On the Participation of Charging Point Operators to the Frequency Regulation Service using Plug-in Electric Vehicles and 5G Communications

Roberto GERMANÀ*, Emanuele DE SANTIS, Francesco LIBERATI, Alessandro DI GIORGIO

Abstract— **This work deals with the problem of enabling plug-in electric vehicles (PEV) to the provisioning of ancillary services to the grid, for frequency regulation purposes. The paper presents and discusses a reference scenario for such a use case, describing the systems and actors involved. A system architecture for enabling the use case is proposed, detailing the relevant system components, technologies, and control algorithms. The paper also discusses the issue of the coexistence of the PEV-based frequency regulation services with PEV smart charging. Finally, it is discussed the crucial role that 5G technologies could play for making actually feasible the implementation of the proposed scheme for PEV-based frequency regulation service provisioning.**

I. INTRODUCTION

The safe and efficient operation of a power system strictly depends on two physical quantities: the frequency and the voltage level of the network [1]. The deviation of frequency and voltage from their nominal values are the effect of disequilibrium in terms of active and reactive power in the network. The so called ancillary services are then designed for the injection/withdraw of active and reactive power to balance the power mismatch. The evolution of the electricity network system and the spread of active components [2], make the involvement of new actors and technologies in the provisioning of ancillary services possible. The growth of electromobility in the last decade has pushed the scientific community and the power system stakeholders to develop new control strategies and concepts in order to improve and implement new paradigms to the ancillary services. The high penetration of Renewable Energy Sources (RESs), with the associated transition of the power systems from synchronous-machine-based systems to inverter-dominated systems, pushed the development of the virtual inertia concept, in which also the inclusion of plug-in electric vehicles (PEVs) is expected to play an important role [3]. From this trend, several works that explore the potential and the issues of PEVs usage for the frequency regulation have been studied. In [4], a review of the strategies used to include the participation of electric vehicles in frequency regulation is provided; the review considers both technical and economic aspects, showing different points of view that have to be faced to move towards the development of ancillary services that include PEVs.

A recent work in line with the activities of this paper is [5], which proposes the use of PEVs for the provisioning of frequency regulation services. The work proposes some control strategies for the optimal control of PEVs' contributions, considering also the impact that such a service has on the battery degradation.

In this work, we elaborate on the design of a frequency regulation service based on the use of PEVs. The coexistence of the frequency regulation service with the smart charging one is tackled, and the advantages and challenges of the proposed scheme, considering also relevant information and communication technologies (ICT) integration aspects, are analyzed. The paper reports preliminary concepts and results established in the context of the European research project "5G Solutions" [6] where innovative use cases enabled by 5G communication technology in the field of smart energy grids are under design.

The remainder of the paper is organized as follows. In section II, the reference scenario is presented, contextualizing the problem and formalizing the objectives of the paper. In section III, the architecture designed to deal with the objectives is presented. Based on the proposed architecture, in section IV the superposition of the smart charging service and the frequency regulation one is discussed. Finally, in section V, the feasibility of the integration between the proposed architecture and the telecommunication systems, including 5G, is discussed.

II. SYSTEM SCENARIO AND OBJECTIVES

The scenario of this paper considers the evolution of the European Energy Market and the related separation of the Balance Responsible Party (BRP) and Balance Service Provider (BSP) roles [7]. The diffusion of distributed generation plants, favoured also by the European decarbonisation objectives [8], and the diffusion of small-sized storage systems, together with the spread of electric mobility, bring to the need of carrying out an important revision of the role played by distribution companies. The Distribution System Operators (DSOs) are considering the possibility of assuming two additional roles compared to those that are traditionally under their responsibility: (i) the role of neutral facilitator for the provisioning of ancillary services made available by the BSP, that are needed for the safe operation of the overall system, and (ii) the role of purchaser of these services.

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The authors are with the Department of Computer, Control, and Management Engineering (DIAG) "Antonio Ruberti" at Sapienza University of Rome, Via Ariosto, 25, 00185 Rome, Italy, e-mail: {germana,edesantis,liberati,digiorgio}@diag.uniroma1.it

* Corresponding author: Roberto Germanà.

Moreover, this evolution changes the role of the Charging Point Operator (CPO): the separation between BRP and BSP, that breaks up the physical positioning and market correlation of generation units and load plants. This separation allows the owner of energy sources to provide only ancillary services without having to care about balancing constraints. This results in the opportunity to participate to the Energy Market in an aggregated way. The separation of physical contribution and market position enables the aggregation of energy sources and, together with the possibility to sell services both at the level of distribution and transmission network, opens to the participation of new actors in the dispatching market, putting the CPO in an interesting market position.

In this context, the CPO can exploit the PEVs flexibility to create the necessary conditions for the participation in the dispatching market.

The authors of this paper already intercepted the potential of the flexibility offered by PEVs in [9] in the cited work the proposed smart charging system empowers the load area with the capability of actuating Demand Side Managment (DSM) signals.

The presence of a smart charging system responsive to external signals introduces an additional factor in the context of smart charging in a load area: the possibility to have *power margins*; indeed, in [9] it is shown how it is possible to drive the aggregated charging sessions power to track a target load curve; even in case of several charging sessions running at the same time, the smart charging system proposed is able to avoid the power saturation of the load area, while ensuring the drivers' requirements [10]. The existence and the proper management of power margins are necessary for resource qualification to the provisioning of ancillary services. Ancillary services are historically entrusted to synchronous machines hosted by the generation units. The reasons why these services are provided by the generators are multiple; focusing on the aspects of interest for this work, there are mainly two reasons: the capability of easily controlling the power generation, thus ensuring the presence of power margins, and the unidirectionality of the distribution network power flow. The change of paradigms presented above for DSOs and Energy Market also affects the way the distribution networks are modelled and, consequently, their role in the power system. Distribution networks become hosts of active loads, storage systems and generation units; the presence of them changes the distribution networks into a set of active nodes with bidirectional flow that can potentially supply ancillary services. The vision of disseminating the provisioning of ancillary service on different portions of the network is nowadays supported and enforced by official entities and stakeholders [11].

The work presented in this paper focuses on the Frequency Restoration Reserves with Automatic activation (aFRR). aFRR is currently entrusted to generation plants relying on synchronous machines. The extension of the aFRR service to the participation of flexible loads is subject of studies and experimentation in Europe. For example, in the Pilot Project *Fast Reserve* [12] the inclusion of Mixed Enabled Virtual Unit (UVAM) - that can be composed by PEVs [7] - in the aFRR service and their impact are investigated. This pilot project imposes specific performances to the units that are involved in the service provisioning like a specific degree of sensitivity to the frequency variations and precise reaction time requirements.

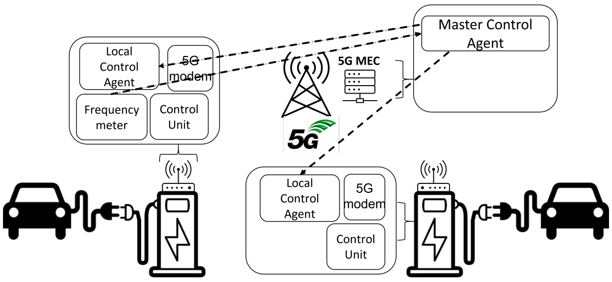

Fig. 1. System Architecture

In the light of the considerations made above, the reference scenario in this paper is as follow: a smart charging load area is considered, the smart charging capabilities are used to introduce power margins at single charging session level and, consequently, in aggregated form at load area level. The presence of charging session margins is exploited by applying a real-time frequency based modification of the smart charging setpoints with the aim of providing the aFRR service. In this work, the Pilot Project *Fast Reserve* requirements are used to drive and validate the results.

In this context, 5G communication technologies, able to guarantee low end-to-end latency and high reliability compared to legacy technologies, together with modular virtualized network functions offered by the 5G Core Network architecture, represent enabling factors. These technologies are expected to allow the communication of frequency measurements to the charging stations within the strict time constraints imposed by the frequency regulation service, instead of relying on frequency meters installed in each unit of the UVAM. Considering the size, the number and the dispersed nature of the flexible loads needed in the aggregate, 5G technologies enable the UVAM to provide the frequency regulation service in a more cost-effective way.

The objectives of this work are: (i) to present an efficient control architecture that enables the exploitation of PEVs for the provisioning of aFRR, (ii) to provide the rationale for the integration between smart charging and the aFRR service provisioning and (iii) to discuss the impact of the telecommunication technologies on the service provisioning requirements and on the quality of the service.

III. SYSTEM ARCHITECTURE

In order to match the objectives described before, a new system architecture has been designed. This system architecture represented in Fig. 1 shows the main components of the frequency regulation control system, together with their logical interfaces. The proposed system makes use of a single frequency meter for each Load Area (reducing a lot the cost for the deployment of such an architecture), that can be installed inside a single Charging Station or in its neighbourhood. Moreover, the proposed system exploits the novel 5G network architecture, where telecommunication operators make some computing power very near to the Radio Access Network (RAN) available for their customers. These computing resources are named Multi-Access Edge Computing (MEC) and enable very-low latency application to work efficiently, since the data packets can be processed (or pre-processed) in the neighbourhood of the customer requiring the service, with a substantial reduction of the end-to-end latency, that is reduced almost only to the radio access link latency (that is further reduced by 5G New-Radio standards, compared to the 4G LTE one).

The proposed architecture makes use of Local Control Agents, installed inside the Charging Stations, in order to compute the control signals in response to frequency disturbances. Each of these control signals can be superimposed over its corresponding slower smart charging scheduling signal computed by a separate system, in order to enable the Load Area both to smart charging functionalities and to frequency regulation functionalities.

In the proposed architecture, the MEC hosts a Master Control Agent module that is in charge of spreading frequency measurements coming from the single frequency meter of the Load Area (that may be installed inside a Charging Station in order to make use of its 5G Modem) to all the Local Control Agents. The possibility to put the Master Control Agent inside the MEC enables a low-latency broadcast of the frequency measurements, avoiding to place a frequency meter inside each Charging Station, while still having the measurements spread with an high reliability offered by 5G communication services and with a delay in line with the time requirements of the frequency regulation services, which will be better investigated in Section V.

IV. THE SMART CHARGING PROBLEM AND THE POWER-FREQUENCY CURVE ASSIGNMENT

The integration between smart charging and aFRR service presented before must consider aspects related to the quality of the charging sessions, while have to guarantee the presence of power margins capable to realize a power-frequency curve that satisfies precise properties. The power-frequency curve properties can differ depending on the country. In this work, the Pilot Project Fast Reserve [12] directed by the Italian Transmission System Operator (TSO) *Terna* is considered as a reference for the forthcoming discussion. The requirements of the above pilot project are many, and the present work doesn't aim to address all of them. The attention is focused on the power-frequency curve shape and on the reaction time, in particular the Pilot Project Fast Reserve requires:

- the power-frequency curve has to be symmetric, continuous and the actuation has to be self regulating;
- the power-frequency curve has to consider the possibility to implement a dead band;
- the fast reserve unit has to react to the frequency variation in a time window less then 300 ms and it should reach the steady state in maximum 1 second.

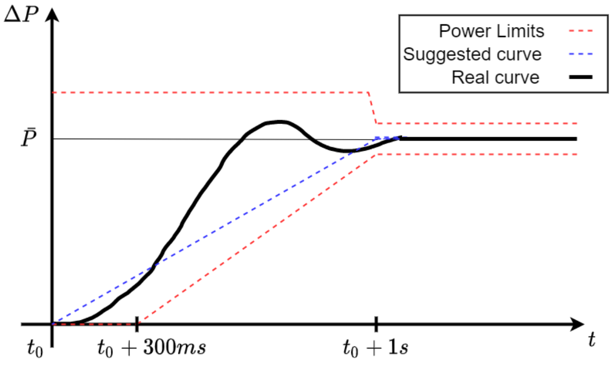

Fig. 2. Expected response of a fast reserve unit [12]

Figure 2 shows an example of the expected response. In this work, the transient specifications, such as the overshoot and the steady-state error, which are strictly related to the power electronics components of the Electric Vehicle Supply Equipment (EVSE), are not considered.

The extension of smart charging with a frequency response base service is explained by the example shown in Fig. 3. The example of Fig. 3 considers a PEV subject to a V1G smart charging session. The figure is composed by two plots: the first one represents the network frequency, the dashed line represents the network frequency nominal value (in Europe $50Hz$) f_n, the continuous line represents the measured network frequency $f(t)$. In the example, the time trajectory of the frequency network is characterized by different distortions, with corresponding frequency deviation $|\Delta f| = |f(t) - f_n| \geq \overline{\Delta f}_{min}$ where $\overline{\Delta f}_{min}$ represents the frequency deviation threshold implemented by the dead-band. The second plot shows the superposition of the frequency response service on the smart charging session: the dashed line represents the nominal charging setpoint $\tilde{p}(t)$ assigned by the smart charging system at different time instants; the continuous line represents the actual setpoint commanded by the system. The charging session presented in the example well shows the concept behind the introduction of power margins: if the power setpoint for the charging session is between maximum and minimum charging power, the power gaps can be used to modify the charging power as a function of frequency deviation. In the figure, the deviation is represented by Δp. The pair of the two plots explains the concept at the basis of the service integration. During nominal frequency operation, the EVSE follows the charging reference generated by the smart charging scheduler. In presence of a frequency deviation greater than the dead-band, the EVSE superimposes an additional contribution $\Delta p(\Delta f)$ to the smart charging setpoint, in order to participate to the actions aimed at steering the network frequency back to the reference value.

A crucial point consists in the construction of the power-frequency (p-f) curve, that defines the variation of the charging power as a function of the frequency deviation.

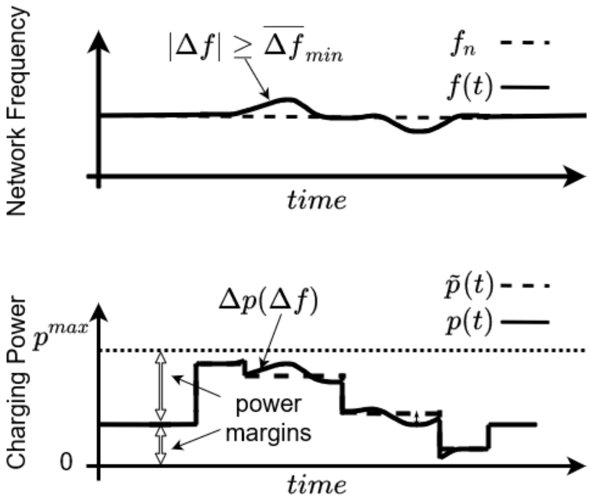

Fig. 3. Example of the superposition of smart charging and frequency regulation services: top - network frequency time evolution, bottom - associated charging session

In this work, we aim at illustrating and discussing different possible strategies, highlighting the differences in terms of performance and compliance with the requirements discussed before.

A. Case I - linear interpolation

A first attempt for the p-f curve assignment is a strict separation between the smart charging service and the frequency regulation service. In this case, the smart charging system does not provide an active contribution for aFRR service, but it only introduces power margins (since typically the PEVs will not be recharged at maximum power, and thus some power margins will be available for the provisioning of aFRR services). Each EVSE equipped with a Local Control Agent, receiving the smart charging power setpoint $\tilde{p}$ and knowing the power limits of the whole charging system, linearly interpolates with two separated curves the points ($\overline{\Delta f}_{min}$, $\tilde{p}$), ($\overline{\Delta f}_{max}$, p^{max}) and ($-\overline{\Delta f}_{min}$, $\tilde{p}$), ($-\overline{\Delta f}_{max}$, p^{min}) where $\overline{\Delta f}_{max}$ characterizes the frequency deviation over which the EVSEs have to provide the full power margins. Figure 4 shows a representative example of this approach in a V2G scenario: the main advantages of this strategy are the decoupling between smart charging service and aFRR service, the possibility to compute the p-f curves at the level of EVSE and the exploitation of all the available margins at the level of EVSE. The drawback of this strategy is in the resulting shape of the load area curve (that is composed by the curves of each active session in the Load Area). Indeed, with this approach, the symmetry requirement for the aggregated power-frequency curve is in general not ensured (see Fig. 4b).

B. Case II - linear interpolation with load area control

The presence of smart charging service is exploited not only to create margins at the level of the EVSE, but it can be also used to manage the power margins at the load area level. As in [9] [10] where an external signal is used to drive the aggregated load area power in order to satisfy a DSM service, the same methodology is used to impose a specific aggregated power withdrawal, i.e., half of the nominal power of the active charging sessions present in the load area at the given time. In this condition, by applying the linear interpolation strategy presented before, even if at the level of the single EVSE the curves are not symmetric, the aggregate p-f curve satisfies the symmetry requirement (Figure 5). Nonetheless, this strategy is characterized by different issues and limitations: first of all, the load area should be operated at half of the nominal power capacity. In addition, the symmetry is strictly related to the ability of the smart charging system to follow the load area power setpoint.

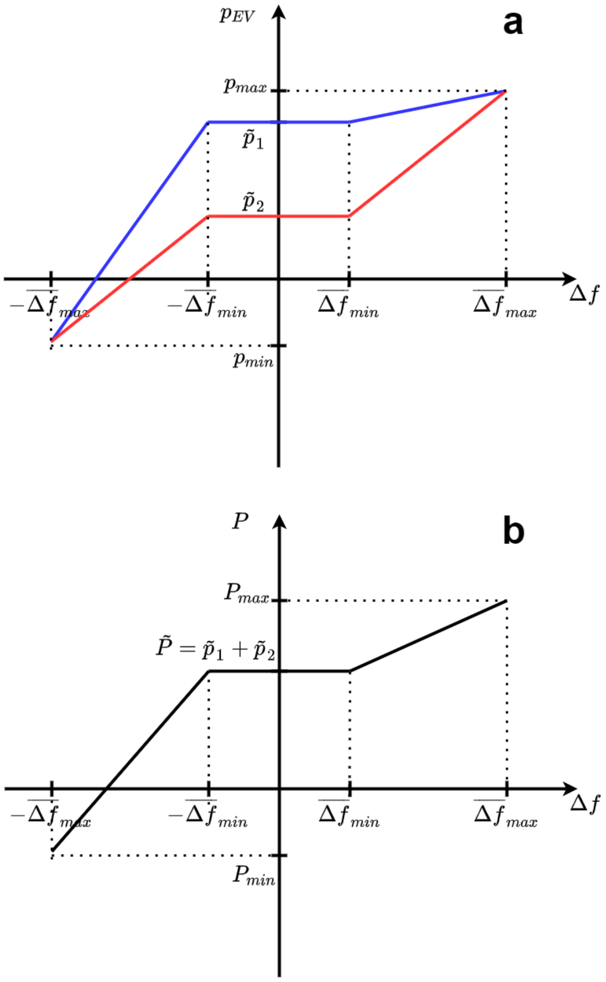

Fig. 4. Case I - linear interpolation. a) frequency regulation p-f curves of two EVs, b) cumulative p-f curve

C. Case III - resources allocation

A more sophisticated strategy considers the implementation of a resource allocation algorithm, which assigns to each EVSE a specific p-f curve (even a nonlinear one), such that the aggregated load area curve satisfies all the requirements discussed before. The integration between the smart charging system and the resources allocation algorithm results in an

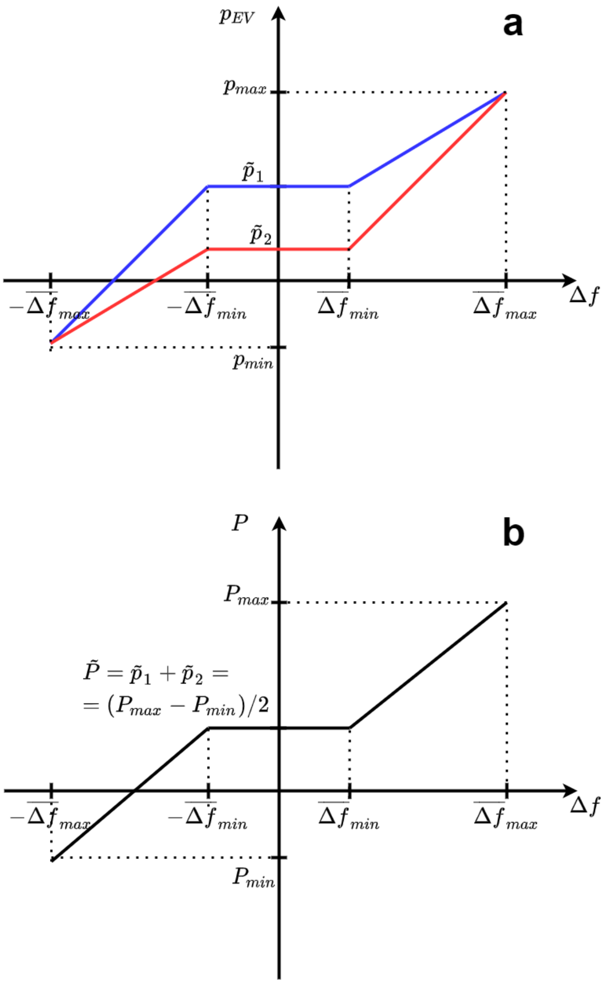

Fig. 5. Case II - linear interpolation with load area control. a) frequency regulation p-f curves of two EVs, b) cumulative p-f curve

integrated system that, managing the two services, allocates the resources considering drivers' requirements, balancing and distributing the service provisioning based on user profiling. The strategies presented before are less complex and easier to implement, while this last one requires the development of a resources allocation algorithm, that implies communications between EVSE and/or a deep integration with the smart charging system. In a future work, a mathematical formulation for computing the (p-f) curves will be proposed.

V. THE DELAY BUDGET PROBLEM

In order to enable PEVs to the frequency regulation functions, some very strict constraints on the delay between the occurrence of the frequency disturbance and the actuation of the control signal by the EVSEs power unit on the PEVs have to be considered. In particular, the Pilot Project Fast Reserve requires an initial response from the PEVs within 300ms from the occurrence of the frequency disturbance event, and a full response of the system (the end of the transient and the establishment of a steady-state at the frequency-dependent power setpoint) within 1s.

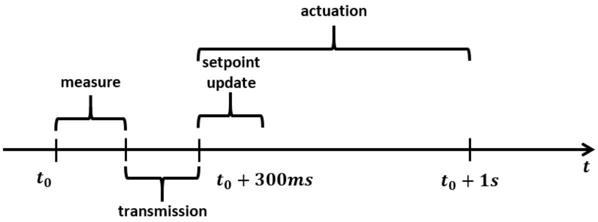

Fig. 6. Delay Budget

As detailed in Fig. 6, and having in mind the proposed architecture in Fig. 1, the system in the first 300ms from the frequency disturbance event (happening at time t_0) have to:

- measure, through the frequency meter, the frequency disturbance;
- transmit it to the Master Control Agent hosted in the 5G MEC;
- the Master Control Agent has to propagate this frequency measure between all the Local Control Agents;
- the Local Control Agents have to compute the updated setpoints;
- the Local Control Agents have to communicate the new setpoints to the Control Units of the EVSEs.

Then, from $t_0 + 300$ms to $t_0 + 1$s, the PEVs must completely actuate the new power setpoints.

Considering the frequency meters available on the market, it is possible to estimate a measurement delay in the order of few hundreds of milliseconds (usually 100ms-200ms), while the computation of the new setpoints, as explained in section IV, can be very simple, and so executed in less than a millisecond, or more advanced, and so executed in few dozen of milliseconds.

The transmission delay is a critical factor in the total delay budget, since the system components must receive the frequency measure well in advance of $t_0 + 300$ms, so to have time to process it and to update the power setpoints. Then, a maximum communication delay must be guaranteed by telecommunications operators, as the TSO requesting the services may apply penalties to the CPO for not providing the service within the time constraints.

Using wired telecommunication technologies, this delay can be in the order of few milliseconds (for optic fiber), or in the order of dozen of milliseconds (for copper wires), that is in line frequency regulation service requirements. However, considering the dispersed nature of the EVSEs, this kind of solutions may be very expensive for the CPO, implying a cost that may be considerably high compared to the investment needed to install a frequency meter inside each EVSE.

Moreover, most of the EVSEs are nowadays connected through cellular networks to their back-end, so, in principle, it is possible to exploit the cellular connectivity already present on the EVSEs. However, the current cellular telecommunication technologies used by the EVSEs (3G, 4G) do not provide enough performances in terms of latency (or guaranteed latency) to perform such tasks. Indeed, 3G and

4G technologies have a end-to-end communication latency respectively in the order of hundreds of milliseconds and about 50-100 milliseconds. 3G communication delay occupies almost all (or even more than) the available time, while 4G latency may not guarantee that there is enough time for measurement and for computation. Moreover, both the technologies do not support slicing, so the overall performances and the end-to-end delay (at least on the radio access part of the network) cannot be guaranteed easily. On the contrary, 5G communication technologies further reduced the radio access delay (to few of milliseconds) as well as the end-to-end delay with a novel fronthaul/backhaul/core network architecture made of Virtual Network Functions. Moreover, 5G introduces network slicing, so the telco operator may provide an exclusive slice of its communication resources to the CPO's frequency regulation system. Finally, 5G architecture introduced, as explained in section III, the MEC at the edge of the radio access network. Indeed, deploying Master Control Agent module inside MEC, it is possible to communicate with the frequency meter and to the Local Control Agent with negligible delays (in the order of few milliseconds), making feasible the provisioning of frequency regulation services with PEVs.

Finally, since the EVSEs already have a modem installed, the only cost for the CPO is to replace it with a 5G-compatible one. This cost for the CPO is justified also by the obsolescence of older communication technologies, that may be discontinued in the next few years, forcing the CPO to change in any case the EVSEs modems.

VI. CONCLUSIONS AND FUTURE WORKS

This paper has presented how plug-in electric vehicles can participate in the frequency regulation ancillary service provisioning. In the paper, the reference scenario, the systems and actors involved are presented and discussed showing how the roles of CPOs and DSO will be expected to evolve in the next few years. The paper provided a control architecture that exploits the novel 5G network architecture and its very low-latency. The paper focused on the superposition between smart charging services and frequency regulation services, providing three different strategies and discussing their properties, pros and cons. The paper also provided a deep discussion on the integration between the frequency regulation service, the ICT infrastructure and charging, measuring and communication components, providing quantitative considerations on the system feasibility also analysing the effects of different ICT technologies on the service quality. In future works, the proposed control strategy and its variants will be extended and tested using hybrid real/virtual test scenarios. The real components, such as 5G network nodes, charging infrastructures and measurement devices, will be used to validate the feasibility of the approach, while high-fidelity real time power network simulators will be used to analyse the impact of the service provisioning strategy.

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