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Implementation of priority-based scheduling for electric vehicles through local distributed control

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***Abstract*—Distributed load management systems can become a crucial enabler for the widespread adoption of electric vehicles (EVs). The present paper experimentally demonstrates a priority-based scheduling algorithm that enables all chargers of an EV parking lot to coordinate their charging processes in a distributed manner. The distributed approach reduces control delays and maintains consistent management complexity, regardless of the number of chargers. A system is developed in which each electric vehicle supply equipment (EVSE) makes local decisions individually, sharing only their priorities with the other EVSEs of the cluster. The approach controls the total cluster consumption to a connection capacity while prioritizing the charging of EVs with the highest urgency. The scheduling algorithm is implemented in a real-life charging cluster, and its working principle is demonstrated through field tests. The system successfully shows the scheduling of two EVs to charge on a shared connection of 9 kW. The common capacity of the cluster showed a utilization ratio of 0.86 without critically overloading the grid connection.**

***Index Terms*—charging clusters, electric vehicles, experimental validation, load management, user-centric.**

I. INTRODUCTION

The worldwide adoption of electric vehicles (EVs) continues at an unprecedented rate [1], generating a need for a robust and futureproof charging infrastructure [2]. Most EV charging will occur in residential areas and workplaces, where each cluster has similar user behavior [3]. With no control of the charging, power consumption will eventually exceed the installed grid capacity, as the areas have high arrival coincidence [4]. Accommodating the added loading without expensive grid reinforcements requires load management, such as smart charging. On the other hand, user behaviour at workplaces and homes is also significant as destination chargers [5], where parking time exceeds the necessary charging time, generating flexibility. An opportunity to perform load management without compromising the users arises with the flexibility, allowing time-shifting of the power consumption of individual EVs.

This paper will address the control of multiple electric vehicle supply equipment (EVSE) installed in a cluster with the same point of common coupling (PCC) at the grid connection. This paper introduces a novel distributed scheduling approach, where the charging processes are scheduled alternatingly in case the available cluster power capacity is reached. As opposed to common power-sharing approaches, scheduling promises higher efficiencies since the converter technology in EVs shows increasing efficiency for higher power values [6]. Moreover, the proposed distributed control is inherently different from common smart charging approaches, which employ principal/agent [7] or central architectures [8]. While such approaches have been predominantly used in the past years, they rely on increased data traffic, are prone to single-point failure, and may have scaling challenges as EVs increase rapidly [9]–[11].

The paper presents a fully implemented distributed energy resource control system where the main contributions are:

- Development of a scalable distributed control architecture tailored for managing large-scale clusters of EVSEs
- Design and implementation of an EVSE state machine for scheduling EV charging sessions for improved efficiency
- Experimental validation through field testing, demonstrating the effectiveness of the proposed system in dynamically managing EV charging infrastructure

This paper is organised as follows: Section II describes the generic architecture of communication and decision-making; Section III presents the implementation of the architecture in terms of equipment and test procedures; Section IV presents and discusses the test results; Finally, Section V offers conclusions derived from the test, limitations, and future work.

II. METHODOLOGY

This paper uses a distributed decision-making approach to include the user inputs in the control architecture. The design of the developed system is first described in terms of the entities and their communications signals and, later, the specific decision-making process done at each EVSE.

A. Control architecture

The developed distributed control architecture is described in Fig. 1, where two layers of decision-making entities control the cluster consumption.

A virtual aggregator (VA) is introduced directly into the EVSE hardware to ensure fast and reliable reactions. Each $\mathrm{VA_i}$ ($i \in 2 \cdot N$) aggregates information and takes decisions for $\mathrm{EVSE_i}$, serving a maximum of one EV ($\mathrm{EV_i}$) at a time. The primary output of each VA is the maximum power consumption reference sent to the connected EV, $P_{i,ref}$.

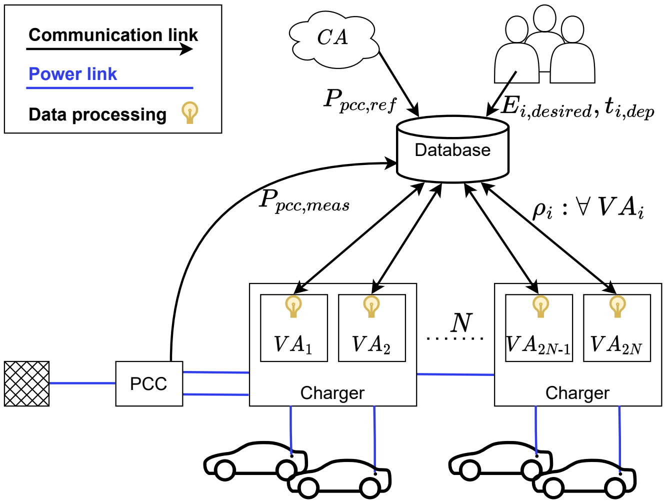

Fig. 1: Architecture of the control. Each VA controls a single EVSE charging outlet based on the data gathered in the shared local database.

To enable collaborative decision-making, the VAs require data inputs from other entities and horizontal communication among the VAs of the cluster. By realizing that flexibility arises from a gap between the user's needs and the individual power capacity ($P_{i,\max}$), we introduce the novel approach. The architecture, therefore, relies on user requests in the form of energy ($E_{i,desired}$) and expected departure time ($t_{i,dep}$) communicated directly to VA_i at the start of a session. The control assumes that the user request is negotiated with a hereby dependent variable energy price. The dependency should reflect possible congestions at the PCC or EVSE level to ensure that the cluster can meet the demand of all users [12]. Based on the user inputs, the VA continuously computes the concealed priority to charge ρ_c:

$$\rho_c = \frac{E_{i,desired} - E_{i,charged}}{(t_{i,dep} - t_{now}) \cdot P_{i,\max}} \quad \in [0, 1) \tag{1}$$

ρ_c is normalized with ($P_{i,\max}$), providing higher priority if power capabilities are low. This value is shared with the other VAs as the broadcasted ρ_i for each VA_i to facilitate horizontal communication:

$$\rho_i = \begin{cases} 1 & \text{when initiating charging} \\ \rho_c & \text{when steadily charging} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Three distinct values of ρ bear significance as information for all VAs of the cluster.

- $\rho = 1$ when a VA needs to initiate charging, requesting other VAs to allocate capacity and avoiding PCC overloading.
- ρ_m the lowest non-zero ρ in the cluster. ρ_m is thus the priority marginally justifying charging during PCC congestions.
- $\rho = 0$ when a VA has no urge to participate in consuming power, either as no EV needs power or the PCC is congested, and it's $\rho_c < \rho_m$.

Further inputs of PCC reference and measured power are necessary for the VA. The measurement of power $P_{pcc,meas}$ is local and broadcasted through the shared database to the VAs. The Cloud Aggregator (CA) is the higher level of decision-making, taking decisions based on outside signals, and provides the cluster reference power $P_{pcc,ref}$, which is fixed at the cluster limit for this paper.

B. State machine of virtual aggregator

Based on the data inputs outlined for the architecture and specific local measurements at the charger, each VA will transit through the state machine in Fig. 2, where the following section will reference the states by their number as {x}.

Each VA will transit from Idle {0} to the Starting point {1} whenever a user has provided the user inputs for an already connected EV. At this point, it will evaluate whether the cluster's current state allows for entry, in which case it will proceed to the initiation sequence {4-6}. Otherwise, it will transit to the Queue {2-3} where it will wait for a predefined time interval t_{wait} after ρ_c has increased above ρ_m. In the initiation sequence, the VA awaits a drop in the PCC power measurements {4} before it allows charging with the minimum power {5} and increases steadily from there {6}. When the single EV's constant consumption is reached, it will steadily charge {7-8}. When a VA already charging {7-8} finds another VA initiating {4-6} with $\rho = 1$, it will make space {9-10}. Only the marginally charging VA with ρ_m will be in {10}, generating the necessary space for the entering VA. While lowering power consumption, it will continuously evaluate if the power level is considered inefficient $P_{i,ref} < \frac{P_{i,\max}}{2}$, in which case it will be queuing itself.

For all the states where charging occurs, the charging will naturally arrive at Session ended {11} whenever the user's desired energy $E_{desired}$ is reached.

The state of the VA is the primary factor for defining the power reference $P_{i,ref}$. For the states where charging is not allowed {0-4} and {11} $P_{i,ref} = 0$. The charging will always initiate in {5} with minimum power $P_{\min}$ and gradually increase as more power becomes available in the PCC {6}. In the steady control states, the VAs will either singlehandedly {8} or as a function of its relative share of ρ {7} perform PI-control of the $P_{pcc,meas}$ towards $P_{pcc,ref}$ for the most congested of the three phases.

While making space as the marginal consumer {8} the control setpoint will be with a margin of $P_{\min}$ towards $P_{pcc,ref}$, while those in {9} will keep $P_{i,ref}$ constant.

III. CASE STUDY

The control architecture described above is tested in a real-life application with EVs and the European AC charging protocol for communication with the EV. The equipment used and test procedure will now be described before the results of the tests are discussed.

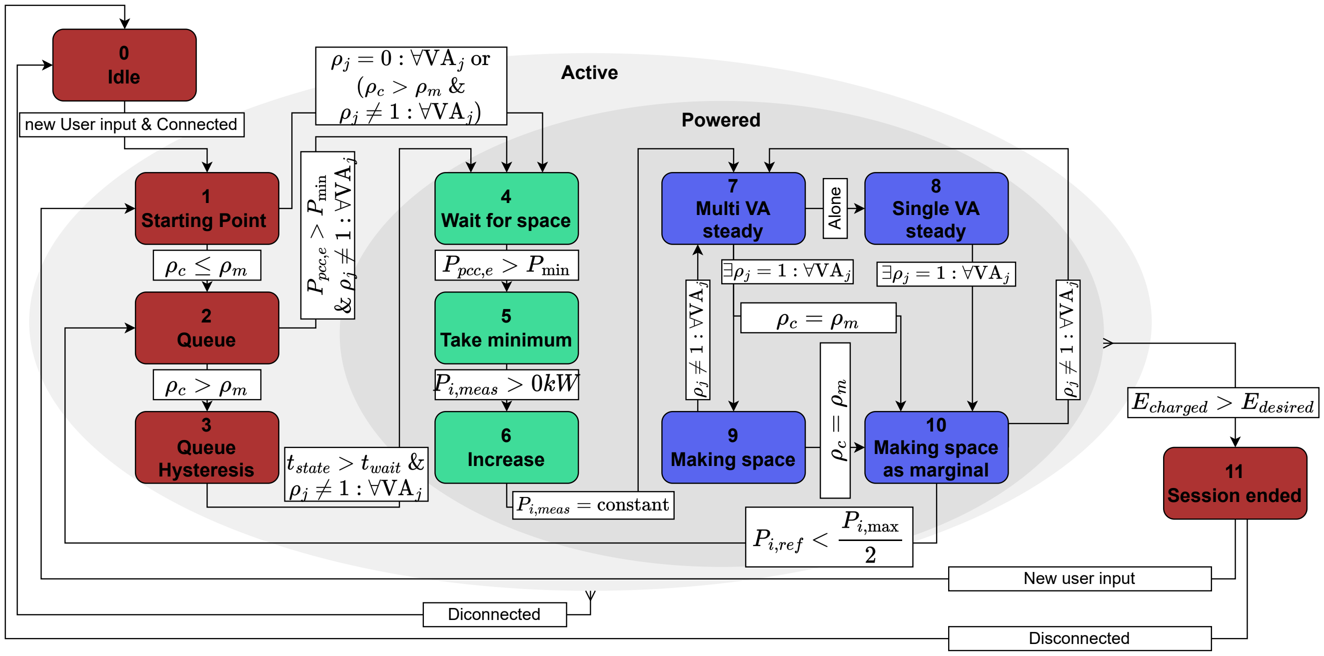

Fig. 2: State machine for the VAs. Subscript i refers to the specific $\mathrm{VA_i}$, and j evaluates all VAs of the cluster. $P_{pcc,e} = P_{pcc,ref} - P_{pcc,meas}$.

A. *Laboratory equipment*

A fully distributed real-time power control loop has been implemented where measurements, decisions and actuation have been made with physically distinct nodes according to Fig. 1.

The chargers, developed for the ACDC project [13], utilize the IEC 62196 Type 2 charging protocol described in IEC 61851-1:2019 [14], and have a 32 A 5-cord connection thus a maximum of 7.3 kW on each three phases. The control range of the charger to each EV is lower bound by the protocol to $P_{\min} = 1.38kW$ and upper bound by equally sharing its grid connection capacity of $\frac{7.3}{2\text{plugs}} = 3.66kW$ per plug per phase. Each EVSE is externally controlled with a single datapoint of allowed power $(P_{i,ref})$ [W] per phase, which the EVSE relays to the EV through the type 2 protocol pilot signal. When using this hardware and protocol, the reference is limited to $P_{i,ref} \in \{0\} \cup [1.38, 3.66]kW$.

Connected to the chargers are two Renault Zoes, each eqipped with a 22 kW onboard charger and a 41 kW h battery.

The chargers connect to the main grid through the PCC equipped with a smart meter (DEIF Multi-instrument MIC-2 MKII) publishing the power consumption $(P_{pcc,meas})$ in 1-second intervals to the MQTT broker energydata.dk. A separate script requests the data of the MQTT broker, which is both logged and pushed to the local database. The local control database is implemented with Whiteboard, a custom-made local server accessible by all system entities. This database contains parameter and value pair instances for all the inputs of the VAs.

To implement the novel algorithms of the distributed control, the controller algorithms (VA and CA) are deployed on three separate beaglebone® black industrial microcontrollers. The controllers have a wired ethernet connection to obtain outside data and communicate $P_{i,ref}$ setpoints to chargers and ρ_i to the local control database for the other VAs. The CA and VA log the current state of all variables internally at the end of each code scan.

To enable user interaction, the chargers have a publicly available website. The website allows users to enter identification and session-specific data: name, EV type, plug ID, requested energy $(E_{i,desired})$ and time of departure $(t_{i,dep})$. The website stores the data in a database and makes the session data of the last entry for each plug available on the local control database.

B. *Test procedure*

A test is set up to demonstrate the scheduling of two EVs. The test was part of the live demonstration of the EV4EU [15] and ACDC [13], [16] projects in Risø September 2023 showcasing multiple features.

To demonstrate the scheduling, the CA broadcasts a constant $P_{pcc,ref} = 9\,\mathrm{kW}$, as this enables a single EV to occupy the total PCC capacity. During the demonstration, the queuing time of the VA was set as $t_{wait} = 30\,\mathrm{s}$. This design parameter was set to demonstrate the switching functionality and should be considered more prolonged for actual implementations to avoid too frequent switches. The EVs are connected with an initial state of charge (SOC) = $40\,\%$ to $50\,\%$ and the user inputs of Table I.

The inputs have been chosen to provide a similar priority of $\rho \approx 0.5$ for both, demonstrating scheduling.

TABLE I: Input data from the users.

Entry time	Plug number	$E_{desired}$ [kWh]	t_{arr} [HH:mm]	t_{dep} [HH:mm]
13:23:15	1	20	13:23	17:23
13:25:28	2	20	13:25	17:24

C. Key performance indicators

The control of a cluster seeks to meet the user needs under the grid limitations. A set of key performance indicators (KPIs) is defined to assess the system's utilization of the PCC power capacity whilst minimizing implications of potential overloadings.

1) PCC energy utilization ratio: A KPI for the system is the ability to utilize the available power when the PCC is congested. The energy utilization ratio (UR) evaluates the ability to utilize the power over a period of time [17]. It evaluates the energy delivered to EVs relative to the potential common energy flow $P_{pcc,ref}$. For the cluster, it is found as follows:

$$\mathrm{UR}_{pcc} = \frac{\int \min\left[P_{pcc}(t)\ ,\ P_{pcc,ref}\right] dt}{\int P_{pcc,ref}\, dt} \tag{3}$$

$P_{pcc,ref}$ is included as a minimum boundary in the calculation not to reward overloading.

2) PCC overloading: Any overloadings should be further quantified as the system controls consumption towards the upper limit of $P_{pcc,ref}$. For the PCC of a cluster, a type C circuit breaker applies, and KPIs are inherited. The analytical parameters of an overload are comprised of I_{ol}, the peak normalized current, and t_{ol}, the total period with current over nominal. The current overloading can be converted to a power for each phase as $P_{ol} = I_{ol} \cdot V_{nom,LN}$, by assuming unity power factor and nominal voltage. A controller of currents could be implemented with the same algorithm to comply strictly with the current limitations.

IV. RESULTS AND DISCUSSION

The results of the scheduling demonstration as described in Section III-B will be presented.

In Fig. 3, a time-history of 7 min of the public priority and power consumption of each EVSE is visualized. Within this period, three switches occur, initiated by the non-charging VA when it sets $\rho = 1$. The VA starts consuming power only after it has observed enough capacity at PCC to begin charging. After it has taken over the power, the priority stabilizes at $\rho \approx 0.5$ and is thus the new marginally charging VA.

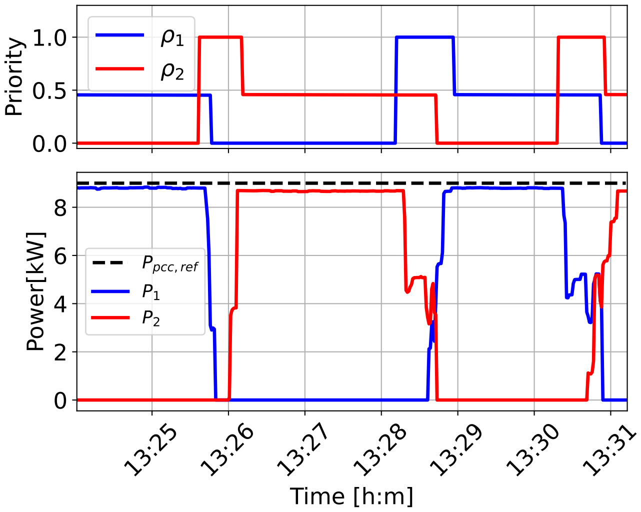

Fig. 3: Representative time window of broadcasted priority and power consumption of two VAs scheduling over time. VA$_1$ is already charging as VA$_2$ receives user inputs at 13:25:28 and starts charging. Scheduling continues from this point with switches every ≈ 2 min.

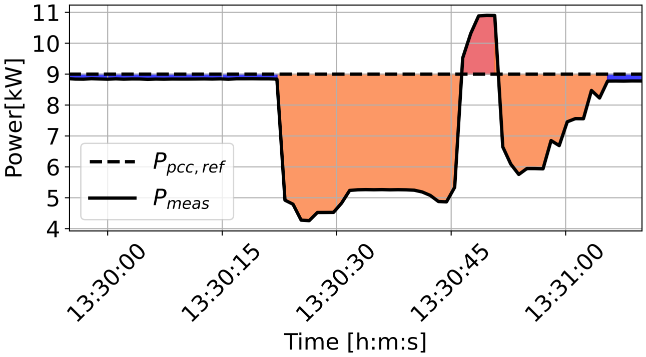

Fig. 4: Cluster reference and consumption measured at the PCC for a single switching period. The consumption follows with a margin the reference during steady charging but drops to make space (orange area) and overloads (red area) during a switch

The UR$_{\text{pcc}}$ is found over the 7 min to be 0.858. The blue and orange area of Fig. 4 indicates the steady state and switching 'non-utilized energy' accounting for 0.017 and 0.132 each. The system-integrated steady state margin for the PI controller affects the steady state, ensuring steady powers with the 1 A resolution of setpoints to the EVs. On the other hand, the switching impact is affected by three parameters. First, the magnitude of the margin P_{min} generated by the marginal VA and is directly related to the type 2 plug protocol of minimum 6 A. Secondly, there are delays in the control system, including the reaction time of the EVs, as one VA cannot allow charging before it has been observed that capacity has been made available for it. Thirdly, the design parameter of t_{wait} impacts the time ratio between steady charging and switching and can allow longer charging periods with priorities drifting further apart.

An advantage of the distributed architecture is the short control path from PCC measurement to reactions of the EV. For this experiment, this advantage is obscured by the inherent delays of the proprietary implementation, as the switches have a 15 s interval from the charging EV modulates down until the new VA starts to consume power. Indeed, the EV down-regulating reaction time of 0 s to 5 s and non-standard defined startup time is part of this delay and is inherent in the startup of the onboard charger. Further, the VA is implemented with a 5 s fixed asynchronous update frequency, which impedes its reaction time. The mentioned delays generate a nondeterministic behaviour, which is apparent in the analysis of the two first switches of Fig. 3, The first switch (13:25:40) makes a complete stop of power consumption, whereas the switch back from VA_2 to VA_1 (13:28:15) has a smoother cluster power consumption.

With the given delays of a proprietary installation, the UR_{pcc} thus shows quite good for a control architecture where the down-modulation of one VA should be observed on the PCC measurements before another VA can communicate a start. On the other hand, the requirement to immediately ramp up the reference to 6 A will inevitably impact the UR_{pcc} negatively.

During the experiment, the cluster overloaded the PCC during two switching events. As shown in Fig. 4 (highlighted in red), this overloading occurred when a new EV initiated charging simultaneous to the already charging EV overcompensating the low overall power consumption. The observed overload peaks of 1.1 and 1.2 times the rated 9 kW, lasting 1.05 s and 5.25 s respectively, fall well within type C breaker standards, demonstrating the system's ability to schedule the two EVs within PCC limitations.

Future work on the control system should address the database as a critical single point of failure. Either bypassing the database with individual distributed communication or incorporating a fallback state in Fig. 2 to handle communication failures.

V. CONCLUSION

This paper proposed a distributed control architecture for coordinating EV charging based on user needs. The system facilitates higher charging efficiency by alternately allocating available cluster power to individual chargers.

The method was implemented in an EV charging cluster and experimentally demonstrated, achieving an utilization rate of 0.86 of the cluster power capacity, while managing occasional overloads within acceptable limits. The distributed control demonstrated strong potential for further research in scheduling control schemes, especially with larger fleets over extended periods. While dependent on pricing models, the system also offers an underlying technical framework for future pricing studies. These studies could explore users' willingness to be flexible and investigate the relationship between departure time, energy requests, and session pricing.

On the technical side, future enhancements may require communication from VAs in the queue to express priority in a separate range, ensuring priorities are followed for reinitiation of charging. The next steps include scaling the system to larger EVSE clusters and extending the testing period, positioning this approach as a significant advancement toward efficient and scalable EV charging solutions.

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