption and conversion efficiency are not compensated. Moreover, the equipment seems to saturate at 9 kW charging power, since higher values would require the EVSE to surpass its 10 kW rated power. For both operation modes, the effective AC/DC power output can be described as a linear function ($R^2 = 0.99$) which depends on the requested power set-point. The EVSE seems to be designed to operate more efficiently close to its rated power, as its efficiency can reduce up to 70 % for low set-points.

The EVSE needed 4 s to 6.5 s to deliver a requested power set-point, depending on the demanded power ramping. These results are in agreement with the ones obtained in [23], where a 7 s response time is reported for a case study done in remote operation. However, this work expands the current literature by being able to disaggregate this time into a communication component (i.e. the time between a power set-point is requested and the EVSE output starts to change) and a power ramping time, and by considering the response time dependence on the requested power ramp. The communication time did not depend on the power ramp magnitude, with an average value of 2.37 s and a 0.33 s (14 %) standard deviation. However, the ramping time seemed to be constrained by the EVSE/EV's ramping ability (here estimated as 3.85 kW/s) added to a constant 1.67 s expense. The communication time would be reduced with better and faster protocols and while the ramping rate limitation can be circumvented by requesting lower magnitude ramps from several EVs, the constant term may be explained by an insufficient data acquisition rate (1 Hz).

The V2G system characterization here presented is of relevance for several reasons: *i)* supports grid planners and operators when defining V2G regulation [36]; *ii)* enables a better equipment operation, maximizing its performance and revenue, what is of major importance when remote operation by aggregators takes place; *iii)* leverages more accurate, and thus credible, V2G simulation works. Then, knowing the V2G response time is of essence for the provision of grid services, since the V2G chargers will be operated using predictive control strategies (i.e. power set-points will be defined ahead in time by load and generation forecasts) and such strategy needs to take into account the V2G response time.

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