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Published in:
Proceedings of 58th International Universities Power Engineering Conference (UPEC 2023)

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Malkova, A., Striani, S., Zepter, J. M., Marinelli, M., & Calearo, L. (2023). Laboratory Validation of Electric Vehicle Smart Charging Strategies. In *Proceedings of 58th International Universities Power Engineering Conference (UPEC 2023)* IEEE.

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Laboratory Validation of Electric Vehicle Smart Charging Strategies

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***Abstract*—Electric vehicles (EVs) are the connecting point of the transportation and electricity sectors and are an important milestone towards the decarbonization goal. Smart charging of EVs is considered a key enabler for the broad deployment of EVs. Acting as flexible demand, smart charging releases stress on the grid infrastructure and enables potential flexibility to the renewable energy sources (RES), thereby enhancing the power system. This paper presents results from experimental tests with two smart charger prototypes developed within the ACDC project. The autonomously and distributed controlled chargers connecting four EVs are integrated into the Energy System Integration Lab (SYSLAB) of the Technical University of Denmark. The conducted tests aim at different flexibility services, namely power sharing, RES following, and transformer protection. The developed chargers fulfil the assigned tasks and are able to provide ancillary services to the grid and RES.**

***Index Terms*—Smart chargers, Electric vehicles, Flexibility, Renewable energy sources**

I. Introduction

The energy transition from fossil fuels is one of the main tasks addressed by governments to reach the CO_2 drawdown. Yet, several tasks need to be solved for achieving a smooth transition, such as the extended deployment of renewable energy sources (RES), electrification of the transport and heat applications, and efficient use of energy [1]. The deployment of both large-scale and domestic RES increases the vulnerability of the network due to their intermittent generation. Increased controllability and predictability of RES and more flexible participation in the electricity market can be achieved using energy storage technologies [2] such as stationary battery storage, electric vehicles (EVs) batteries and others.

At the same time, according to transport electrification trends by 2030, the number of EVs will also grow and reach 200 million globally [3] and 0.8 million in Denmark [4] in particular. As the number of EVs increases, their uncontrolled charging impact on the energy infrastructure will also increase. This could create challenges, e.g., network congestion, generation capacity expansion, and reduction of transformers' lifespan, among others [5]. Nevertheless, EVs have a potential of flexibility reserve for the power system with a sufficiently large battery capacity (global average of EV battery capacity is 65.8 kWh [6]) and high availability to charge (e.g. more than 90% of daytime in Denmark [7]). Ref. [8] suggests that by aggregating EVs and deploying smart charging strategies, it will be possible to limit, or even avoid, the aforementioned problems in the electrical grid, as well as reduce investment in essential stationary storage systems. Smart charging is defined in [9] as an adaptation of EVs charging process to meet power systems conditions and EV users' needs. Smart charging can be implemented with respect to different objectives (technical, financial), control approaches (centralized, distributed, decentralized) and scaling factors (residential buildings, parking lots, regional level) [10]. According to [11] ancillary services for the grid provided by smart charging can be divided into frequency and flexibility services. Further, the authors in [12] distinguish local flexibility services between front-of-the-meter (FTM) and behind-the-meter (BTM). FTM services, such as prevention of transformer and load peaks congestion, voltage control, loss reduction, and power quality enhancement, are dispatched by the distribution system operator for grid needs. In turn, BTM services aim to reduce the energy bill using price signals and increasing the rate of self-consumption (if distributed RES are applied) while also serving as a backup power battery.

Despite extensive research on the modelling of smart charging strategies, their experimental implementation and testing in real systems are still limited and only little literature exists on this topic. Frendo et al. [13], for instance, developed a smart charging algorithm for EVs parked at a workplace, which was validated through a one-year field test. However, the algorithm was designed solely with the objective of improving customer satisfaction and did not take into account grid services or RES. On the other hand, in [14] a centralized smart charging approach was explored, aiming to provide multiple ancillary services, but the study was limited to a single EV and did not consider any RES integration.

This paper presents the results of a field demonstration of two chargers providing a broader spectrum of smart charging strategies. The demonstration has been performed in the Energy System Integration Lab (SYSLAB) located in DTU Risø Campus, Denmark. The smart charging logic implementation is based on previous models described in [15] and [16]. The

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smart charging strategy embedded in the chargers is developed on a rule-based method and considers a distributed approach (according to the classification of the authors in [17]) with the combination of both the FTM and BTM services. The goal of the ACDC project is to implement smart distributed charging control in workplace parking lots. Four control objectives are demonstrated in this article:

- Power sharing
- RES following
- Transformer protection (TRAFO)
- Cloud aggregator communication failure

All four modes are working together, reacting to the dynamic conditions and requirements of the system. However, during the demonstration, the tests have been conducted on the individual modes to explicitly showcase the performances of each mode separately.

The rest of the paper is structured as follows. Section II describes the smart charging control architecture description; Section III presents the actual electrical experimental setup; Section IV specifies the system limitations; Section V describes the control objectives in a more detailed way; Section VI introduces the results of the smart charging experiments; and Section VII provides the conclusions and future work prospects.

II. Control Architecture Description

In this section, the communication and control architectures of the laboratory setup are presented.

A. Communication architecture

The communication scheme can be observed in Figure 1. Initial information necessary for smart charging implementation includes wind-produced power, PV-produced power, transformer loading, fuse limit at the point of the charging cluster connection, and EV connection status. This information is sent every 1 s to the central cloud server, which is implemented through Amazon Web Services (AWS). Subsequently, AWS broadcasts such information to the virtual aggregators (VA) of the chargers. The VAs are the controllers of each plug. When the first EV is connected the corresponding VA becomes the primary VA and dispatches power for all connected EVs (on Figure 1 the EV1 is connected first and hence VA1 becomes the primary VA). The AWS also stores the latest status of each VA: EV connection status, current, and charging phases.

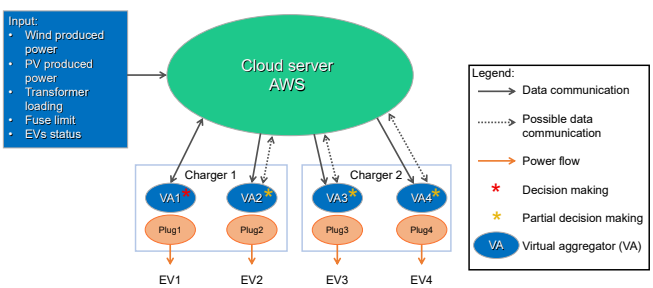

Fig. 1: Communication scheme

Information from the AWS to the charger and vice versa is transmitted via mobile Internet using SIM cards placed on the chargers' control boards. The information flows in the following order:

- Input information from measurement boards and chargers arrives at the AWS cloud server.
- The AWS broadcasts this information to the primary VA.
- Primary VA processes the received information and sends control outputs to the AWS.
- The AWS then dispatches those signals to the other VAs.

If there is a fault event and the primary VA goes offline, the next available and operating VA (i.e., an EV is connected) will take on its role (shown through dashed arrows in Figure 1).

B. Control architecture

The control scheme (Figure 2) shows the control loop and the key roles of the actors in the system. The responsibility of the AWS is shown in light green and the VAs in blue. The primary VA (VA1) receives the system data and EVs connection status from AWS, executes the power allocation and produces power references for each plug. The main logic behind power allocation is to provide maximum available power while sharing it equally between connected cars and following the designated mode of operation. The charging power is measured at the chargers' connection points and transmitted via the AWS to the VA1. Then these two $Pmeas$ go through the processing inside the VA1 and transform into measurements of each plug. The transformation happens according to the EVs status and the power sharing principle. For example, if all four EVs are connected then the measurements from the chargers $Pmeas_{ch1,ch2}$ convert into four plug measurements: $Pmeas_{1,2,3,4} = [\frac{Pmeas_{ch1}}{2}; \frac{Pmeas_{ch1}}{2}; \frac{Pmeas_{ch2}}{2}; \frac{Pmeas_{ch2}}{2}]$. If only one EV is connected to a charger, the respective $Pmeas_{ch}$ is allocated to that EV. After summation of $Pref_{1,2,3,4}$ and $Pmeas_{1,2,3,4}$ in VA1, the four errors are produced. All errors except the error of VA1 are redirected to other VAs through AWS. Error 1 of the VA1 is transferred internally. Then the PI controller inside each VA reacts to the received error and controls the power flow to the plug.

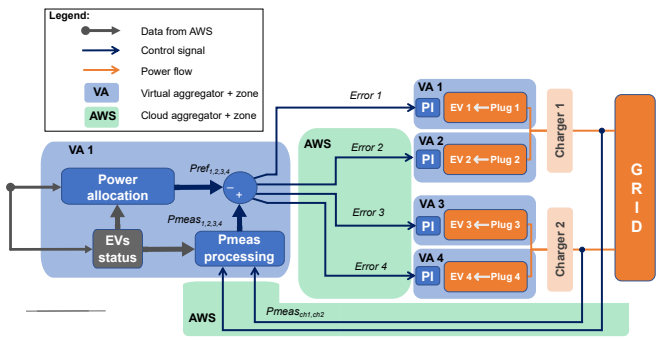

Fig. 2: Control scheme

III. Experimental Setup

The experimental microgrid is predominantly powered by RES connected to an external grid through a 200 kVA trans-

former. The system is composed of the following components (from left to right in Figure 3): external grid connection, transformer, 5 kW PV system, 20 kW emulated PV, 10 kW Aircon wind turbine, controllable load, PCC with two three-phase chargers (C1 and C2). Each charger has 2 plugs: C1 has Plug 1 (P1) and Plug 2 (P2); C2 has Plug 3 (P3) and Plug 4 (P4).

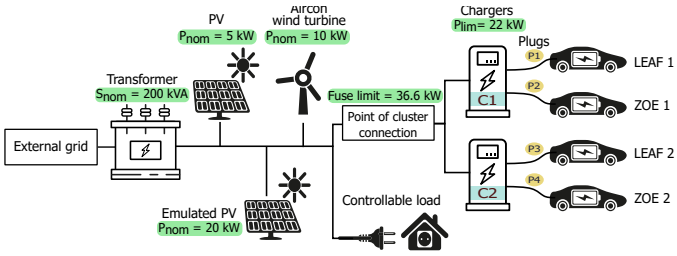

Fig. 3: Electrical system setup

The emulated PV is established using an external transformer to the system and a controllable back-to-back inverter. This is used to reproduce the PV power production in case RES during the testing day are absent or very limited. The controllable load simulates varying grid loading to test the smart charging logic's capabilities under varying conditions.

The maximum charging power is 22 kW (32 A) per charger. This means that if two vehicles are connected to the same charger, each EV can charge with maximum 11 kW. The fuse limit at the PCC is set to 36.6 kW (53 A). This means that if four cars are connected to the chargers (two per charger) the total maximum charging power is 36.6 kW and not 44 kW.

During the experiments, four electric vehicles (EVs) are considered - one for each plug of the chargers. To create more variability, two Renault ZOE with three-phase charging capability and two Nissan LEAF with single-phase charging capability are chosen. The allocation of the EVs to their respective plugs is shown in Figure 3 and their charging characteristics are displayed in Table I.

TABLE I: EVs charging parameters

Parameter / EV	Renault ZOE	Nissan LEAF
Battery capacity, kWh	41	62
Charging power capacity, kW	22 (7.36 per phase)	7.36
Maximum charging current, A	32	32
Number of possible phases for charging	3	1

IV. Limitations of the setup

Some features of the current implementation of chargers require further development and thereby pose limitations on the demonstration installation.

A. Ghost phases limitation:

Due to the absence of an internal electrical meter, the chargers do not yet recognize single-phase cars and therefore treat all connected cars as three-phase ones. Indeed, the chargers are still prototypes and their PI controllers dispatch the set point current to all three phases of the plugs, even if the connected car is one phase. The power consumed by a single-phase car is only one-third of the power set point of the charger.

B. Reactive power limitation:

The actual control signal is a current, not an active power. The part of the current goes to the system elements' magnetization, and therefore to the reactive power, which is not measurable yet. The choice to utilize active power in this article is based on its convenience regarding comprehension and visualization.

Also, in cases where the setpoint current for three-phase ZOE decreases, the share of reactive power in it increases. As a result, the decrease in the current setpoint is not proportionate to the decrease in active power. Therefore, in demonstration modes with small or zero setpoints, the single-phase LEAFs were used, where this issue does not appear.

V. Definition of control objectives

Smart charging can be designed to achieve various control objectives aimed at enhancing grid stability, lowering charging expenses, facilitating renewable energy integration, extending battery lifespan, and improving user convenience. Those objectives can be applied independently or in combination as long as they do not conflict with each other. In the following sections, the implemented control objectives are described by providing first the concept and then the demonstration methodology.

A. Power sharing mode

Power sharing is the ability of smart chargers to distribute limited available power (station connection limit, fuse limit or other) proportionally between the outlets and chargers (if there are several) and thus between the EVs at the charging station.

Maximizing the number of EVs charging at a single connection point is crucial. Charging station operators can benefit from charging more EVs within the available power limit to reduce the need for grid expansion capital expenditure, prolong the lifespan of existing infrastructure, and increase revenue by accommodating more customers. Although power sharing results in a lower charging power per EV, this may not pose an issue during extended EV connection periods, such as at workplace parking lots or overnight at homes. In this way, it can be ensured that in those hours all EVs will be charged with the desired energy even with lower charging power.

Both chargers and all four cars are used to demonstrate power sharing. Firstly, ZOE 1 is connected to C1, then ZOE 2 to C2 to show power sharing between chargers. Afterwards, the remaining LEAF 1 and LEAF 2 are sequentially connected to C1 and C2 allowing observation of the chargers' ability to distribute power within one charger and keep power sharing between chargers.

B. RES following mode

This test demonstrates the architecture's capability to match charging power according to RES power production.

EV charging coordinated with local RES production offers several advantages depending on the intended goals and the power supplied by RES such as increased self-sufficiency of the system with local RES, mitigation of RES variability, and avoidance of RES curtailment, among others.

In order to match EV charging power with the RES production test two EVs were used (only ZOEs due to the *Ghost phases* limitation), and each of them was connected to a separate charger. Moreover, an additional emulated PV production of 20 kW was added due to weather conditions affecting real PV panel capacity. This in turn improved the demonstration proof of concept as created more variable RES output power which the chargers had to adjust to.

C. TRAFO protection mode

The TRAFO protection mode is aiming at adjusting the charging power of the chargers to avoid transformer overloading.

The transformer is usually considered a bottleneck in future smart grids, where the electricity demand and the penetration of renewables are forecasted to increase. The increase in power flowing and production volatility could in the future overload the transformers, resulting in damages, shorter life spans and overall increased costs.

During the TRAFO protection test, the transformer limit was set manually using the AWS cloud system and two EVs connected to both chargers were used (only LEAFs due to the *Reactive power* limitation). Then local system consumption was increased applying the auxiliary load of the laboratory to see the system reaction to this demand spike.

D. Cloud aggregator (AWS) communication failure mode

The last test was performed to investigate the chargers' capability to remain operational in case of communication loss with the cloud aggregator.

The ability to remain up and running despite various disruptions (cyber-attacks, equipment failure, or just a short-term loss of communication) is essential for maintaining the stability of the power system. After all, when charging stops, an imbalance will be created in the network, which will increase the risk of even greater consequences, such as protection tripping, cascade failure, and over-voltages, among others.

In this test, only one EV (LEAF 1) connected to C1 was used. To reproduce the communication failure simulation the SIM card with mobile 3G Internet was physically removed.

VI. Results

In this section, the results of the demonstration experiment are presented in chronological order. In total, the tests ran for 55 minutes, which is displayed on the x-axis of the results graphs in seconds.

A. Power sharing test

The test performance can be seen from Figure 4 with the following test description. A colour difference on the graph corresponds to different chargers (blue - C1; red - C2) and a line style - to car brand (solid - ZOE; dashed - LEAF).

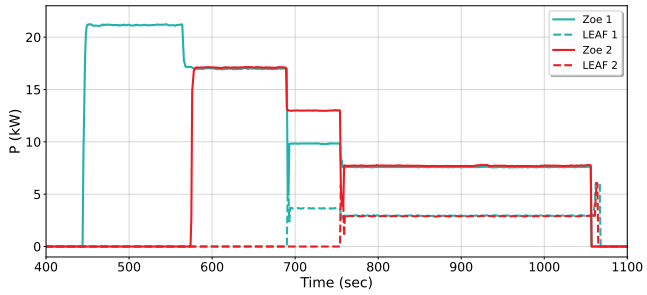

Fig. 4: Power sharing test: active power of EVs

The first EV – three-phase Renault ZOE 1 - plugged to C1 at 440 s and started charging with three phases with almost maximum power of 21 kW. At 560 s a second EV – ZOE 2 - is connected to C2 and the ZOE 1 started to decrease its consumption to give space for power to the second EV to avoid overshooting the PCC limit. 10 s later (570 s) both cars were charging at the same power of 17 kW which is almost the P_{max} of PCC – they are sharing the limited power between chargers.

At 690 s, a third EV – Nissan LEAF 1 capable of charging with single-phase - is connected to C1, in response, both ZOEs decreased their consumption, and after 5 s LEAF 1 started charging 4 kW on one phase. Then, at 750 s the fourth EV – LEAF 2 connected and started to charge. It is clear that the cars were not charging with their maximum power. This is due to the *ghost phases* limitation. If the charging power of single-phase cars is multiplied by 3 the charging power of all EVs is actually close to the P_{max} limit of PCC (36.6 kW):

$$P_{EVs} = 3\,\text{kW} \cdot 3\,\text{phases} \cdot 2\ \text{EVs (LEAFs)} + \\ +8\,\text{kW} \cdot 2\ \text{EVs (ZOEs)} = 34\,\text{kW}$$

The output power is less than the maximum due to the *reactive power* limitation.

Moreover, the power consumption of each charger is not greater than 17 kW – the chargers limit is also respected. With this knowledge, there is a clear observation of power sharing between chargers' plugs and between chargers themselves.

B. RES following test

A demonstration of the architecture capability to match the charging power according to RES power production is shown in Figure 5.

The first EV - ZOE 1 is connected to C1 at 1380 s and started to charge with maximum power. The RES production is above the P_{max} limit of the charger and that is why the consumption of the EV is constant. The second EV - ZOE 2 is plugged in at 1425 s and started to charge after the power

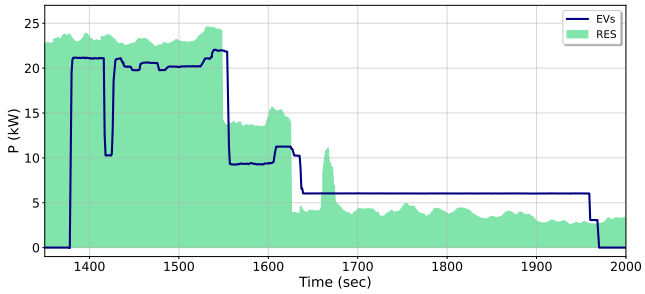

Fig. 5: RES following test: total EVs active power and RES production

sharing procedure with the first EV. The charging power of the EVs follows the RES production with a small time delay of 5-7 s. A small discrepancy of 1.0-2.5 kW between RES production and EVs' total power consumption is again due to reactive power consumption, which increases as the power curtailment of the car increases. At 1550 s there is a steep decline in RES power production from 25 to 14 kW. The EVs reacted to that change with the above-mentioned delay within which the system was importing power from the grid to support the power balance. At 1625 s RES power again declined to 4 kW, which is now not enough to charge EVs with minimum power. So, both cars have reduced their consumption to a minimum and remained in a state of waiting for better conditions of RES production. The time sensitivity of the charger communication and control was not enough to detect and follow the RES production spike at 1675 s. At 1960 s the EVs are disconnected.

C. TRAFO protection test

A demonstration of the capability of the architecture to adjust its charging power in order to avoid transformer overloading is presented in Figure 6.

The transformer loading limit is set to 10 kW. At 2100 s RES production was shut down and led to an interruption of power export (no negative values of P_{Trafo}) in Figure 6. The LEAF 1 is connected and started to charge at around 2200 s. At 2300 s LEAF 2 is connected and since the chargers consider the EVs to charge with three phases, the first LEAF leaves space for the second diminishing the charging power. Then they both are charging at 5 kW – sharing power and without exceeding the established transformer limit.

At 2370 s an external controllable load of 40 kW is connected. The transformer has a power import spike of 50 kW. After a few seconds, the TRAFO protection mode was deployed: the EVs reacted to the transformer overloading and stopped charging to mitigate the power congestion (shown in purple circles in Figure 6).

At 2410 s the external load is disconnected, thus relieving congestion of the transformer and, with an 8 s delay, the EVs started to charge again, reaching the transformer limit.

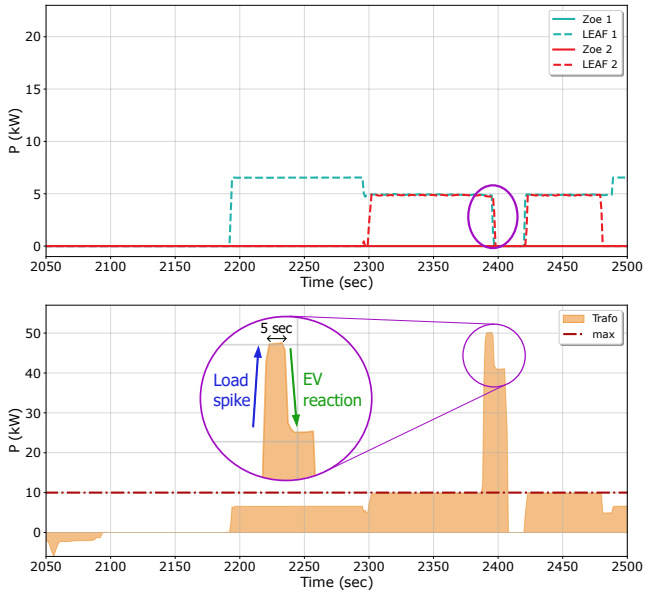

Fig. 6: Active power of EVs (top plot) and at transformer (bottom plot) in the TRAFO protection test

D. Cloud aggregator (AWS) communication failure test

In this last demonstration phase, the SIM card from C1 was removed, in order to demonstrate the capability of the charger to remain operational in the absence of communication. The SIM card was responsible for communicating with the cloud aggregator via mobile Internet. The LEAF 1, still connected to C1 from the previous test, was charging with 6.5 kW (Figure 7). After removing the SIM card the LEAF 1 is charging with the same power, while the charger is waiting to reconnect.

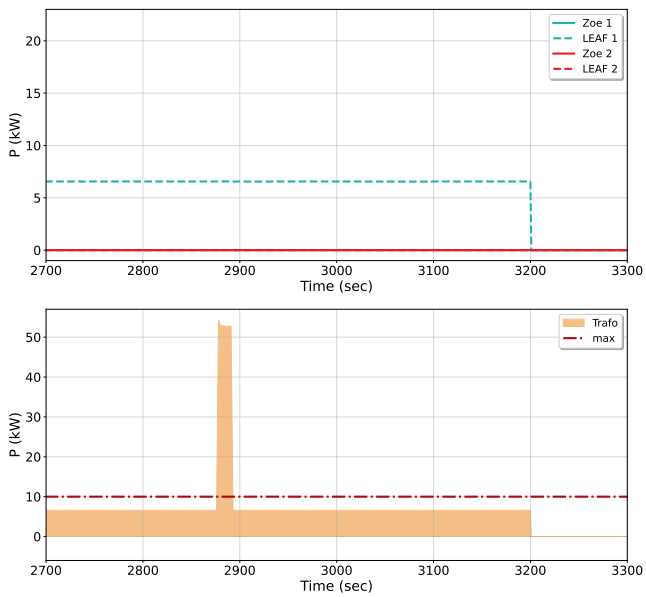

Fig. 7: Active power of EVs (top plot) and at transformer (bottom plot) in the AWS failure test

In order to show that now the charger does not have communication, the TRAFO protection mode was repeated. At 2870 s an external load of 45 kW was connected and overloaded the transformer by around 40 kW. However, this time the EV did not react to the transformer overload and did not decrease its consumption. The EV kept charging at 6.5 kW until it was plugged out at 3200 s.

Thereby, the charger demonstrated the ability to charge the EV even in the absence of communication, prioritizing the EV charging needs.

VII. Conclusions

This paper describes the experimental performance of two smart charger prototypes towards several flexibility services. The experimental system was built in DTU SYSLAB, a grid-tied microgrid laboratory, for the public demonstration of the ACDC project. The communication and control architectures have a distributed approach and are implemented in an AWS cloud with a 3G mobile Internet connection. The setup consisted of different RES, a grid connecting transformer, an auxiliary load, and two smart chargers connecting four EVs. Four smart charging control objectives (modes) are illustrated in detail: power sharing capability, RES following mode, TRAFO protection deployment, and cloud aggregator (AWS) communication failure. In the first mode, smart chargers efficiently distribute power among connected cars, considering both charger-to-charger and plug-to-plug scenarios. They adjust the charging power of already connected EVs when another vehicle is plugged in to avoid exceeding the limit. This solution optimizes the use of existing grid infrastructure and facilitates greater EV adoption by accommodating more vehicles. In the second mode, chargers demonstrate their ability to follow the RES power production, aligning the EVs' charging power with the RES curve. When RES production is insufficient, EVs charge at minimal power to minimize energy import from the grid. This mode offers multiple benefits, including reduced grid feeder load, optimized RES utilization, and RES variability mitigation. Enhancing the system architecture's communication bottlenecks analysis can further improve response time. The third mode aims to protect the transformer from overloading. The chargers react to the exceeded transformer loading limit and stop the charging. After the overload is removed, they return to normal operation. The final mode showcases chargers' capability to remain operational during communication loss by maintaining the last power set point. This mode enables the system to handle unforeseen circumstances and maintain consistent performance. In summary, the experimental tests confirmed the viability of coordinated smart charging among multiple chargers with varied control objectives.

Future work aims to address the setup limitations by installing an electrical meter in each charging station. This will enable the distinction between three-phase and single-phase EVs and the measurement of reactive power to ensure correct control independent of EV performance. Additionally, the control logic will be expanded to incorporate user preferences, prioritization, and charging scheduling.

Acknowledgment

The work in this paper has been supported by the research project ACDC (EUDP grant nr: 64019-0541) www.acdc-bornholm.eu and by the research project EV4EU (Horizon Europe grant no. 101056765) https://ev4eu.eu/

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