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Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives

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A R T I C L E   I N F O

Keywords:
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Flexibility services
Frequency services
Electric vehicles
Charging clusters
Smart chargers

A B S T R A C T

The transformation towards a sustainable power system calls for new ways of operating the network. In that regard, electric vehicles (EVs) with their charging infrastructure qualify as a flexible resource. This paper interconnects ancillary services and EV flexibility to help system operators (SOs) and flexibility providers understand the role and localize EV-chargers in the power system. First, the focus is on SOs. The manuscript reviews ancillary services based on power system operational challenges. The ancillary services are differentiated between 8 frequency and 32 flexibility services. These are then subdivided depending on the management control: the first group includes inertia, primary, and secondary/tertiary frequency control, while the second includes congestion management, voltage regulation, power quality, grid stability, and emission management. Of all the different services, the ones that can be provided by EV-charger are highlighted and classified into 12 geo-electrical charging clusters. Second, the focus is moved to the flexibility providers. Independently from location, to provide ancillary services with EVs, multiple actors are recognized: the end-user, the charging site operator (CSO), the charging point operator (CPO), the aggregator, the energy community, the distribution system operator (DSO), and the transmission system operator (TSO). The collaboration between the actors is today carried out by making alliances, to help exchange knowledge and gain confidence in ancillary services provision. In conclusion, the literature review presents the characteristics of 27 slow (up to 50 kW) smart chargers, the common flexibility features being scheduling (100%), modulation (89%), and phase switching (10%).

1. Introduction

The conventional grid planning process requires the decision of the grid components capable of covering the maximum demand of the system and generally have a useful life between 25 and 50 years [1,2]. However, grid sizing and normal operation are challenged by the increasing penetration of intermittent renewable energy resources (RESs) and new distributed technologies [3]. For instance, the EVs rapid growth has an adverse instantaneous power delivery effect; the simultaneous charging can potentially harm the grid or require large grid upgrade investments [4,5]. Therefore, power system flexibility (PSF) is a possible solution to the sustainable power system paradigm [6]. For example, the authors of [7] highlight how PSF can substitute unnecessary grid upgrade or support the grid infrastructure. Fundamental work on flexibility in the power system has been presented in [8–14]. Authors agree when defining flexibility according to (i) type of flexibility resource (ii) duration and (iii) incentives for activation. In addition, authors of [15,16] emphasize the importance of relating flexibility with geographic granularity, system operators, and market interoperability. Thus, a flexibility solution is the combination of flexible resources, which can be further categorized on (i) demand, (ii) supply and (iii) grid-operation flexibility [8,10], with market enablers [11,12] on a predefined time and space domain [14,15]. Hence, highlighting the need for new markets, regulations, and codes of practices to harvest the flexibility value proposition. Furthermore, the authors of [17] define the flexibility value proposition on current markets and systems, while the authors of [18,19] suggest that the network can become more cost-effective by incorporating flexibility into the grid planning phase.

1.1. Motivation and research gap

The first step in a successful implementation of PSF is to agree on a definition of PSF. The authors of [6,9] have provided a historical background for the flexibility term used in the context of power systems and have underlined the lack of clarity in reviews of the literature. Our manuscript agrees with the PSF definition proposed by authors of [9],

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where PSF is strictly connected with the ancillary services and reads as follows:

“The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions”.

The British PAS1879 code of practice [20] provides a standardized control for the power of domestic smart appliances subject to consumer consent. In Denmark, instead, the flexibility services procurement guidance [21] displays a market structure that exploits the current infrastructure for data management, monitoring, and validation. This guide, heavily based on the findings of the EcoGrid 2.0 research project [22], aims to stimulate DSOs to procure flexibility services instead of grid reinforcement without compromising their radial network N-1 spare operational capacity. Taking inspiration from such British and Danish initiatives, the rich PSF literature, and the current infrastructure for data management, monitoring, and validation, this article aims to stimulate DSOs to procure flexibility. The rest of the paper is structured as follows. Section 2 describes the paper methodology and the conducted review workflow. Further, Section 3 introduces frequency and flexibility services, which Section 4 utilizes to sketch the framework of the services. Section 5 classifies the current smart chargers’ state-of-the-art technology and Section 6 concludes the article with the main findings.

2. Methodology

The methodology and workflow are presented in Fig. 1. The goal of the paper is to link ancillary services provision with electric vehicles. To do so, two parallel workflows are performed (Steps 1–4 and 5–9). Starting with the literature review, ancillary services (step one) and EV grid integration (step five) are the keywords used on the Google Scholar and IEEE Xplore search platforms. The introduction of the EU Electricity Market Directive (2019) [29], the British PAS1879 code of practice, and the Danish flexibility procurement guidance are important directives to gain confidence in ancillary services provisions. Hence, the ancillary services literature screening process (step two) benefits from the chosen eligibility criteria and limiting the scope to European ground. Similarly for the EV grid integration literature, the eligibility criteria (step six) is the charging behavior studies and notchings followed from the IEA. On the one hand, ancillary services are classified on frequency and flexibility services (step three). On the other hand, charging behaviors are classified on the basis of charging locations as electrical and geographical charging clusters (step seven).

Step four analysis the ancillary services by highlighting services delivered from EVs. Additionally, based on market platforms proposed from demonstration projects, the paper recommends a flexibility supply...
3. Ancillary services and electric vehicles grid integration

3.1. Electric vehicles potential

Authors of [31] quantify the demand response flexibility potential for two European system scenarios. By 2050, there is a flexibility potential from EVs of 878 out of 1648 GW for the centralized system scenario and 260.7 out of 370 GW for the decentralized system scenario. Thus, by acknowledging even the large potential of economical savings from smart charging [23,32], this article focuses on EVs charging operation. Flexibility from EV and charging station is dependent on user constraints, time availability, charging location, etc. [33]. In particular, the residential and workplace charging environment top the parking lot, while it remains dominated by slow charging, commonly below 50 kW charging power [34]. To perform EV ancillary services, a smart charger (unidirectional (V1G) or bidirectional (V2G)) is required [23, 35]. Unidirectional smart chargers (V1Gs) can only draw power from the grid, while vehicle-to-grid (V2G) chargers can also inject power to the grid. This study focuses on V1Gs, which are reviewed in Section 3.5. The V2G technology, previously discussed in [23,36], will become more attractive when future vehicles are equipped with on-board bidirectional chargers, or the price of V2G chargers decreases significantly [37].

Further, the recent update on the Danish grid code has included the V2G technology part of the same group with battery energy storage [38]. Depending on the storage size (kWh), different groups are present in the Danish grid code. These different groups mandate which ancillary services should the V2G technology provide. To the authors’ knowledge, ancillary services from EVs have been discussed in the literature without a full comprehension of all services. On top of that, the literature is missing a geographical localization of ancillary services from EVs.

3.2. Ancillary services

Under the new sustainable power sector paradigm, the operational needs of the power system can be grouped into three pillars: (i) Adequacy and security of supply (having enough generation to cover peak demand at any time) [39], (ii) Power system stability (the ability of the power system to regain the operating equilibrium state after experiencing a physical disturbance, for a given initial state without violating system variables, hence the system remaining intact) [40,41], and (iii) Power system resilience (ability of the system to react to extreme, or catastrophic events) [42]. The conventional way to cover such requirements is through grid codes, wholesale/retail energy markets and ancillary services markets, more specifically balancing markets [43,44]. However, these services have limitations on the upcoming decentralized grid, because they were initially developed for the centralized one [45]. Therefore, extensive research is conducted on complementary services [46,47]. The entirety of the services required from the power system perspective falls under ancillary services [48]. Those account for all services offered in the balancing and flexibility markets. Frequency services maintain the system-wide frequency characteristic, while the flexibility services assist local challenges.

3.3. Frequency services

The conventional method for controlling the system frequency depends on inertia, primary, secondary, and tertiary frequency control [44]. This section describes the frequency stability and services first, and then it highlights the services that can be delivered by EVs.

3.3.1. Frequency stability conundrum

First, the integration of converter-based generation, phase-out of thermal units lead to the reduction of system inertia [49,50]. The system inertia and rotating load-damping effect are further challenged by the growth of high voltage direct current connections [51] and the uptake of load frequency drivers [52], respectively. Second, the increased penetration of RESs and the phase-out campaigns of polluting thermal units reduce the number of generators able to provide reserve...
power for primary (containment reserve) and secondary (restoration reserve) frequency control [53]. On top of that, the frequency stability is threatened by both the loss event of generating units [40] and the ill generation forecast of RESs [48]. Hence, due to the low-inertia in the system, even mild disturbances would cause a large enough rate of change of frequency (RoCoF) to activate defense plans [54], such as under-over-frequency schemes [55]. In addition, a large RoCoF can activate protection relays, resulting in cascaded trips and leading to system collapse [56]. Acknowledging such challenges, the Nordic TSOs have proposed three low-inertia mitigation measures [57, 58]: (i) restricting the dimensioning incident; (ii) assessing the minimum systems’ inertia; and (iii) dispatching faster active power reserves that supplement the primary frequency control. Such measures also address the participation of converter-connected RESs in frequency services [59–61]. Similarly recommendations are followed-up in North America [62, 63], Australia, United Kingdom [53,64], and Ireland [53,65]. These measures try to arrest RoCoF, avoid a low frequency nadir, and help the system land at a desired steady-state frequency, which is affected by the size of the contingency, systems’ inertia [66], speed, and magnitude of injected active power response from generators [62].

3.3.2. Conventional and novel frequency services

Fig. 2 describes frequency regulation services by timeline and distinguishes between conventional and novel services (supporting a low-inertia system). Frequency services are divided into activation periods and service types. The periods are the arresting, rebound, and recovery period [60], while the types are I (un-sustained), II (sustained), and III (sustained) [53, 67]. The nomenclature in Fig. 2 is adopted from ENTSO-E [68].

After a mismatch between production and consumption, a sharp increase/decrease of the frequency is experienced. Here, the frequency-arresting period is the most critical. Multiple varieties of the system inertia are automatically and instantaneously activated. However, such measures are not sustained, hence, those are complemented by the governor/droop-based control of frequency containment reserves (FCRs), and the novel fast frequency reserves (FFRs). The latter one does not intend to replace FCRs rather support them [57]. From the observed implementations and their respective requirements, two FFRs activation approaches exist. Nordic TSOs and ERCOT are dispatching FFRs after the FCRs [63, 69], while EirGrid and NG ESO are dispatching the FFRs before the FCRs [65, 70]. Another difference is the hard constraints of delivering FFRs. The NG ESO and ERCOT require full delivery below 1 s, while EirGrid and Nordics TSOs require full delivery below 2 s. On the one hand, this hard time constraint is a reason that conventional steam and hydro turbines are unable or do not desire to participate in such reserves [58]. On the other hand, converter-connected resources and frequency-responsive demand response cope well with such constraints, and those might dominate the FFRs [58].

After experiencing the minimum frequency (frequency nadir), there is the rebound period, which goal is to land the frequency in a steady-state. The amount of time and the frequency deviation from the nominal value are subject to the speed and the magnitude of injected power response (type II reserves) [68]. After reaching the frequency steady-state, the power system requires automatic generation control (AGC) to clear the frequency deviation by activating frequency restoration reserves (FRRs). Hereafter, the system is entering the recovery period where the frequency should adhere towards the normal operation. Once the AGC is provoked, the type II reserves are automatically deactivated. Further, the replacement reserves (RRs) replace the FRRs, and the FFRs can be restored for a new event [67].

Frequency control techniques are out of the scope of this paper, however, for a detailed review it is recommended to refer to: (i) photovoltaics [85, 86]; (ii) wind [67, 86]; (iii) battery energy storage system [47, 76] and (iv) different energy resources [62, 87]. The characterization of the frequency services depending on the type is presented in Table 1. This characterization per type is based on three reasons: (i) the goal of the service (reduce RoCoF, delay and prevent critical frequency nadir, clear frequency deviation), (ii) the stretch on the frequency excursion period (arrest, rebound, and recovery period) and (iii) the activation topology (RoCoF or frequency-based). The table summarizes the services presenting type and criteria. According to ENTSO-E, frequency service providers can be generators or loads [88]. The table also highlights in bold and * the five services that can be provided by EVs and their V1G or V2G chargers. Examples of how frequency services can be provided are as follows: (i) phase-locked loop (PLL) to measure RoCoF and a proportional-based control deploys synthetic inertia [89], (ii) virtual synchronous machine [90], and virtual oscillator control [91] methods to deploy virtual inertia from grid forming inverters [92], (iii) droop-based control for deploying FPR, or FCR [78], and (iv) the AGC which is a proportional integral-based control for deploying FRR or RR [82].

These services have already been validated in research; however, fast delivery services such as synthetic inertia, virtual inertia, and FFR are not commercially available. The main reason for this is the requirement to deliver such services with response time below 1 s. Of the rest of commercially proven services, due to economic feasibility, only FCR is applied in the field, i.e., droop-based control in Denmark [78]. FRR and RR have only been applied in pilot projects. The
increase penetration of EVs can mature (reduce the cost) the charging technology, and the rising electricity spot-prices could make FRR and RR economically viable very soon.

3.4. Flexibility services

Frequency regulation is a system-wide characteristic that cannot be contained locally. On the contrary, flexibility services reflect a local problem. Thus, flexibility services are, among others, linked to reactive power support, congestion management, power quality, power smoothing, and post-fault restoration services [93].

3.4.1. Flexibility services definition

Moving forward, this study lists the flexibility services that can be provided from EVs. While for frequency services there is an available market framework [94], the flexibility services are lacking, or rather are on the first steps of the implementation of such markets. For example, the authors of [95] discuss how flexibility products can be delivered, as ramp or energy, whereas in [6] a capacity allocation product is discussed. Recalling from the aforementioned literature [9,24], they agree on the allocation of flexibility services based on five features: resource type, duration, incentives, location, and enablers. Therefore, the authors propose the following definition for flexibility services:

Flexibility service refers to scheduling and/or modulation of the collective/single consumption or generation of electrical appliances or distributed technologies, in agreement with the customer (consumer or generator) or mandated in the grid code, after responding to signals from market enablers, to increase network reliability and efficiency on a predefined time and location.

3.4.2. Flexibility services classification

Based on the aforementioned pillars of power systems operational needs and on the Danish flexibility services procurement guidance, this paper characterizes the flexibility services into three categories: natural, scheduled, and conditional. Natural flexibility services refer to actions actively enabled by the SO without the need for a procurement process, namely demand response programs, control of network components and grid code requirements. Scheduled services account for measures procured by the SOs to not jeopardize system safety operation or counteract N-1 situations. Conditional flexibility services are activated to restore system stability or increase power system efficiency. The difference between conditional and scheduled services is the activation type. For conditional services the activation is post-event, whereas for scheduled services it is a pre-event or during event activation. Natural flexibility comes first, it is a tool only based on the agreement with the user, and it potentially reaches the highest number of flexibility providers, along the timeline. If natural flexibility is not enough, scheduled flexibility is used by SO in a dedicated area, with a specific timeline and fewer providers. Similarly, conditional flexibility is the last resource to avoid further escalation of the problem or help the system recover. In addition, what may sound important to the reader are the steps SO takes to acquire flexibility services (Table 2 and Figs. A.8, A.9): first, exhaust the available (natural) services and then use the market ones (scheduled or conditional). Table 2 categorizes the flexibility services by type – natural, scheduled, and conditional –, by area DSO or TSO and by topic. Also, the table gives a short description of the services and highlights the services that can be delivered by EVs by bold style and *. Here, 26 and 20 out of 32 flexibility services can be provided through V2G and V1G, respectively. The extra services that can be provided through V2G refer to the possibility of injecting power into the grid and providing reactive power support. Further, the V1G can deliver flexibility services via scheduling or modulating the charging process. These features are fully investigated.
Table 2  
Flexibility services classification based on type, enabler and grid location. * marks services that can be delivered from EVs via both unidirectional and bidirectional smart chargers (V1G and V2G), or only bidirectional chargers (V2G).

<table>
<thead>
<tr>
<th>Type</th>
<th>DSO area</th>
<th>Explanation</th>
<th>TSO area</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion management (DSO) via non-dispatchable demand response programs such as [96–100]:</td>
<td></td>
<td>It provides an economic incentive for consumers to reduce their consumption.</td>
<td></td>
<td>It intends to reduce consumption from polluting generators.</td>
</tr>
<tr>
<td>1. Time of Use (ToU)*</td>
<td></td>
<td>1. Putting an extra flat fee on particular hours.</td>
<td>1. Type of Use (TyO)*</td>
<td>1. Inducing an extra fee related to grid carbon intensity.</td>
</tr>
<tr>
<td>2. Dynamic pricing (DP)*</td>
<td></td>
<td>2. Putting an extra dynamic fee.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Critical peak pricing (CPP)*</td>
<td></td>
<td>3. Putting an extra fee on energy used during peak time.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Peak-time rebate (PTR)*</td>
<td></td>
<td>4. Offering payments for those who reduce consumption during peak time.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Extreme day pricing (EDP)*</td>
<td></td>
<td>5. Increasing DSO fees on a high loading day.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Inclining block rate (IBR)*</td>
<td></td>
<td>6. Increasing the electricity price rate with the end-user consumption rate.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Peak upgrade*</td>
<td></td>
<td>7. Proposing an end-user peak value and peak time-span (forcing an infrastructure upgrade if the time spent on the peak is met).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congestion management (DSO) via network components [102,103]:</td>
<td>8. Remote control of radial networks components to better manage their loading.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Network reconfiguration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid stability (DSO) via network components [104–106]:</td>
<td></td>
<td>It mandates capability features from the grid code to assist system stability.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Low-voltage ride through*</td>
<td></td>
<td>1. Requesting to withstand a low-voltage event in the network (high Q consumption nearby).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Fault ride through*</td>
<td></td>
<td>2. Requesting to withstand a voltage-dip (grid fault) for a defined time, as stated in the grid code.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Power factor control (TSO)*</td>
<td></td>
<td>3. Requesting reactive power control proportionately (determined by the droop) to active power in the point of connection.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Anti-islanding*</td>
<td></td>
<td>4. Requesting from grid connected inverters to be able to recognize islanding events and prevent them.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage regulation (DSO) via network components [103,107]:</td>
<td></td>
<td>It tackles voltage unbalances, under and over-voltage challenges.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid stability (TSO) via network components [108–110]:</td>
<td></td>
<td>1. FACTS 2. Reactive power support*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage regulation (TSO) via network components [108–110]:</td>
<td></td>
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<tr>
<td>1. FACTS</td>
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<td></td>
</tr>
<tr>
<td>2. Reactive power support*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage regulation (DSO) [111,112]:</td>
<td></td>
<td>Congestion management (DSO) [113]:</td>
<td>Congestion management (DSO) [113]:</td>
<td>It dictates a load reduction or induced power to manage high-voltage network loading.</td>
</tr>
<tr>
<td>Voltage regulation (DSO) [114,115]:</td>
<td>3. Requesting active or reactive power support for under and over-voltage networks.</td>
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</tr>
<tr>
<td>3. Under/over voltage regulation*</td>
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</table>

In Section 5. Five major topics are recognized: congestion management, voltage regulation, power quality, grid stability, and emission (CO2) management.  

Congestion management refers to measures taken from SO to maintain the desired loading on their network components, such as transformers and electric lines. The reasons for doing so are twofold: (i) high overloading of a grid component will instantly damage the component [135] and (ii) moderate overloading will produce heat higher than normal from the current flowing through the device. With time, extra heat shortens the lifetime of the device, requiring earlier maintenance [136]. In Appendix A a Danish city distribution network [137] named Frederiksberg is taken as example to present the provision of congestion management.  

Voltage regulation refers to measures taken from SO to maintain voltage stability and overcome short-circuit scenarios. Here, the paper distinguishes between voltage and reactive power support. In the former, both active and reactive power play a role, while the latter is more related to reactive power support with a focus on weak grids [138]. The cause of voltage instability derives from the fact that the power network...
Table 2 (continued).

<table>
<thead>
<tr>
<th>Type</th>
<th>DSO area</th>
<th>TSO area</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power quality</td>
<td>[116–119]:</td>
<td>Grid stability (TSO)</td>
<td>1. RES power smoothing*</td>
</tr>
<tr>
<td>1. DER power-smoothing*</td>
<td>2. Damping harmonics*</td>
<td>[120–125]:</td>
<td>2. Emergency power*</td>
</tr>
<tr>
<td>3. Power factor control*</td>
<td></td>
<td></td>
<td>3. Black start capability*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. Energy arbitrage*</td>
</tr>
<tr>
<td>Voltage regulation</td>
<td>(DSO) [126–128]:</td>
<td>Congestion management</td>
<td>1. Requesting to smooth power variations from RES.</td>
</tr>
<tr>
<td>4. Voltage unbalance</td>
<td></td>
<td>(TSO) [133,134]:</td>
<td>2. Requesting to energize lines or start-up larger power plants.</td>
</tr>
<tr>
<td>mitigation*</td>
<td></td>
<td></td>
<td>3. Requesting to energize large renewable energy surplus and deliver it back on low renewable season production.</td>
</tr>
<tr>
<td>Reactive power support*</td>
<td></td>
<td></td>
<td>4. Requesting to fill the mismatch absent from BRP commitment, by reducing the load.</td>
</tr>
<tr>
<td>Grid stability (DSO)</td>
<td>[129,130]:</td>
<td></td>
<td>5. Requesting to store large renewable energy surplus and deliver it back on low renewable season production.</td>
</tr>
<tr>
<td>3. Intentional islanding*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Emergency power (DSO)*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congestion management (DSO) [112,131,132]:</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>10. Peak-shaving (DSO)*</td>
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<tr>
<td>11. DER power matching*</td>
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<tr>
<td>12. Phase balancing*</td>
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</table>

is operated close to stability limits and different load characteristics trigger it [139]. In Appendix A the provision of voltage regulation is illustrated from the perspective of DSO.

Power quality refers to the measures taken from DSO to improve supply quality and reduce grid operational losses. Here, the voltage regulation service is distinguished from the power quality service because it belongs to both DSO and TSO. In contrast, the latter belongs to the DSO. Besides, voltage regulation itself has become quite important; hence, it deserves to be mentioned separately. Power quality is focused on the fast dynamics of switching of electronic devices [140], the mitigation of distributed energy resources (DERs) power flickers [116,121], and the control of the end-user power factor [141].

Grid stability services cover the power system stability, adequacy, and security of supply outside of the wholesale electricity and balancing markets and are operated by DSO and TSO. Services such as low-voltage/fault ride through, power factor control and anti-islanding are generally capabilities mandated in the grid code. In a high integration scenario of RESs, RESs power smoothing services might be required to operate the system safely and preserve frequency power reserves [121]. Similarly, energy arbitrage and seasonal balancing are believed to be necessary services to cope with the unpredictability of RESs [142, 143]. Additionally, emergency power and black-start capability are programmed for blackouts (according to ENTSO-E) [144], or to provide emergency power to areas affected by local emergencies [130].

As the name suggests, emission management relates to a demand response service type of use (TyoU) that intends to avoid RES spilling and reduce consumption from polluting generators. TyoU induces fees for the carbon intensity depending on the generation mix. Higher fees correlate with high polluting generators.

Flexibility services are provided in the active and reactive power domains. For both domains, Table 2 noted flexibility services that are, on a dominant majority, at least research proven. Acknowledging the recommendations from [30] and the novel applications of commercial flexibility [20,21], stakeholders are only looking at active power services, mainly congestion management (refer to Table 2). In the short term, possible commercial flexibility services are demand response programs, TyoU, valley-filling and peak-shaving actions. In the long term, with large penetrations of EVs other flexibility services such as phase-balancing, power matching, and voltage regulation actions could be required.

4. Flexibility framework

4.1. Flexibility architecture and clustering

Another important step towards full activation of flexibility markets is the design of flexibility market platforms [145]. This has been researched and demonstrated through pioneer projects such as Piclo, Enera, Flex, GOPACS, NODES [30,146] and EcoGrid 2.0 [22]. The goal of such platforms is to couple flexibility providers with buyers of flexibility. Buyers of flexibility are SOs and providers of flexibility are aggregators or energy communities. Such aggregating entities utilize in an agreement the end-customer flexibility (flexibility resource) and provide a flexibility offer to the flexibility platform. The flexibility platform decides for the winning bids. Taking advantage of the learning from these projects a stylized illustration of such platforms is displayed in Fig. 3.

4.1.1. Clustering

One important step before matching the flexibility services is clustering the EV owners based on their charging behavior. The results can be biased to early movers [147] as the industry is still in the early stages. However, by looking at different databases and clustering investigations, in Figs. 4 and 5(a), we first cluster according to the grid connection (low, medium or high-voltage) [148] and second based on the charging behavior. Here, a complete picture of the available
charging data sets can be found in [149], while for charging behavior, it is recommended [150,151], and for infrastructure deployment, it is recommended [152,153].

The literature review distinguishes between destination charging and charging destination. In the first, charging is complementary to other user needs, such as going to the supermarket, in the second charging drives the choice of the user needs. Furthermore, charging behaviors are reflected at different charging sites: (i) home [155,156] and public residential charging [157,158]; (ii) curbside [159–161] and semi-public charging [162,163]; (iii) workplace charging [164]; (iv) fleet charging [165]; (v) large semi-public charging [166]; (vi) fast( en route) charging [167,168]; (vii) special semi-public charging [169, 170]; (viii) charging forecourts [171,172]; (ix) semi-private charging [173] and (x) charging hubs [174]. Although it is still quite early for the clusters to mature, the charging clusters derived from the review are in line with the clusters used in the Working Group 4 of the IEA GEF Global e-mobility program [175,176].

Accordingly, Fig. 4 illustrates with examples the CSO, which is the representative of the cluster. The CSO can incorporate one charger, in the case of a home charger or include multiple chargers such as the charging forecourts. The higher the site hierarchy, the fewer chargers there are, while the site connection capacity increases. Furthermore, it is a challenging task to estimate the number of chargers in each cluster. This factor is one of the current limitations on forecasting flexibility of charging clusters. In addition, the charging technology needs to be mature before trying any estimation. For example, most slow chargers today are single outlet; however, to increase utilization efficiency, dual outlet options are investigated. After identifying the charging clusters or CSOs, Fig. 5 (a) matches the charging clusters with their grid location (low/medium/high voltage). Besides, it couples CSOs with possible delivery of flexibility and frequency services. This is achieved by matching the previously discussed ancillary services depending on V1G or V2G. The V1G represents a smart load, while V2G (converter technology) is similar to the battery energy storage. Further, the drawing in Fig. 5(a) pairs each CSOs with the charging technology (AC and DC smart chargers) and with different EVs ownership types (passenger cars, taxis and fleets, autonomous vehicles, shuttles, and public transport buses) [175,176].

4.1.2. Flexibility architecture

Based on the generalized flexibility architecture and clustering above displayed (Fig. 3), in this subsection we intend to provide an
overview for the EV flexibility architecture. Fig. 5(b) displays the flexibility architecture with all stakeholders, namely the EV-user, the CSO, the CPO, the aggregator, the energy community, the DSO, the TSO, and the flexibility platform. The EV-user provides consent of using its flexibility to the CSO [156]. The CSO is the first flexibility provider. Furthermore, the CSOs require an infrastructure to operate, namely the EV charger. The CSOs are supplied from charger manufacturers and can operate the infrastructure on their own or delegate it to someone else. Here, the CPOs concept is introduced, which can control (back-end control) the charging infrastructure. Further, it is recently observed alliances between CPOs and charger manufacturers. Hence, these alliances are made to offer a complete charging infrastructure package to the end-users and CSOs. A CPO can fully control one or multiple CSOs accordingly to the CSO desires.
or an energy community to participate in the flexibility market [178]. In this case, a larger entity is created, and CPO can help the process by providing flexibility forecasts of their sites to the aggregator or energy communities. Subsequently, the aggregator or energy communities bid a flexibility offer in the flexibility platform related to the DSOs or TSO network. The platform decides the winning bids and activates the flexibility service. Lastly, in Fig. 5(b) a summary of flexibility services from the aggregating entity is presented. Further, a novel aggregator-free approach is investigated from Danish ACDC and FUSE research projects [179,180]. Both projects investigate the bilateral flexibility services CPO-DSO.

4.2. Electric vehicles flexibility alliances

To participate in electricity markets an entity must become a balancing responsible party (BRP) and fulfill size, market, and grid requirements. Barriers such as size and market requirements can be overcome by forming alliances between SOs, and CPOs. To recall from above, CPOs are already forming alliances with charger manufacturers. Thus, different stakeholders are bypassing such barriers by offering full charging services package that include charging infrastructure and smart charging incentives (among others, smart charging is comprised of flexibility and frequency services).

Fig. 6 illustrates the supply chain of flexibility services provided by EVs, including examples from the Nordic countries. CPO can offer a bilateral flexibility service to SO, with the consent of CSO through centralized or distributed control of smart chargers [181]. A typical example is Powerloop, a project implemented in the United Kingdom between Wallbox, Octopus EV, and UK Power Networks [182]. Wallbox supplies a V2G technology to Octopus EV (the commercial name of the charger is Quasar). Octopus EV provides congestion management services to UK Power Networks (DSO) in agreement with end users. Similarly, FUSE research project aims to combine Zaptec, Spirii, and Radius to simplify the development of flexibility services [180]. Zaptec supplies a state-of-the-art V1G to Spirii, which is the CPO. Spirii offers to its customers the possibility to participate in congestion management services. Radius, a Danish DSO will utilize the Spirii infrastructure to further their flexibility services. Additionally, a more ambitious aggregator and CPO-free path is followed from the ACDC project [179]. The project aims to deliver an autonomously controlled distributed smart charger. The charger developed from Circle consult couples the DSO (TREFOR El-Net Øst) directly to the CSOs.

5. Smart chargers

After considering what services SOs require to maintain fully operational grids and highlighting which services can be delivered from the EVs charging cluster, this section reviews the slow smart charger technology. The charging infrastructure plays a central role in supporting EV adoption, and smart chargers are a promising distributed infrastructure coupling power system with the transport sector [143]. Therefore, first, we provide a definition for the smart charger, which will facilitate the correlation between ancillary services and EVs. Second, we review the current state-of-the-art of slow smart charger technology.

5.1. Dumb and smart charger comparison

International charging standards are well covered in the literature [35,36]. In this paper we focus on IEC 61851 [183], and based on it we define the differences between a dumb and a smart charger, as shown in Fig. 7. A dumb charger is a device comprised of circuit breakers, relays, and voltage oscillator, which maintains a constant control pilot duty cycle to charge the EV. The scheduling devices outside the dumb charger (on the grid and EV side) can turn on or off charging process. In addition, it illustrates a smart behavior from the user side, even though users own a dumb charger.

Fig. 7. Smart charger and dumb charger comparison.

A smart charger contains a communication module and can control the control pilot duty cycle, thus modulating or scheduling the charging process.
5.3. Flexibility services and smart chargers

EVs can benefit the power system providing as a large flexible energy resource. Nevertheless, such services are one side of the charging process decision-making. The other side relies on infrastructure owner’s economic benefits and user’s comfort. The authors of [192] highlight the EV multi-use or optimal designed strategies that combine different value streams for EVs. Here we argue the difference between flexibility services and smart charging strategies. The charging process can be scheduled or modulated. Smart chargers can offer both scheduling and modulation, while dumb chargers can provide scheduling via external interface.

Smart charging strategies aim at increasing consumer acceptance and satisfaction rate. Further, coordination is required to deliver a smart charging strategy. Examples of strategies are (i) scheduling-based control, the simplest smart charging strategy that can be performed from both dumb (with external help) and smart chargers [193], and (ii) modulation-based control, the exclusive feature of smart chargers. Smart charging strategies combine technical grid requirements with the economical benefits of owners and user comfort. Other examples of such strategies can be found in [192,194].

As discussed previously in Section 3, flexibility services aim to increase the reliability and efficiency of the grid. Flexibility services are key elements for designing smart-charging strategies that are beneficial for the power system and can be enabled from SO. Examples of such strategies comprising only flexibility services can be found in [195,196]. This means that smart-charging strategies can: (i) be beneficial to the grid or not and (ii) involve different flexibility services or none at all. Here, it is relevant to underline the importance of designing well-thought strategies due to the risk of causing grid avalanche effects [197]. For example, a smart charging strategy synchronized only with electricity spot prices can result in overloading of grid components [133]. Therefore, to limit the potential danger, the smart-charging strategies development should include more variables and account for possible rebound effects [198,199]. One example is the bill optimization strategy for a residential consumer, which can comprise of stacked services such as spot-price, time of use (ToU), avoid peak upgrade, offer valley-filling (DSO) and TyoU among others.

Table 3 Advantages and drawbacks of EV chargers control approaches.

<table>
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<tr>
<th>Control approach</th>
<th>Advantages</th>
<th>Drawbacks</th>
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<td>Centralized</td>
<td>Vulnerable to cloud aggregator malfunction being spread on all chargers. System wide observation. Easier implementations of optimization algorithms.</td>
<td>Need of a backup server system. Heavy communication and computation when scaled-up. Subject to cyber-attacks and possible data privacy violation.</td>
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small as possible. Although the lightest AC charger is 1 kg, the DC one is minimum 47 kg. For further details, refer to Table B.1. The minimum observed enclosure rating standard is IP54 and in six other charger alternatives, an improved standard followed (four options stick to IP55 and two options keep IP65). Further, 3 out of 27 chargers include cooling options, while all chargers embody DC current leakage protection and third category surge protection.

All the chargers presented in Table B.1 are controllable. According to the description of Open Charge Alliance, open charge point protocol (OCPP) is an open protocol that allows CPO to control the smart charger. Here, the smart chargers observed tend to converge to the OCPP 1.6 protocol that allows smart charging features [202]. Nevertheless, to be future-proof some manufactures have or are ready to implement OCPP 2.0, since the protocol was made available in April 2018. The OCPP 2.0 is designed to be flexibility friendly [203] and it offers improved functionalities such as device management, transaction handling, security, smart charging functionalities, ISO 15118 support, display and messaging support. Furthermore, five options are observed to be used to communicate and be integrated with external devices, namely 4G (24/27), WiFi (22/27), Ethernet (20/27), Bluetooth (11/27), and RS485 (10/27). The last two are range-limited alternatives. The typical example for such implementation is a local controller-communication as displayed from Schneider EVlink smart charging controller [204].

Furthermore, the smart features section incorporated in Table B.2 attempts to distinguish the inputs each charger can receive and use in a decision-making process. First, the power set point (27/27) is a user or CPO reference input to follow. Second, the smart charger can receive consumption measurements from the energy meter (16/27), or otherwise, the charger has its own meter that closes the control loop. The home area network (HAN) protocol allows smart chargers to become part of a larger smart infrastructure. A majority (17/27) of chargers are HAN friendly meaning that they are able to communicate with other smart home devices. In addition, smart charging options can be provided, such as price-based charging (21/27) or power-sharing between devices or using local generation (14/27).

Lastly, flexibility features of the chargers are also provided, to recognize what flexibility capability each of the smart chargers offers. The scheduling feature is the minimum feature a charger needs to be called smart charger. In addition, 24 out of 27 chargers can modulate the charging current, while only three out of 27 can make the three to one phase charging switch.

6. Conclusions

By looking at the future of the power system, this study reviewed how smart chargers can be used to provide flexibility and what is the technology status at today. First, the ancillary services available in the power system are presented, by distinguishing between frequency and flexibility services. Then, these were discussed in terms of the type of action, namely frequency regulation, congestion management, voltage regulation, power quality, grid stability, and emission management. Five out of eight frequency services and 26 out of 32 flexibility services can be derived by EVs. However, only three out of eight frequency services the charging technology is on a commercial stage. Similarly for flexibility services, mainly congestion management services are being further developed for commercial applications. Furthermore, the study recommends that SOs should exhaust available non-market flexibility services before purchasing market-based flexibility.

In this sense, it is necessary to understand how EVs can provide these services. Thus, the supply chain of flexibility services from EVs is presented. Seven actors are identified: the end-user, the CSO, the CPO, the aggregator, the energy community, the DSO, and the TSO. The end-user is the main actor due to its large influence (charging behavior) on supply chain decisions. To link charging behavior and charging location clusters, 12 geo-electrical charging clusters (CSOs) are proposed. Additionally, the frequency and flexibility services are coupled with CSOs, and are matched with their grid location (low, medium, or high voltage).

To provide such services, CSOs can delegate their control to CPOs. CPOs can be further aggregated into energy communities or aggregators, and become a BRP to participate in electricity markets. However, to encourage the growth of the new technology/service provision, CPOs, charger manufacturers, and DSOs are forming alliances offering complete charging packages to the CSOs. Such packages include smart charging infrastructure and incentives to participate in ancillary services while bypassing current technological and market barriers.

Although, to perform ancillary services smart charger infrastructure is needed. Thus, this article provides an overview of current market available slow smart chargers with up to 50 kW. Three main flexibility features were observed to be commonly provided by the chargers: scheduling, modulation and switching from three-to-one phase during charging. All observed smart chargers can schedule, while 89% can also modulate. Only 10% can switch the charging from three-to-one phase.

Regarding future work, having a map of ancillary services coupled with EVs charging clusters opens up the door on one side for full exploitation of smart charging strategies and on the other side for different stakeholders to better understand their roles. Further, the available flexibility of each charging clusters needs to be quantified and proper smart charging strategies should be investigated to avoid avalanche or rebound effects. The Nordic case highlight the need for simple regulations to attract flexibility providers, looking primarily at congestion management actions. Novel approaches, such as flexibility alliances, bypass market barriers and bid size to help SOs gain confidence in flexibility service provisions. For example, Dansk Energi, an organization representing the Danish energy companies, is proposing a bid size of 10 kW, however, such approaches are still in the early stages. Lastly, smart charging infrastructure is developing rapidly. Most of the modern smart chargers are cloud-based and with a single outlet. To improve utilization factor and reduce the cost of smart chargers, double or quadruple outlets are being developed. In addition, new distributed controlled chargers are being investigated to tackle possible cyberattacks leading to a massive infrastructure being compromised.

CRediT authorship contribution statement

Kristian Sevdari: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. Lisa Calearo: Conceptualization, Methodology, Investigation, Writing – review & editing, Formal analysis. Peter Bach Andersen: Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition. Mattia Marinelli: Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Examples of DSO flexibility services provision.

A.1. Congestion management

Fig. A.8(a) reflects the location and size domain, while Fig. A.8(b) reflects the time and size domain. The Frederiksberg distribution
network comprises of three separate 10 kV networks supplied by a medium voltage transformer each [137]. The DSO congestion management can be first achieved from demand response programs, like ToU, or network reconfiguration on a wide area. For instance at Fig. A.8(a), ToU is activated but one of the three transformers, transformer X.5, is still overloaded, as shown in Fig. A.8(b). Thus on a second step, Fig. A.8. Illustration of (a) flexibility services granularity with DSO congestion management and (b) the transformer loading. The distribution network map is adapted with permission from [137].

Fig. A.9. Illustration of flexibility services (voltage regulation) implementation from the DSO.
the DSO activates the procured services for feeder X, such as valley-filling. Transformer X.5 is still highly loaded, thus the activation of peak-shaving services closer to the location is required. Each flexibility service activation reflects a loading reduction. Nevertheless, the load reduction of each service is highly case dependent, so it is difficult to quantify before-hand. Further, the activation of the services could also cause rebound effects which should be carefully considered when designing these services [197].

### A.2. Voltage regulation

Similarly, for an illustrative purpose in Fig. A.9, it is shown the voltage regulation activation. The DSO can adopt voltage regulation in three steps. First, the DSO can remotely control the transformers' tap-changers. Second, the DSO can acquire market-based voltage regulation. To design these services [197].

Part 2 of the smart chargers technology overview. "Y" means yes, "N" means no and "NA" means the information is not available. To the reader please keep track with Table 3

### Appendix B. Overview of slow electric vehicles (EVs) smart chargers

See Tables B.1 and B.2.


[185] The FUSE (Frederiksberg Urban Smart Electromobility) danish research project, https://danskelbilalliance.dk/fuse.