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Validating a centralized approach to primary frequency control with series-produced electric vehicles

Mattia Marinelli*, Sergejus Martinenas, Katarina Knezović, Peter Bach Andersen

Centre for Electric Power and Energy, Technical University of Denmark, Risø Campus, Roskilde, Denmark

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ABSTRACT

The aim of this work is twofold: on one hand it proposes a centralized approach to primary frequency control by using electric vehicles as controllable units; on the other hand, it experimentally validates whether series-produced EVs, adhering to contemporary standards, can be an effective resource for providing primary frequency control. The validation process is realized in an islanded system with renewable sources and it relies on verifying that the frequency values are within the desired limits following severe load steps or wind power fluctuations.

In order to reflect today's situation, the used EVs, three Nissan Leaf, are not taking advantage of any V2G capability, but rely solely on the possibility of limiting the charge between 6 A and 16 A. The centralized approach implies that the frequency is not measured locally as it is a common practice today, but is routed via the Internet in order to include potential communication delays that would take into account the presence of different entities for controlling the vehicles, such as aggregators and utilities.

The centralised approach is pursued to support aggregators in participating in current ancillary service markets. Ultimately, this paper aims to strengthen the applied research within EV integration through the practical validation of smart grid concepts on original manufactured equipment.

1. Introduction

With conventional units being replaced by renewable resources, there is an increased demand for additional ancillary services, such as frequency control. Due to their defining property of being quick-response high-power units, electric vehicles (EVs) emerge as a viable actor for providing frequency regulation. A noticeable amount of research efforts is put nowadays to investigate all different aspects needed to shift from the traditional power system, where frequency and voltages are controlled by a relatively small set of large units, into a futuristic system, where potentially all power devices can be involved in the controlling actions. For instance, in the ELECTRA project, innovative control schemes are being investigated in order to assess whether conventional frequency and voltage controlling approaches are still suitable, or which aspects need to be revised for scenarios with massive amounts of small distributed energy resources [1,2]. It is argued that TSOs alone will not be able to effectively manage the overall system balance and will have to partially delegate frequency control responsibility to DSOs as already happens today for congestions management and volt-reactive power provision [3–10].

Regardless of who will be responsible for frequency and voltage control, several technical challenges are ahead. For instance, will the aggregated provision of thousands of few kVA-units at low voltage level be as effective as the one of MVA-units response? Moreover, considering the traditional 3-phase system, will the response of groups of single-phase devices be as effective as the response of similar size 3-phase units? With a specific focus on frequency control, is it reasonable to expect millions of accurate local frequency measurements to be used for decentralized, traditional, droop controllers or is it rather better to have a limited set of centralized controllers, which rely on a few accurate

Abbreviations: DSO, distribution system operator; ENTSO-E, European Network of Transmission System Operators for Electricity; EV, electric vehicle; EVSE, electric vehicle supply equipment; FCR, frequency containment reserve; FRR, frequency restoration reserve; ICT, information and communications technology; OEM, original equipment manufacturer; OR, Operating reserve; PFC, primary frequency control; RES, renewable energy sources; RR, Replacement reserve; SOC, state-of-charge; TSO, transmission system operator; V2G, vehicle to grid.

* Corresponding author.
E-mail addresses: matm@elektro.dtu.dk, marinelli.mattia@gmail.com (M. Marinelli).

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measurements, sending out power set-points via normal Internet connection?

1.1. Background and literature analysis

Electric vehicles are one of the imminent candidates for providing ancillary services. Most of the time (typically about 90%) they are plugged into a charging post and can, in principle, provide fast-regulating power in both directions, or just modulate the charging power. A noticeable amount of literature has already been written supporting this statement [7–22].

It is argued that EVs with V2G capability can provide regulation services, and can compete in electricity markets, such as markets for ancillary services, where there is payment for available capacity, apart from the payment for the actual dispatch. Frequency control is one of the services which can be provided by EVs through this market. More specifically, primary frequency control (PFC) can be suitably provided by EVs due to their flexible operating mode and ability to seamlessly alter the consuming/producing power under the V2G concept [12–14]. The work described in [15] presents an aggregated PFC model, where a participation factor, dependent on the state-of-charge (SOC), is associated with each EV to determine its droop characteristic. It was shown that EVs can effectively improve the system frequency response, as well as that V2G-capable vehicles have better power response, due to more available primary reserves. Furthermore, a decentralized V2G control for primary frequency regulation is presented in [16]. The proposed method considers customer charging demands and adapts the frequency droop control to maintain or achieve the desired SOC. A comparative study is performed in [17], in order to evaluate benefits of EVs performing primary frequency control in an islanded system with high penetration of renewable resources. The presented study case argues that system frequency oscillates in a 0.3 Hz band if the EVs contribute to primary regulation, compared to 1 Hz in the case of only using available hydro units. Two studies, respectively from Japan and Great Britain, analyse participation in frequency control on large systems considering traveling constraints and including large amount of renewable sources [18,19]. However, even though the mentioned studies analysed different strategies for providing primary frequency control, rarely have they dealt with the experimental validation, but mostly remained on modelling and simulations. For example, the works described in [15–21] have implemented different droop controls and shown that EVs can be effective in primary frequency regulation, likewise in isolated microgrids and larger systems. Still, they assume an ideal EV response to the control signals, both in the reaction time and the provided power, and they omit communication and control latencies which may greatly impact the results.

In addition, technical challenges may arise due to the limited power and energy size of each individual unit, as well as the need to have simple and effective measuring and controlling capabilities for primary frequency regulation. Transmission systems operators may be sceptical about the possibility of having demand participating in the frequency regulation, mainly because of response uncertainties and metering inaccuracies. Therefore, an extensive experimental activity is required to prove the feasibility of these solutions. The activity described in this paper is carried out using series-produced vehicles and the universally supported IEC 61851 standard, to prove the applicability of the solution.

1.2. Objective of the manuscript

Most of the literature identified during the literature review focuses on modeling and simulating the EV primary frequency control, whereas the experimental validation is rarely touched upon. Therefore, this paper focuses on the evaluation of EVs' ability to provide primary frequency control in a centralized fashion. The frequency control analysis of three EVs connected to a small islanded power system is proposed. Having the system islanded gives the possibility of emulating realistic frequency events, which could hardly be appreciated if connected to the national grid. It is important to note that the experiments are carried out with commercially available vehicles without taking advantage of any V2G capability, but only with the possibility to modulate the unidirectional charging current. This limit is part of internal standards (IEC61851/J1772) for conductive AC charging and supported by the vast majority of EVs today.

A classical droop control function is utilized. However, contrary to today's practice, which relies on local measurement, the frequency measurement is routed via the Internet to the controller, which sends the current set-point to the EV. The authors believe that in the near future, it will be highly unlikely to equip each EV with a precise measurement device which meets the TSO requirements. This means that the used technology resembles that of an operational environment: a fleet of EVs providing frequency regulation on market terms through an aggregator who has the certified frequency measurement device. Such setup allows the inclusion and assessment of potential communication delays, especially their influence on system stability. This work does not take in consideration vehicle unavailability due to owner usage. However it has to be reminded that, due to the system wide nature of the service, the location of the resource providing frequency control is not extremely important. In that sense, it is the aggregator's best interest to rely on a higher number of vehicles to account for the plug-in uncertainties, whilst it is less important to know their exact location, as long as the utilized vehicles are connected to the grid and not used for other services.

Ultimately, the research question tackled in this paper is: can small size, single phase distributed energy resources, such as commercially available electric vehicles, effectively provide primary frequency control relying on a centralized controller which sends out current set-points?

The rest of the paper is structured as follows: Section 2 briefly recalls how the control of frequency is traditionally organized in Europe and in Denmark. Section 3 describes the controller characteristics, the communication architecture and the implementation in the laboratory. In Section 4 numerical and graphical results of the experiments are presented and discussed; several scenarios are investigated from load step, through steady state analysis to wind power balancing. Section 5 reports conclusions and lessons learned.

2. Current framework for frequency control in Europe and Denmark

2.1. Frequency services according to ENTSO-E division

Based on the European Network of Transmission System Operators for Electricity (ENTSO-E) definitions, reported in the Network Code and Operation Handbook, frequency control includes [23]:

- Primary frequency control;
- Secondary power-frequency control;
- Tertiary control.

ENTSO-E refers to the reserves for frequency control as Operating Reserves (OR), and specifically, indicates the above-mentioned controls as: