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Frequency Control in EV Clusters: Experimental Validation and Time Response Analysis of Centralized and Distributed Architectures

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***Abstract*—The increased penetration of Renewable Energy Sources and of Electric Vehicles (EVs) in the electrical grid poses challenges to the stability and performance of the electrical system. To mitigate these problems, ancillary services can be provided by clusters of EVs during the charging process. The delay in the provision of frequency services from a cluster of EVs is analyzed, considering both a centralized and a distributed control architecture. The distributed architecture was tested on a cluster of EVs in the DTU Risø facilities. The communication delays in the system have been quantified. Both the centralized and distributed architectures have been modeled on Simulink® using the estimated delays, and the average delay following the grid frequency has been determined. After comparing the results, the distributed architecture was found to slightly be faster in following the reference than the centralized architecture, even though different aspects of the control system have been identified to be responsible for an increased delay, including saturation in the power setpoint for each EV, and presence of instability in the control system.**

***Index Terms*—electric vehicles, frequency control, communication delay**

I. INTRODUCTION

In recent decades, decarbonization policies have led to a substantial increase in the penetration of Renewable Energy Sources (RESs) and Electric Vehicles (EVs) in the electrical grid. However, the integration of these technologies poses challenges due to their unpredictable nature and impact on system stability. RESs introduce uncertainty and reduce system inertia [1], while EVs exacerbate issues like increased short-circuit currents and voltage fluctuations [2], especially during fast-charging. To address these challenges, enhancing grid flexibility is crucial. This can be achieved through Demand Side Management (DSM) and ancillary services like frequency and flexibility services [3]. However, Transmission System Operators (TSOs) have strict requirements [4] regarding the reaction time between a variation in the grid frequency, and a following variation in the power absorption. The control of clusters of EVs can be performed using a centralized [5] [6] [7] or a distributed architecture [8] [9] [10]. In [11], Mingshen Wang *et al.* assess probabilistic control of an EV cluster to provide frequency regulation, while Neofytos Neofytou *et al.* [12] analyze the effectiveness of Vehicle-to-Grid operations in primary frequency regulation. None of them, however, validates experimentally their simulations. The present paper closes this research gap and provides the following contributions:

1) Quantification of control delays in smart EV cluster,
2) Experimental validation of EVs providing frequency control with distributed control architecture,
3) Simulated comparison of distributed and centralized control architecture using validated models.

The research is structured as follows: in Section II, we provide a description of the system and we describe the case studies, together with the Key Performance Indicators (KPIs) used to evaluate the system's performance; in Section III, we describe the measurements of the communication delays, and the results obtained from the validation of the model, and from the comparison of the centralized and distributed configuration, exploiting the model. In Section IV, we draw the conclusions from the study.

II. METHODOLOGY

A. Theory

The aim of the system is to control the unidirectional charging process of a cluster of EVs, to provide frequency services to the grid. The power absorbed by the cluster is controlled by modulating the charging power of each EV, according to the energy required and the charging time available to the user.

1) Control Architectures: In this research, we compare two types of control architectures, i.e. centralized and distributed. The difference between the two lies in the controller where the algorithms run. In the distributed architecture, most of the functions and measurements are managed by local controllers called Virtual Aggregators (VAs), while the central controller (Cloud Aggregator, CA) only computes the Point of Common Coupling (PCC) reference power through a droop control. On the contrary, in the centralized architecture all the control functions are carried out by the CA, while the VAs only forward setpoints to the EVs. An overview of the distributed control architecture is reported in Fig. 1.

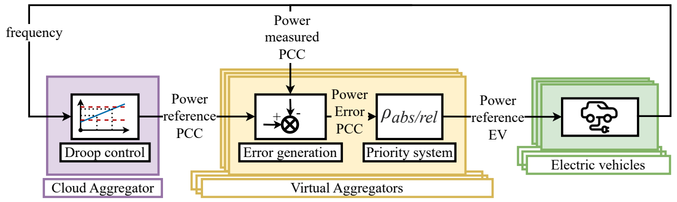

Fig. 1. Scheme for the distributed architecture. In the centralized architecture, all the control decisions of VA are transferred to CA. VA remains as the communication interface for the charger, but no longer performs any control functions.

2) Control Functions: We can isolate three main functions in the control system.

Droop control: this technique is used to regulate the power absorbed by the cluster, reacting linearly to a change in the grid frequency. The frequency measurement is provided to a Cloud Aggregator (CA), which provides a power reference to the whole cluster.

Error generation: The output of the droop control, that is the reference power for the cluster, is then compared with the power effectively absorbed by the cluster. The difference between these values represents the error of the control loop and must be brought to zero by changing the charging power of the EVs in the cluster. The evaluation of the error is performed by the CA in the centralized architecture, and by the VAs in the distributed architecture. Each VA sets the power reference for one EV.

Priority system: Once the power error for the whole cluster is computed, it is necessary to determine which EVs must increase/decrease their consumption, to bring the error to zero. This is done through a priority concept, previously introduced in [13]. Every time a user connects their EV to a charger they provide the requested energy E_{req} and the time of departure t_{dep} to start a session. The energy requested and the times of arrival/departure are used to compute an *absolute priority* for the user, as in (1):

$$\rho_{\text{abs}} = \frac{\text{E}_{\text{req}} - \text{E}_{\text{charged}}}{\text{t}_{\text{dep}} - \text{t}_{\text{now}}}. \tag{1}$$

Where E_{req} is the energy requested by the user and $\text{E}_{\text{charged}}$ is the energy already provided to the user. t_{dep} and t_{now} are respectively the arrival and departure times, which are set by the user. In the distributed architecture, the absolute priority in (1) is computed internally to each VA, and must be normalized in relation to the priorities of other users. In the centralized architecture instead, it is computed by the CA. The *relative priority* for the *k*-th user $\rho_{\text{rel},k}$ is obtained as in (2):

$$\rho_{\text{rel},k} = \frac{\rho_{\text{abs},k}}{\sum_{i=1}^{\text{No. EVs}} \rho_{\text{abs},i}}, \tag{2}$$

where the denominator represents the summation of the absolute priorities of all the users, and *No. EVs* is the number of users. Thus, the sum of all the relative priorities is equal to 1. The absolute priority is shared among all the chargers, to compute the relative priorities, while each charger computes its own relative priority, and does not share it. Each charger receives/computes (depending on if the architecture is centralized/distributed) the error between the measured cluster power and the required cluster power. Through the relative priority, each charger can exploit a part of the total error, without the risk of overloading the PCC.

B. Implementation

The described theory is implemented in the DTU Risø facility with the system configuration shown in Fig. 2.

1) Devices and Communication: We describe now the hardware used to perform the presented functions and the platforms used to exchange and store data.

a) Aggregator, EV and meter: Each of the CA and VAs algorithms runs on a dedicated microcontroller, the Beaglebone Black Industrial. They are connected to the internet through a wired Ethernet connection and are operated via Python scripts. The EVs are interfaced with the grid through chargers. Each charger features an internal VA and two plugs, meaning that one single charger can be connected to a maximum of two EVs and can control its charging pattern independently. The EV models are all different from each others. The relevant differences for this study are relative to the maximum charging power, the battery capacity, and the reaction time after a variation in the input PWM signal.

The cluster consumption at the PCC is measured by the MIC-2 MKII smart meter. It measures voltage, current, active/reactive/apparent power, and frequency and logs data onto a platform called Energidata.dk approximately every second.

b) Data Transmission and Storage:

Whiteboard (WB) is a database which allows information storage and access across different scripts. Data can be uploaded/downloaded by any CA or VA through a Python script [14].

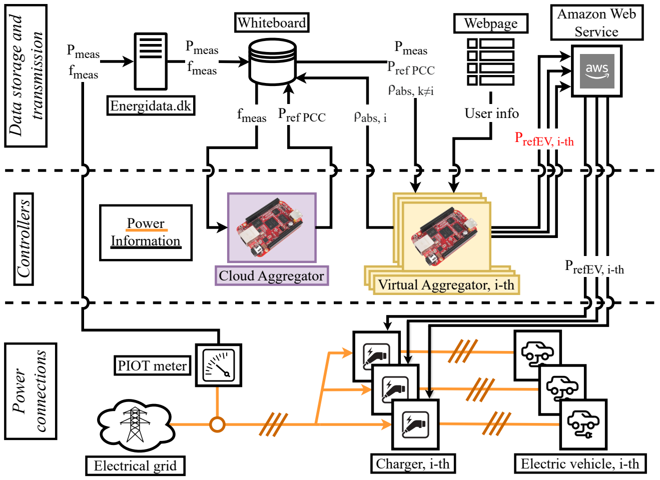

Fig. 2. Complete overview of the system for the distributed architecture. In the centralized architecture, the same elements are present, but the control functions are all performed by the CA. The reference power for each EV $P_{\text{refEV},i\text{-th}}$ (highlighted in red), in the centralized configuration is centrally computed by the CA.

Amazon Web Service (AWS) provides a secure connection to the VAs inside the chargers. It allows the external VAs, where the control algorithm runs, to transmit the setpoint to the VAs internal to the chargers, which just forward the power reference to the chargers' actuators.

Energidata.dk is a platform used by the smart meter to upload measurement data. From there, a Python script accesses data and rewrites it on WB. From WB, data is made available to either CA or VAs, depending on the control architecture (centralized or distributed). The complete scheme of the system is reported in Fig. 2. In the centralized architecture, every information (including user information) is sent to the CA which performs all the computations and generates a setpoint for the different VAs. In the distributed architecture instead, the CA only receives the power and frequency measurements at the PCC, while the VAs receive every other information, including the PCC power error, and the user information from the Webpage.

C. Case Studies

The research of this paper is structured as follows:

1) First, we quantify the communication delays of the system to develop a Simulink® model of the cluster. For the description of the Simulink model, the interest of the reader is referred to [15].
2) Consequently, we perform a frequency control experiment, using the proposed distributed control scheme.
3) Finally, we carry out a simulative comparison of the distributed and centralized control architectures, using the developed model.

A flowchart summarizes the described steps in Fig. 3.

To evaluate the system's performance, the following KPIs are introduced.

1) Cluster Delay: To evaluate the overall system's reaction speed and accuracy in following the reference signal, we compute the Euclidean norm between the reference signal and the output signal, varying the shift between the two. The Euclidean norm between two signals is calculated as the square root of the sum of the squared differences between corresponding points. It is a common measure of distance or dissimilarity between signals. A lower Euclidean norm indicates that the signals are more similar, while a higher norm suggests higher dissimilarity. Given two signals x and y represented as vectors, the Euclidean norm between the two is computed as in (3):

$$||x+y|| = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}. \tag{3}$$

To identify the optimal shift that minimizes the Euclidean norm, we systematically shift the output signal relative to the reference signal within a predefined range. The shift with the lowest Euclidean norm indicates the most overlapping point, providing an estimate of the delay. The norm is then plotted against the shift, allowing us to identify the shift with the minimum norm. The Euclidean norm and its corresponding plots were generated using Matlab®.

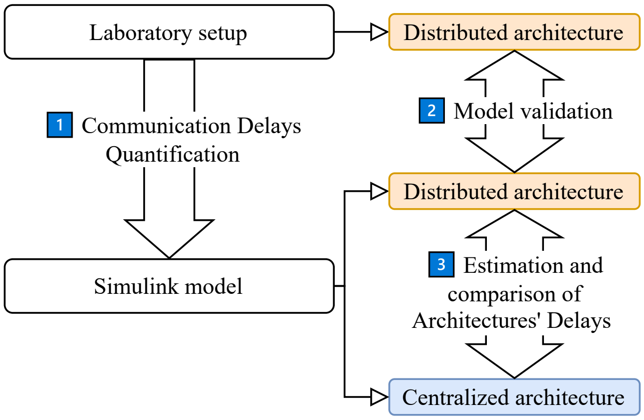

Fig. 3. Flowchart highlighting the research steps.

2) EV Power Limit: The power reference for each EV is increased or decreased at every iteration, according to the power error at the PCC and the relative priority of each EV. However, the power reference may reach its maximum allowed for an EV. In the analyzed system, the maximum power for each EV is set at 9.3 kW. When value is reached, the share of PCC power which was destined to the saturated EV is not taken up by the cluster, and the system's performance decreases. To identify signal saturation in our research, we monitor the output signal for instances where it remains constant despite changes in the input signal. Additionally, we observe whether the output signal reaches the upper or lower bounds of its dynamic range.

III. RESULTS AND DISCUSSION

A. Communication Delay Measurement

The values of the communication delays have been evaluated through tests. A picture of the test setup is shown in Fig. 4. The averages of the three individual delays are used in the Simulink model, inside the respective blocks. We conducted the measurement of the communication delays in the control system. For a more detailed description of the measurement campaign, the reader can refer to [15].

1) Definition of Delays: The delays are defined as follows:

- Whiteboard delay d_{WB}: it is defined as the time necessary for the complete process of uploading and downloading data to and from Whiteboard. The estimated value is less than 10 ms and thus neglected in the model.
- AWS delay d_{AWS}: it is defined as the time elapsed between the variation of the reference signal from the VA, and a variation in the PWM duty cycle of the charger. Estimated value: 1.39 s.
- Energidata.dk delay $d_{energidata}$: it is defined as the time necessary for the PCC meter to record and make available on WB the frequency and power measurements at the PCC. Estimated value: 1.06 s.

We show the different signals and the way the delays are evaluated from the measurement readings, in Fig. 5.

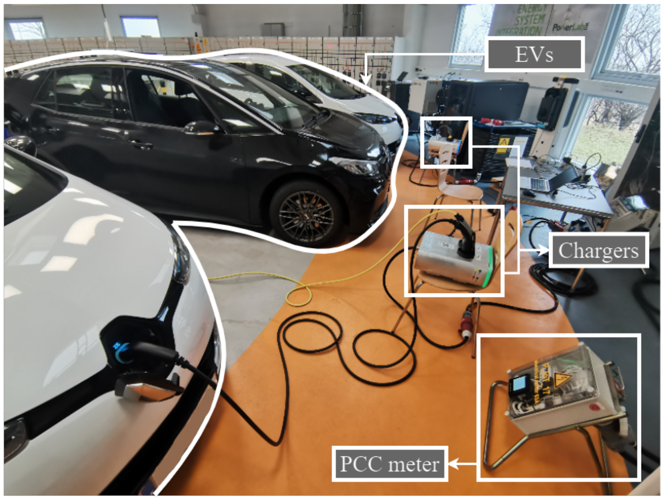

Fig. 4. Test setup in the DTU Risø facilities.

B. Frequency Tests and Simulations

To validate the simulation model, we performed one frequency test in the DTU Risø laboratory, on a cluster of 2 EVs. We logged the reference signal and the power absorption at the PCC. Then, we replicated the test on Simulink, and we compared the simulation output with the test measurements.

- EV1: Renault Zoe 40, initial rel. priority: 70%, req. energy: 19 kWh, available charging time: 3 h.
- EV2: Renault Zoe 40, initial rel. priority: 30%, req. energy: 8 kWh, available charging time: 3 h.
- Controllers (distributed architecture): CA update period: 2 s, VAs update period: 4 s.

We then run a simulation using the model tuned with the measured parameters. As reference signal for the cluster, we used the same frequency measurements recorded for Frequency test n°1, to allow for an easier comparison between the test and the simulation. In addition to using the distributed architecture, as in the frequency tests, here also the centralized architecture is employed. In the centralized architecture we use the same aggregators update periods as in the distributed configuration. This may lead to instability, due to the different control loop delays of the two architectures.

C. Results

In this section, we report the results of the model validation, and the estimated values of the system delay, for both the distributed and centralized control architecture.

1) Model validation: After measuring the PCC power absorption in the laboratory test, and simulating the same conditions in the Simulink model, it is possible to compare the two results. The comparison is shown in Fig. 6. When the test measurements (red) are compared with the simulation of the distributed architecture (blue), it is possible to notice that the two results are comparable, and the simulation predicts satisfactorily the behavior of the cluster. It is worth noticing that the behavior of the cluster is not ideal, since one EV has reached the maximum allowed charging power, and thus the cluster has problems in following an increase in the PCC power reference. This phenomenon is also predicted by the model.

2) Architectures comparison: When we analyze the simulation output using the two different configurations in Fig. 6 (distributed in blue and centralized in yellow), it is possible to notice the presence of instability when the centralized control architecture is employed. More particularly, when the cluster is controlled in a centralized way, the absorbed power at the PCC undershoots with respect to the reference one. This is caused by update frequencies of CA and VAs, which are not optimized for the centralized configuration. The CA, more specifically, is the controller accumulating the error signal. The accumulation however is performed too frequently (every 2 seconds) with respect to the delay along the control loop (approximately 4 seconds), causing instability. It is also possible to notice that the overshoot is present only in the lower direction. This is caused by the fact that one EV (EV1) has reached its maximum power absorption capability, and thus it does not contribute to the increase of the cluster power absorption, counterbalancing the effect of the instability in the upper direction. In the lower direction the situation is not balanced anymore, since both the EVs are able to decrease effectively their consumption.

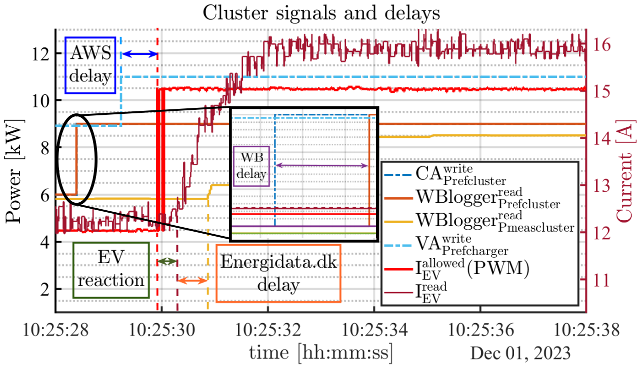

Fig. 5. AWS, EV reaction and Energidata.dk delays. A zoom on the WB delay is also shown. WBlogger is a Python script used to record data on Whiteboard.

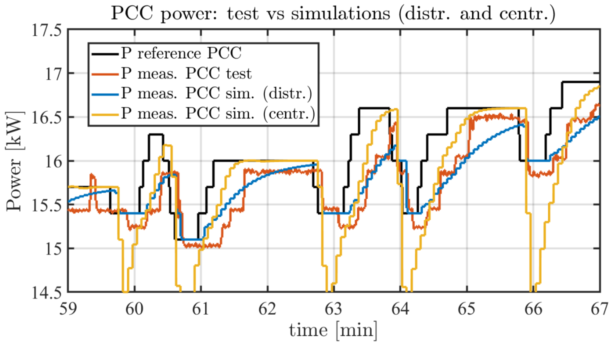

Fig. 6. PCC power: comparison between the test measurements and the simulation output.

Another interesting aspect to consider, is the fact that the centralized architecture appears to be more effective in following the reference power, when this is increasing. This is due to a key difference in system configuration: in the centralized control every control function is managed by a central entity, the CA, and thus the different algorithms run synchronously. With a distributed control, instead, each VA updates with some phase shift with respect to the other VAs, and to the CA.

We can now analyze the estimated delay of the two simulation outputs, exploiting the Euclidean norm as described in Section II-C1. The distributed architecture appeared to be faster (estimated delay = 10.65 s) than the centralized one (estimated delay = 10.74 s), although by a small amount. The two values are quite similar with each other and higher than expected, especially when we consider the entity of the communication delays measured in Section III-A1. In both simulations the system is affected by saturation (EV1 has reached its power capability) and the centralized configuration presents instability which causes only undershoots, since in the upper direction it is counterbalanced by the saturation. The system is thus in sub-optimal conditions, due to the non-optimized update frequencies of the controllers. For this reason, it is possible to affirm that the values of the delays are not indicative of the effective speed of the control system, but rather negatively influenced by the presence of saturation and instability. The estimation of the system delay in absence of saturation, and with optimized update frequencies, can be object of future research.

IV. CONCLUSIONS

This research focused on the analysis of possible controls for regulating the charging process of cluster of EVs. In the DTU Risø facilities, we first measured the communication delays present in the system and then we used them to characterize the Simulink model of the cluster. The model was validated, by comparing the results from the laboratory test and the simulation outputs considering the same initial conditions and the same update frequencies of the controllers. Then, using the model and keeping the same parameters, we compared the performances of a distributed and a centralized control architecture, and estimated the delay in following a power reference signal. The distributed architecture was found to be slightly faster (10.65 s) with respect to the centralized configuration (10.74 s). Both control architectures were affected by saturation, i.e. one of the EVs had reached its maximum power capability. Moreover, the centralized architecture experienced instability due to non-optimized update frequencies for the controllers (CA and VAs). The centralized architecture, however, when not affected by instability was found to follow the reference more closely, due to the absence of lag between the execution of the different functions, being all run in the same central controller.

In summary, a model for evaluating the response delay of a cluster of EVs with different control architectures (centralized and distributed) was created and validated. The presence of instability (due to non-optimized update frequencies) and of saturation (due to the cluster initial conditions) was found to sensibly increase the delay of the cluster for both the configurations.

As possible future steps, it would be beneficial to compare the two architectures considering optimized update frequencies and initial conditions, thus avoiding saturation from both the configurations, and eliminating instability from the centralized architecture, increasing the general performance and decreasing the delay at the lowest level possible.

This paper considered a cluster composed of two EVs. Future research could enquire the validity of the model and the system performance for a cluster composed of three or more EVs.

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