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Development and testing of smart charging strategies for a workplace parking lot

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Date

Abstract

The need for Electric Vehicle Supply Equipment, EVSE, is increasing as the transportation sector swiftly transforms to electric drive trains. The integration of EVSEs in the grid carries both challenges, such as overloading of the distribution grid and opportunities of providing flexibility for intermittent source or grid instabilities. By implementing real-time control of clusters of smart chargers, both challenges and opportunities can be addressed.

This thesis proposes a distributed control architecture which promises various advantages over the conventional central architecture of cluster control systems. The architecture builds on the commercial agents of aggregators. A Cloud aggregator, CA, participates in real-time flexibility by controlling a cluster of EVSEs. To take the local control actions for each EVSE, the Virtual Aggregator, VA, is contained in the EVSE. Specifically for a cluster, a coordinated response to CA control signals is wanted. It is thus investigated how the VAs within a cluster can collaborate to respond to multiple parallel charging sessions.

The core focus of the project is to enable autonomous decision-making of each VA. With information on the expected departure time and requested energy from the user, the option to provide flexibility is enabled. The information allows to schedule chargers for later charging as a control option. It is shown that the scheduling among chargers provides the best results of providing flexibility, power transfer efficiency and accommodating the user needs. The proposed architecture relies on the total cluster consumption at the Point of Common Coupling, PCC, and the charging-based priority as the only two necessary parameters to be shared between the VAs. The cluster can thereby take distributed decisions which secure scheduling and adherence to a cluster-wide CA set point signal.

The control architecture has been tested on a real-life parking lot cluster with 6 AC EVSEs at DTU Risø Research Facilities. The 6 EVSE share a PCC capacity of 22 kW. The control has been implemented modularly in a central controller. Despite the neglect of delays and multi-threading, the emulated system has showcased the dynamic response of the strategy in preparation for integration into the EVSE control system.

As a completely autonomous system, the cluster of VAs exhibits a collaborative capability to respond to a real-time changing power reference signal from the CA and concurrently control the scheduling to ensure all user requests are satisfied. The tests expose EV behaviours which are significant for developing a dynamic cluster control system, as the on-board chargers have diverse behaviours, which complicates the operation of the cluster.

The analysis employed four consecutive methods; define significant objectives, consolidate them into a strategy, support the strategy with a control architecture, and develop the corresponding control system. The developed controllers in the system take individual decisions, enabling simple control of the cluster consumption with minimal information sharing with the CA. Hence, the solution promises a smooth integration of EV charging clusters in the electric grid.

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Thank you!

Contents

List of Abbreviations

AWS amazon web service.

BTM behind the meter.

CA cloud aggregator.

CC Circle Consult.

CCCV constant current constant voltage.

CP pontrol pilot.

CPO charge point operator.

DER distributed energy resource.

DSO distribution system operator.

EV electric vehicle.

EVSE electric vehicle supply equipment.

FSM finite state machine.

FTPCC front of the point of common coupling.

OBC on board charger.

OOP object oriented programming.

PCC point of common coupling.

PP proximity pilot.

PV photovoltaic.

RES renewable energy source.

SOC state of charge.

TSO transmission system operator.

V1G Uni-directional smart charger (oppose to V2G) bi-directional smart charger.

VA virtual aggregator.

Nomenclature

Latin Letters			
D_n	Duty cycle	[%]	
f	frequency	[Hz]	
$I_{allowed}$	Allowed Current	A	Communicated by EVSE to EVCharging
J	inertia		
$N_{cluster}$	number of electric vehicle supply equipment (EVSE) in cluster		
P_e	Converter connected units	[kW]	
P_C	Nameplate power capacity	[kW]	(=Specific power capacity)
P_{db}	Deadband power	[kW]	
P_m	Mechanical generation	[kW]	
s_{EVSE}	state of hardware		see Section 2.4
s_{VA}	Current finite state machine (FSM) state of VA		
t	time	[h], [s]	
Greek Letters			
1ϕ	utilizing 1 phase		
3ϕ	utilizing 3 phases		
Φ	set of 3 phase specific values		
$\phi_{allowed}$	control parameter of charging phases.	[]	
ρ	priority		
ρ_r	relative priority		[0..1]
ρ_{bc}	broadcasted priority		[0..1]
ρ_{int}	internal priority		[0..1]

List of Figures

List of Tables

1 Introduction

It is a governmental goal of Denmark to reduce carbon emissions by $70\,\%$ in 2030[1]. The electric energy and transportation sectors are bound to undergo huge transitions to meet this goal. It is a supplementary political ambition to have 1 million EVs by that time [2] and further stop sales of new fossil-fueled vehicles by the same year[1]. As the number of EVs increases, the number of EVSE, needs to follow. The EVSE is a crucial part of this thesis, defined as the electrical circuit equipment necessary to charge 1 EV at a time, i.e. One charger may contain two EVSEs and, thereby, two plugs.

With the EVs coming to the grid, more power and energy are needed. The most critical problem arises from the power needed if all EVs charge simultaneously [3]. Integrating EV charging with controls becomes an asset for the market equal to that of battery storage units[4]. Battery storage units may participate by shifting power consumption and levitating the stress on the grid[5].

To accommodate the need for charging, there will be a need for a range of charging stations. Sevdari et al. [6] describe how the range goes from destination chargers at households and workplaces to charging destinations at dedicated charging hubs. For longer hauls, destination chargers are placed strategically on highways to allow for fast charging of up to $1000\,$kW. Destination chargers are placed where the parking time exceeds the needed charging time as the user intends to be at the location. The destination chargers are, therefore, usually AC chargers with a capacity of up to $22\,$kW.

Thingvad et al. found in [7] that for Denmark, $5.39\,\%$ of the power necessary for driving can be charged at workplace parking lots. Charge points at workplaces are compelling cases as user behaviour as a population is predictable. A typical charging session at a workplace starts at the beginning of the workday and ends when the employee is off from work. To forecast the behaviour is especially interesting in combination with knowledge of the users, as it is also expected that the charging necessary for the daily commute is less than the charging capacity an AC charge point may provide. These two aspects allow shifting their consumption without compromising the users' service.

Integrating EVs into the electrical grid does come with challenges [4]. The challenge mainly resides in the power domain (as opposed to the energy domain)[8]. Bowen et al. [9] have gathered data for a workplace parking lot where the charging has been found to take place with a pattern which will generate a peak demand. For DC charging, Engelhardt et al. [10] discuss the challenge, which is also present there. The limitations experienced in the connection point of a cluster of slow chargers share similarities to those experienced by a DC fast charging [11], [12], [13], [14].

To overcome the challenges, AC EV smart charging is seen as a solution. Smart chargers defer by implementing functions that allow active control of the charging process to adapt to an outside signal [6], [5]. These signals could potentially be from any entity with an (economic) incentive to control the mentioned challenges. Sevdari further notes that the OCPP protocol allows a central entity to control multiple chargers to overcome the mentioned challenges. Fauziah et al. evaluated a system [15] which utilized the protocol for control of a charger from a charging station management system. By letting the central charging station management system become a cloud aggregator (CA) appointed by the charge point operator (CPO) multiple challenges can be addressed. The current central control architecture is easily implemented, but as discussed by Han et al.[16] increases complexity when the system size increases.

Addressing the prospect of utilizing the transportation sector going electric as a means to the anticipated concerns of the electrical energy sector requires leaps in EV charging research. Much has already been done and will be presented now as the background for this thesis.

This thesis builds from Chapter 2 ‘Background’, providing a review of the studied literature. This leads to the problem statement in Chapter 3 ‘contribution’. To initiate Chapter 4 ‘Method’, the thesis objectives will be individually analysed in further detail, and the outcome hereof will be merged into a signal strategy. To keep the general applicability, the proposed architecture solution is described as the final part of Chapter 4 ‘Method’. The implementation of the proposed solution is described in Chapter 5 ‘Implementation’, where it is applied to a real-life system. In Chapter 6 ‘Results’, the tests of the implementation are presented and discussed. This leads to the concluding remarks of the thesis in Chapter 7.

2 Background

This chapter explores the intricacies of EV charging, its dynamics, and the concept of flexibility in the power system. It delves into various control architectures employed to manage the increasing demand for EV charging and provides an overview of the related work already performed in the ACDC project.

2.1 EV charging

The basic topic in the thesis is the charging of EVs. Therefore, the technical details of the charging process are essential to highlight. For this thesis, the basic setup, as shown in Figure 2.1, describes the generic connection for a workplace parking lot. AC charging which will be investigated in this thesis distinguished from DC charging by letting the AC/DC conversion take place in the on board charger (OBC). The OBC is thus the controlling unit of the charging which adjusts to the need of the battery and the grid. The OBC is typically rated for $P_{C,OBC} = 11$ kW to 22 kW if charging on all three phases, 3ϕ. Some EVs are still observed which charges only through one phase, 1ϕ, with different power ratings. AC charging, therefore, takes the AC power at $230\,\mathrm{V_{LN}}$ to the EV, where the OBC controls the load. The EVSE differs from a usual power outlet by providing local knowledge of the grid constraints of the EV, just like a maritime pilot in the shipping industry boards large vessels to assist in navigating the specific harbour. All the EVSE connect to their PCC from which additional capacity constraints may come into play for the combined cluster. At the top of the distribution grid is the transformer, trafo, that connects it to the transmission system. The cluster naturally shares the transformer connection to the grid with some other demand in households and workplaces, and additional renewable energy source (RES).

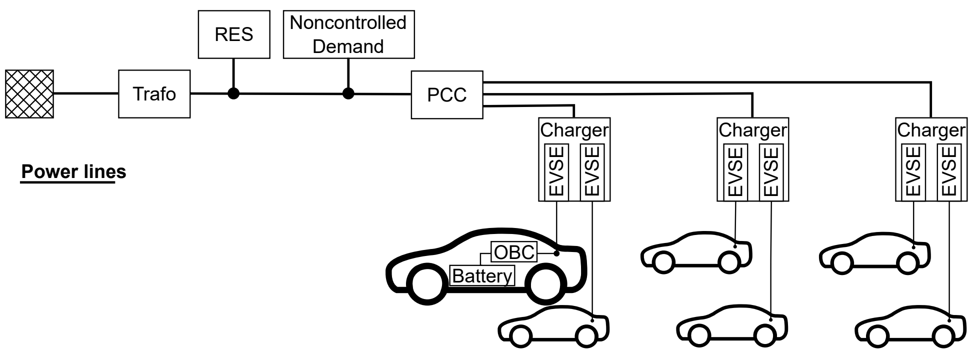


Figure 2.1: The components and their power line connections. Each CH contains two EVSE units. The RES and Uncontrollable Demand are placeholders for distributed renewables and household loads.

For a workplace which will be utilized for this thesis, it is estimated to have a range of 4 EVSEs to 30 EVSEs. If a larger number is introduced at the same parking lot, the architecture may be revised as the power line topology complexity may increase equally. The EVSEs could be contained in any arrangement of chargers at no specific configuration.

2.1.1 Electric vehicle supply equipment

The term EVSE is used for the electric circuits that reside in a charger. Several EVSEs may be included in a charger to charge multiple EVs from the same charger. From a control perspective, the EVSE provides local information on the grid to the EV. The grid AC power lines are directly connected to the EV through the cable. The only power electronics are relays and power line measurements to ensure that if the EV violates grid rules, it opens the relays to stop the charging session.

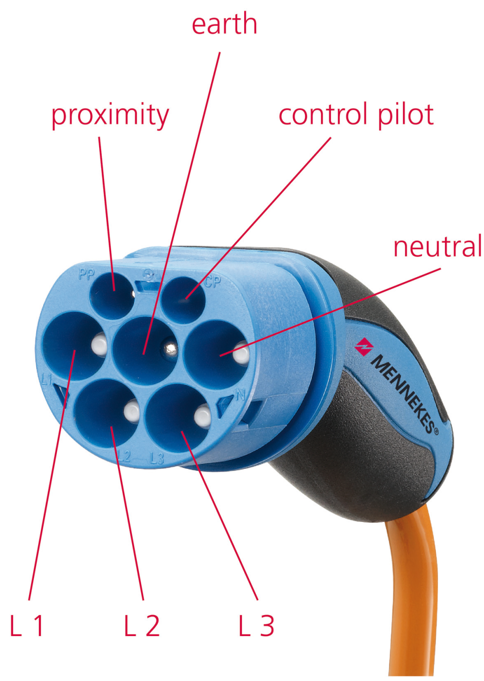


Figure 2.2: The Type 2 (Mennekes) EVSE to EV charging cable and the internal connection lines evblog.wanjon.nl.

New smart chargers also feature to switch a 3ϕ to 1ϕ charging by opening the relays for phase L2, and L3 see Figure 2.2 as the only control of the charging process performed directly by the EVSE [17].The control parameter will for this thesis be $\phi_{allowed}$, and either take the value 1ϕ or 3ϕ. This feature can benefit the grid if the primary phase has more available power than the other two phases. This would be the case when a photovoltaic (PV) unit is connected as RES on just a single phase. Switching off the two phases tests on some of today's EVs shows this feature open for additional capabilities discussed in Section 2.4 and limitations discussed in Section 2.1.3.

2.1.2 Charging communication

For this thesis, we will primarily work with AC charging in the EU. The dominating connection between the EVSE and EV in the EU is with a Type 2 connection cable as shown in Figure 2.2. The cable is described in the standard[18]. The cable consists of 5 power lines, one for each phase (L1-L2-L3), the neutral, and a line for potential ground (earth). On top are two lines for communication: CP and PP which provides valuable communication to enable smart charging. The shared information is therefore explained below.

Control Pilot: EVSE to EV communication

For the communication protocol, the standard [18] refers to the standard: [19]. The CP is utilized for communication between the EVSE and EV. Its medium is a combination of

Table 2.1: Voltage levels of the CP generated by the EV for EVSE to interpret.

V_{nom} $[V]$	Interpretation
12	No EV connected
9	EV connected not ready
6	EV ready
3	EV ready, ventilation required

a PWM signal generated by the EVSE to communicate the allowed current, $I_{allowed}$, and an array of resistors on the EV side communicating information about the charging status. The PWM signal informs the EV of the current limitations, which it should consider when charging with the function visualized in Figure 2.3.

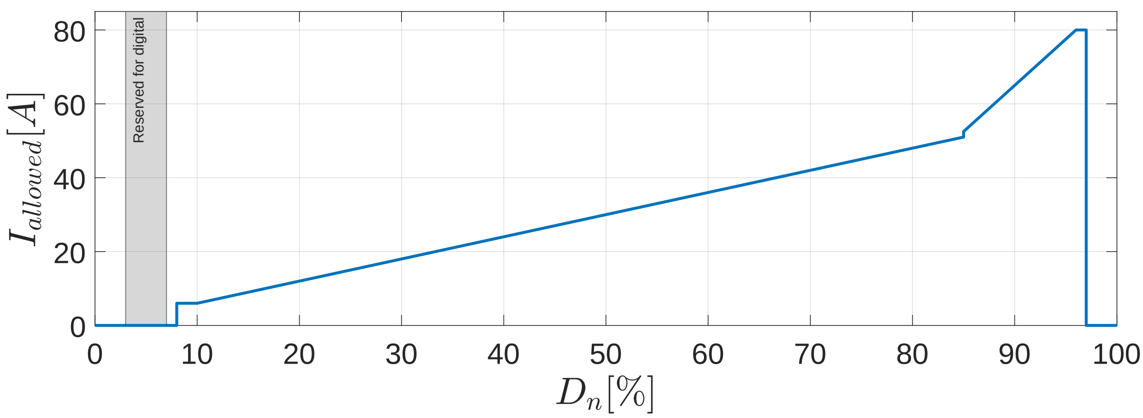


Figure 2.3: The conversion from PWM-signal duty cycle $I_{allowed}$

Even though the protocol allows for a signal of up to 80 A, the components both on the grid side and by the OBC of current systems constrain the charging power to $P_{C,OBC} = 22$ kW, hence 32 A (3ϕ).

Information is also shared through the CP line in the opposite direction. This is provided by letting the PWM signal see a changeable array of resistors on the EV side to reveal different voltage drops back to the EVSE. The nominal values and their interpretation is presented in Table 2.1

As this is the only communication line defined in the protocol, no other information sharing exists between the EV and EVSE. It is therefore not possible with this standard to let the EV identify itself or provide its SOC for the EVSE [20].

Proximity Pilot: cable to EVSE and EV communication

The PP communication is also described in the standard [19] but differs as the cable is a passive element without any control logic. The critical parameter for the cable to reveal is its current capacity. That is the cross-sectional area of the power lines, which is listed in table Table 2.2. For the ability to be revealed, a coding resistor (R_c) is connected between the CP and ground.

The PP, therefore, provides valuable information which puts an upper constraint on the charging current. This information is also provided to the EV, which will adhere to it, and the $I_{allowed}$ from the EVSE through the CP.

Table 2.2: Resistances R_c of the cable PP connection and the allowed current, $I_{allowed}$, which the cable can handle.

I_{max} $[A]$	nominal R_c $[\Omega]$
0	0
13	1500
20	680
32	220
$63(3\phi)$ $70(1\phi)$	100

For local grid control, it is necessary to have the geographically stationary unit, i.e. the EVSE controlling, as it is responsible for keeping within the local constraints and has communication set up with other grid controlling units. And for the EVSE, only two variables are practically possible to control:

1. $I_{allowed}$ per phase: which can be set to 0 A or a range from 6 A up to the constaints of the hardware present.
2. $\phi_{allowed}$: 1ϕ or 3ϕ

It should again be noted that these variables are upper limits of the actual charging. The EV may, at any time, choose to diverge downwards.

2.1.3 EV charging dynamics

As the EVSE only may provide the upper limits for the charging process and the EV user and their EV have autonomy of their own, these parameters from the OBC dynamics and the user should also be considered as their decisions within the EVSE constraints also affects the quality of the control by the EVSE. The parameters and decisions of the EV and user of the EV will therefore be discussed to provide the background of their dynamics in different situations.

High SOC charging behaviour

As the battery capacity is a given parameter that sets the upper limit of how much to charge for any session, there exist two different behaviours the EV may produce when an EV wants to stop charging. Either the EV has programmed a specific upper limit, e.g. $SOC = 80$ % at which it stops charging, or it engages the constant voltage behaviour of the constant current constant voltage (CCCV)see. sectionSection 2.1.3 behoviour. CCCV is the charging behaviour of an OBC to have a constant current flow towards the battery by satisfying $V = V_{int} + I_{bat} \cdot R_{int}$, where V_{int}, the internal voltage, will increase with SOC [21]. When the maximum allowed voltage forced on the battery is reached, the OBC will keep this voltage for the remaining charging session until $SOC = 100$ % is reached. A preliminary test has shown that the total power consumption starts to decrease about 10 minutes before the EV reaches SOC = 1 (see appendix B), with a 11 kW charging session independent of the CP signal from the EVSE.

Accuracy towards a Power setpoint

When the battery is $SOC << 100$ % the charging will use the converter hardware, the user set max charging current in the EV, and the $I_{allowed}$ as the upper boundary constraints of the converter throughput. However, as discussed by [17] and [22], the converter hardware may not be accurate to the constraint of the $I_{allowed}$. This may be caused by a mismatch in the consumption of the three phases or simply that the logic of the OBC counts in its precision and, therefore, intentionally sets a lower setpoint. For this thesis, power control is one of the objectives, which relates to the current communicated from the EVSE as $I_{allowed} = \frac{P_{ref}}{V_{LN} \cdot \phi} \cdot \cos(\theta)$. The EVs will produce or consume reactive power, and the line to neutral voltage, V_{LN}, will not constantly be 230 V (LN). The former causes the power output will be lower than what is wanted from a direct calculation of P_{ref}. The latter also impacts the equation but can be overcome as the EVSE can measure the voltage and use it for the calculation.

On another note, by [17], it is observed how the OBC manages to stay within the requirements of the protocol to respond to a change in the $I_{allowed}$ given by the EVSE within 5 seconds. This will become very useful when closing the control loops in the EVSE.

Efficiency of charging
Lastly, as a note on the OBC behaviour is how effectively the energy from the grid is transferred to the battery. When dealing with power, one of the major issues will always be to convert power as efficiently as possible. For the full charging process of a charging session, this is given as follows:

$$\eta_{charging} = \frac{\Delta E_{EV}}{\Delta E_{grid}} \tag{2.1}$$

$$\approx \eta_{converter} \cdot \eta_{battery} \tag{2.2}$$

Where ΔE_{EV} is the energy delivered to the battery of the EV within the charging session and ΔE_{grid} is the energy taken from the grid. The main losses in AC charging arise from the converter and the battery's internal resistance (joulean losses). These components reside in the EV and therefore come with a very different nature for a parking lot. As input for this research, the results of a simple test carried out with the OBC charging of a 1ϕ EV (Nissan Leaf) and a 3ϕ Peugeot 208e charging at both $\phi_{allowed} = 3\phi$ and $\phi_{allowed} = 1\phi$ shows the efficiency at different power levels. The measurements on both sides of the OBC give converter efficiency, which, combined with the internal resistance explicitly found for the Leaf in [21], may provide the total efficiency which is given in Figure 2.4. The calculations for the joulean losses are based directly on the empirical found data from the Leaf and are assumed to be the same for the Peugeot 208e. The internal resistance and voltage do depend both on the temperature and the SOC but is, for this purpose, assumed constant at 170 mΩ and 360 V on the battery side. Thus from this empirical data, it may be assumed that the OBCs are optimised for charging at $P_{C,OBC}$.

Note that the customer is charged based on ΔE_{grid}; therefore, the EV manufacturers are incentivised to implement a high efficiency. In contrast, from a purely economic viewpoint, the charge point operator wants the EVs to charge at low power to get low efficiency.

2.1.4 User behaviour
On the EV side, the periphery outermost entity of the 'system' is the users who, as opposed to a stationary battery, only have the flexibility provision as a secondary objective of the EV. Every EV will, therefore, only be connected to the grid-specific period when it is not driving and the user has plugged it in. As this thesis focus is on Uni-directional smart charger (oppose to V2G) bi-directional smart charger (V1G) the amount of charge needed for each EV is from a cluster perspective predefined. Thingvad et al. [7] has found the distance driven by the Danish population. And with the driving efficiency of the EV that gives the energy needed, e.g. each day. Some of this energy may be charged at a workplace parking lot. Workplace parking lot chargers distinguish as destination chargers used by employees coming into work. A typical workday has a length of 8 h to 10 h [24], [9]. The

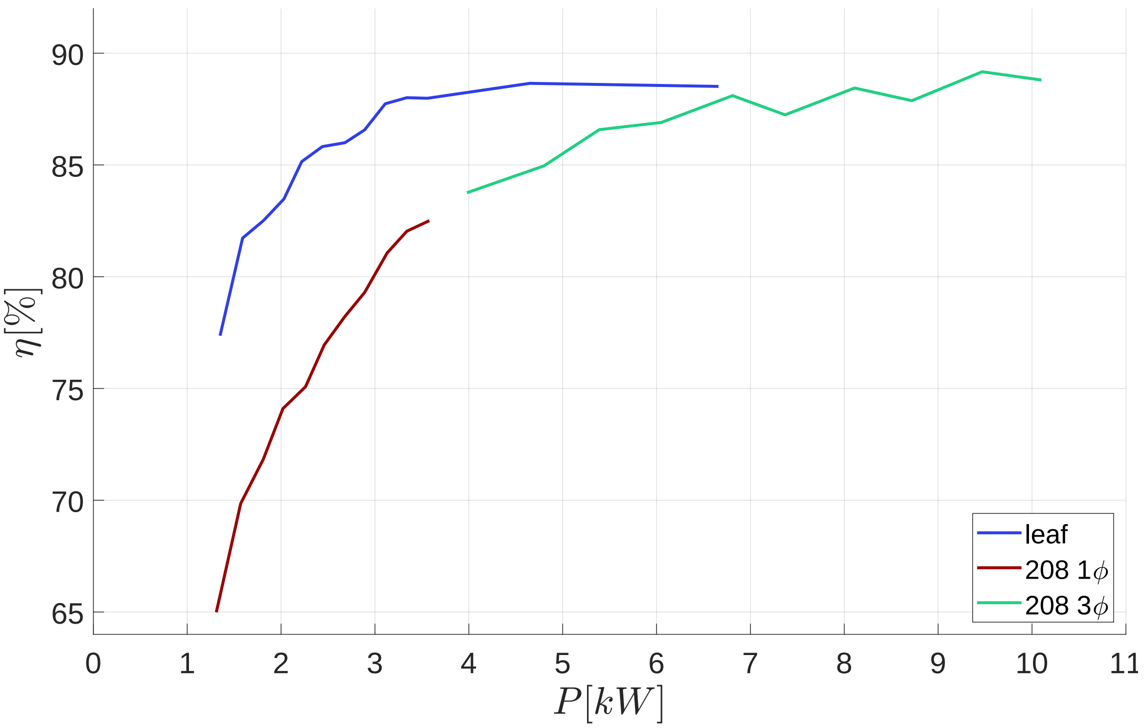


Figure 2.4: Total charging efficiency of a Nissan Leaf and a Peugeot 208e charging at $\phi_{allowed} = 1\phi$ and $\phi_{allowed} = 3\phi$ respectively [23].

amount of energy necessary for a typical day is on average 50 km/day for those who have good parking conditions at their workplace in Denmark [7]. This amounts to an average charging power:

$$P_{avg} = \frac{50\,\text{km}\,\text{d}^{-1}}{6\,\text{km}\,\text{kWh}^{-1}} \frac{1}{\{6\,\text{h to }9\,\text{h}\}} = 0.93\,\text{kW to }1.38\,\text{kW} \tag{2.3}$$

where 6 km kWh^{-1} is assumed as average driving efficiency of EVs [21]. This rough estimation does not consider how EV users will behave when given the ratio between employees who want to charge at work and the number of EVSE available at the worksite. Further, some may not even plug in daily, especially if the ratio of EVSEs per EV is low.

The fact that the necessary charging power is less than the capability of a single charger (at 11 kW to 22 kW) is one of the prime motivations for this thesis which will utilise this freedom to provide flexibility.

2.2 Flexibilty in the power system

The electrical energy sector is also undergoing the same transition towards a more sustainable future as the transportation sector. The RES planned to take over energy production is known for being intermittent and less incentivised to participate in providing flexibility. Wind turbines, PV, and nuclear have a high investment cost but low operation and maintenance costs. This incentivises them to produce at maximum power rather than offsetting their setpoint to enable participation in providing flexibility. At the same time, wind turbines and PV cause a need for flexibility as their production is weather dependent. Lastly, introducing RES will put the conventional generators to rest, removing the usual flexibility providers. This is further outlined in [25, p.21], which states that flexibility will be needed in future energy systems.

2.2.1 Introduction to types of flexibility

For a healthy electrical energy system, it is vital to have providers of flexibility for four different domains; wholesale market, transmission system operator (TSO), distribution system operator (DSO) and behind the meter (BTM) [5].

The wholesale market utilises the competitive market structure to shift elastic demand. Hourly dynamic price schemes have recently been introduced for regular household customers and are, therefore, easily accessible[26]. The price indicates where bids for selling and buying energy for a given hour have met. For EVs, it is especially interesting to look at the changes in price throughout the day[27]. For this type, the power system will 'compensate' the provider with a lower price by shifting their load to a price valley[28].

Thingvad et al. [29] have covered the TSO needs, mainly frequency regulation. This is done by addressing the relationship between active power and frequency with the swing equation interpreted below:

$$P_m^c + P_m^{nc} - (P_e^c + P_e^{nc}) = J \cdot (2\pi)^2 \cdot f \frac{df}{dt} \tag{2.4}$$

Where f is the frequency, J is the inertia of the synchronously connected units, t is time, P_m is the grid-connected mechanical machines (with generation convention), and P_e is the converter connected units(with consumer convention). The superscript c and nc denote controllable and non-controllable, respectively. The equation shows how any mismatch in the energy grid between the uncontrolled and controlled units on the left-hand side will cause the $\frac{df}{dt}$ to be nonzero, and thereby the frequency will deviate. EV chargers participating in the controlling belong to the group P_e^c. The markets differ by the activation criteria, mandatory response time, and most importantly, the capacity [29]. López et al. [26] report a tendency in European markets to lower the capacity barriers for smaller entities to participate. Currently, the minimum bidding capacity for the Danish TSO is 0.1 MW to 5 MW depending on the service and region (DK1, DK2)[30].

The DSOdomain further focuses on the parameters specific to the local area of the distribution network. The focus is, therefore, the voltage and congestion control. Voltage may be addressed with control of the reactive power, and as this is not directly possible with the EVSE explained in Section 2.1, it will not be further investigated. However, congestions are a more relevant case. With the recently added loads in the distribution grid, upgrading the distribution grid (transformer stations and cables) will not have the necessary capacity[25]. Especially as the congestion is a measure of the current through cables or the apparent power of a transformer, these relate more to the control variables of EV charging [31].

Lately, the interest in Behind The Meter, BTM services has increased as self-consumption of produced energy is incentivised by the price difference of power sold and bought from the grid [32]. This type of flexibility requires a control connection between an energy source connected on the local side of the billing meter in combination with flexible demand[33]. This topic is explored in depth by the [6] and [34] in simulation environments connecting the EV consumption control directly to the output of PVs or wind turbines, which is mutually connected inside the same meter.

2.2.2 Aggregators

For the four domains, the response needs to be linked to the flexibility providers, i.e. the responsible needs a backend architecture to control the setpoints of the flexibility providers. For distributed entities, like EV chargers, an aggregator coordinates the setpoints of a larger population to meet the desired need of the responsible party[35]. The aggregator has no physical control in/output; however, it takes input from other entities and sends control signals to generate an economic benefit for the distributed units.

Three main architectures for controlling distributed units are Central, Decentral and Distributed Control[16]. The architectures will be discussed in the next section. For the central control architecture, all setpoints go through a central Cloud Aggregator, CA, where all decisions for the system are taken, and specific setpoint values are sent back to the units. With a decentralized architecture, all units have a VA, which takes its own decisions only considering its output. The distributed architecture utilizes both a central CA, which may send out control signals, and VAs that can take local decisions themselves, but where they consider the CA control signal whenever it is present[5].

2.2.3 EV providing flexibility

To address the aspects of providing flexibility generally, there are specific requirements set by the responsible parties that need to be met by the technology before it can participate in the flexibility markets. The authors of [6] have gathered an extensive review of the possibilities for clustered EVs to provide the flexibility needed by the TSO and DSO technically.

In parallel to the controlling is a need for a financial architecture. To incentivise all parties of the system to participate, all parties should get a share of the economic benefits. The financial architecture is less time critical as the settlements are done after a session. The Charge Point Operator, CPO, is linked to the CA (who may operate multiple clusters) and will gain financially from decisions made by the CA [6]. The CPO should therefore decide how to financially include the possible gains of flexibility participation with the EV users who provide their capacity for the services [36].

2.3 Control architecture

As a component, an EV charger alone may only control its consumption. It does therefore require collaboration to provide acceptable integration and flexibility. For collaboration between autonomous components, it is imperative to define where decisions can be made and what information to communicate between nodes of the architecture. Every use case is different and should be fitted specifically for the application.

It is suggested for distributed energy resource (DER) in general by [16] and specifically for EV charging by [28] to maturing the distributed control architecture as it has promising advantages in future flexibility providing system. Even though distributed architecture has been discussed for decades, confusion still exists on the definition and will therefore need to be introduced.

2.3.1 Introduction to distributed architectures

Control architectures for DERs have been investigated in [16] and specifically for EV charging in [28]. It may rely on vertical communication to a unit with a broader perspective than the distributed units. But also horizontal information sharing, either through shared memory or directly between the units[16].

A distributed architecture benefits from the possibility of communicating in the most relevant manner. If a signal is needed by a charger measured close by, there is no need to communicate through a central entity in the cloud. However, a unit with a systemwide perspective may broadcast a need for flexibility to the entire cluster. The complexity of a distributed system may increase with the different types of communication included. Therefore, developing a structure that fits the application's purpose and specific needs for sharing information is essential.

An exciting approach to the architecture is found in [35], which seeks to have multiple units make decisions in a market-based manner for the distribution grid.

2.3.2 Comparison to other control architectures

Focus has been on the distributed architecture, which now will be compared to the central and decentralized control architecture.

Central control architecture builds from a single central controller which makes decisions for all entities. The controller receives all periphery data input directly and, based upon those, takes a decision and sends setpoint values to the periphery output. The decentralized, on the other hand, has no real-time communication. All units have a predefined behaviour to inputs, e.g. multiple droop controllers reacting to the frequency.

Compared to central architecture, the distribution has the benefit of more local control. As the possible decisions are taken in the local unit, there is no need to share data. This both increases the privacy and information isolation as well resilience to operation failures of the central unit [16]. It is a further advantage that the response time of local control is faster and independent from the central controller [37]. Most importantly, with the increasing number of EVSEs that need to be controlled, the centralised control architecture will have a significant increase in complexity [16]. The downside of a distributed system is the chances of reaching suboptimal states as the distributed control units will have to take their own decision, which may cause a lack of broad overview and instability in the output[16].

Compared to a decentralised system, there are advantages to the ability to control the system. As the decentralised system relies on predetermined, non-real-time control schemes, there is only a limited possibility to provide flexibility and monitor the individual controls [16]. A distributed architecture also relies on the same local decision-maker. But integrates a chance to communicate with other units to reach a collaborative response to a signal of needed flexibility. The issue of the distributed architecture comes when integrating additional units into the system and ensuring that data is kept private.

Distributed architectures have now been generally discussed compared to the central and decentralised. The distributed control architecture is not as matured yet, and therefore, multiple sub-architectures exist [16]. These will best suit different scenarios, and individual assessments should be done for each application. With the rapid increase of chargers, a scalable solution should be integrated and investigated.

2.4 Related work of the ACDC project

The Autonomously Controlled Distributed Chargers project is led by DTU and started in April 2020 and is set to be terminated September 2023[38].

2.4.1 Demonstration setup

Within the ACDC project, a physical system has already been set up. The chargers are developed by the participating stakeholder Circle Consult (CC), who has also set up the amazon web service (AWS), which hosts a secure connection to the chargers. The AWS connection enables DTU to control the setpoint for the chargers and get feedback from it through a prototype server, Whiteboard. The full setup is depicted in Figure 2.5 and the specific functionality of each component is described below.

Chargers

The chargers of the ACDC project has throughout this thesis period been those depicted in Figure 2.6b. They have 2 plugs each connected to their own EVSE circuit inside. The control interface for the chargers goes through AWS. The VA functionallity has already been included in the chargers. The internal VAs will however function as a relay directly

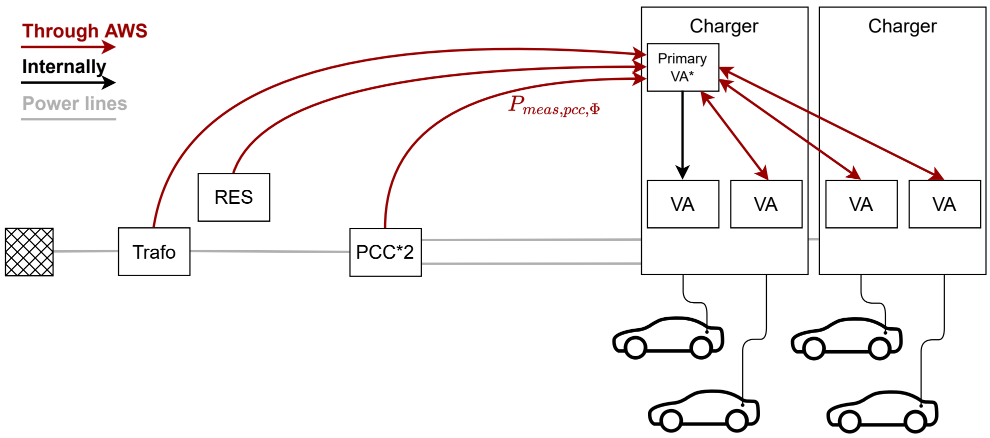


Figure 2.5: Interpretation of the setup with the physical components and controlling components of the setup in the ACDC November 2022 presentation. Arrows indicate with their color the means of communication between the different components.

passing the $I_{allowed}$ read in AWS to the control unit of the CP. To control the chargers a `Json` message should be sent to AWS containing the charger name, EVSE name, the $I_{allowed}$, and the $\phi_{allowed}$. As feedback from the chargers the code gets the charger status, s_{EVSE}. This data is relayed through AWS to Whiteboard and may take one of four string states:

- `Charging`
- `Connected`
- `Idle`
- `Error`

Luckily the chargers has no need to bill the customers as they still lack the metering board. This further disables the controlcode to know the exact consumption of each EVSE.

On top of the normal work is being done to integrate the possibility to dynamically turn the phases so that the EV on line L1-L2-L3 of Figure 2.2 sees B-C-A or C-A-B of the grid. This specifically becomes useful in combination with the control of $\phi_{allowed}$ as described in Section 2.1. With this functionality, the smart charger is enabled to align the consumption on the phases or perform voltage control for the grid. For this thesis, it has however not been fully implemented and will therefore not be utilized.

Point of common coupling
The two chargers are supplied with power through a single point of common coupling. A PIOT (Power IOT) smart meter developed for SYSLAB at DTU is situated at the coupling (see Figure 2.6a). It contains a meter which, for the full cluster, measures voltage, current, power, reactive power and apparent power for each phase. Additionally, it measures the frequency of the system. The collected data is broadcast to energidata.dk as the generic data acquisition server of the PIOTs. The ACDC project has, from there, developed a python script, `query_PIOT.py`, which subscribes to the data and brings it to the Whiteboard for ACDC project-specific purposes.

Webpage
To provide a user interface a prototype webpage has been set up on a DTU server. The webpage is for the prototype chargers the interface where the users insert data of their requested charging. The data collected from the users is stored in a SQLite database

(a) The PCC and Chargers in background

(b) Chargers on lightpole with one EV connected each.

Figure 2.6: The physical setup with the PCC, chargers and 3 EVs Connected. The PCC is positioned approximately 10 meters from the chargers, as the pictures have been taken from both sides of the setup.

format `database.db`. For each entry the following data is stored:

- Entry time, as $< YYYY - MM - DDHH : MM : ss.\mu\mu\mu\mu\mu\mu >$
- Plug number
- Name of user
- EV model
- Wanted energy in kWh
- Arrival time as $< HH : MM >$.
- Departure time as $< HH : MM >$.
- Email of user.

Whiteboard
The Whiteboard has been mentioned a few times throughout the presentation of the demonstration setup. It is a simple database which allows scripts running both inside and outside the SYSLAB domain to pass information to each other. The Whiteboard resides on a prototype server setup by Oliver Gehrke, specifically for the ACDC project. Any entry in the database contains the following four data points:

- Source: The unit that sent it there.
- Time: Epoch timestamp of when the Whiteboard received the data.
- Key: The parameter name.
- Value.

2.4.2 Preliminary implementation of sharing strategy

Another participating stakeholder is the automobile manufacturer Nissan, which has been developing a priority-based sharing strategy.

As the most recent test within the ACDC project, it provides the foundation for further work within the ACDC project within the domain of sharing strategies. The algorithm and main ideas have therefore been visually explained in Figure 2.7 (and subfigures). The explanation only provides an overview of the ideas and functions that are implemented in the algorithm. The code is a pure dynamic control system. The dynamic control is hard coded to the setup used in November 2022, with a preset t_{dep} and E_{wanted}; hence the only input for the code is the connection status of each EVSE and $P_{ref,CA}$ and $P_{meas,PCC}$. The s_{EVSE} is utilized to initiate the charging session. If it is `Charging` or `Connected`, the session is on otherwise values like P_{avg} and ρ is set to 0. As may be seen in the figure, it contains three inputs. The charging status of each EVSE, Power reference and power measured at PCC. The user input is for this demonstration, not an input, hence when an EV connects, it is assumed that the user has inserted how much energy they want (from 10 kWh to 30 kWh) and how much time the EV will be parked. (all at 7 h).

To let the chargers compete for the available power, the parameter priority, ρ, is introduced. The idea is that the chargers or EVSEs contain the same algorithm, but they act differently based on ρ. For Nissans code, it is given by:

$$\rho = \begin{cases} 0.05 + 0.1 \cdot \frac{P_{avg,full}}{P_{C,EVSE}} & \text{if } E_{req} \text{ is reached} \\ 0.15 + 0.8 \cdot \frac{P_{avg}}{P_{C,EVSE}} & \text{otherwise} \end{cases} \tag{2.5}$$

Where P_{avg} is the average power needed for the rest of the session to reach the energy demanded (E_{req}) by the user before the given departure time (t_{dep}). After E_{req} is reached, the priority is instead found with the average power needed to reach SOC = 100 % by using $P_{avg,full}$. P_C of the EVSE normalizes the power to within the capability of the charger or EVSE (22 kW). From Eq. (2.5), it is seen that ρ first and foremost is given to an EV that has not yet reached the goal; a minimum of $\rho = 0.15$ and entities that already have been satisfied will only have $\rho < 0.15$ if their $P_{avg} > P_C$. For those who have not yet reached their E_{req}, the highest ρ will be granted to entities with a higher urgency to receive power. With this strategy, it is observed that the charged energy may go above the negotiated energy the user wants. The priority of the charger is as described above, a value of the needed power used on the charger level in Figure 2.8 where it is utilized to calculate the `tentativeChargePower` as the gain variable of the in case the P_{error} is below 0 hence a decrease of the cluster consumption is necessary.

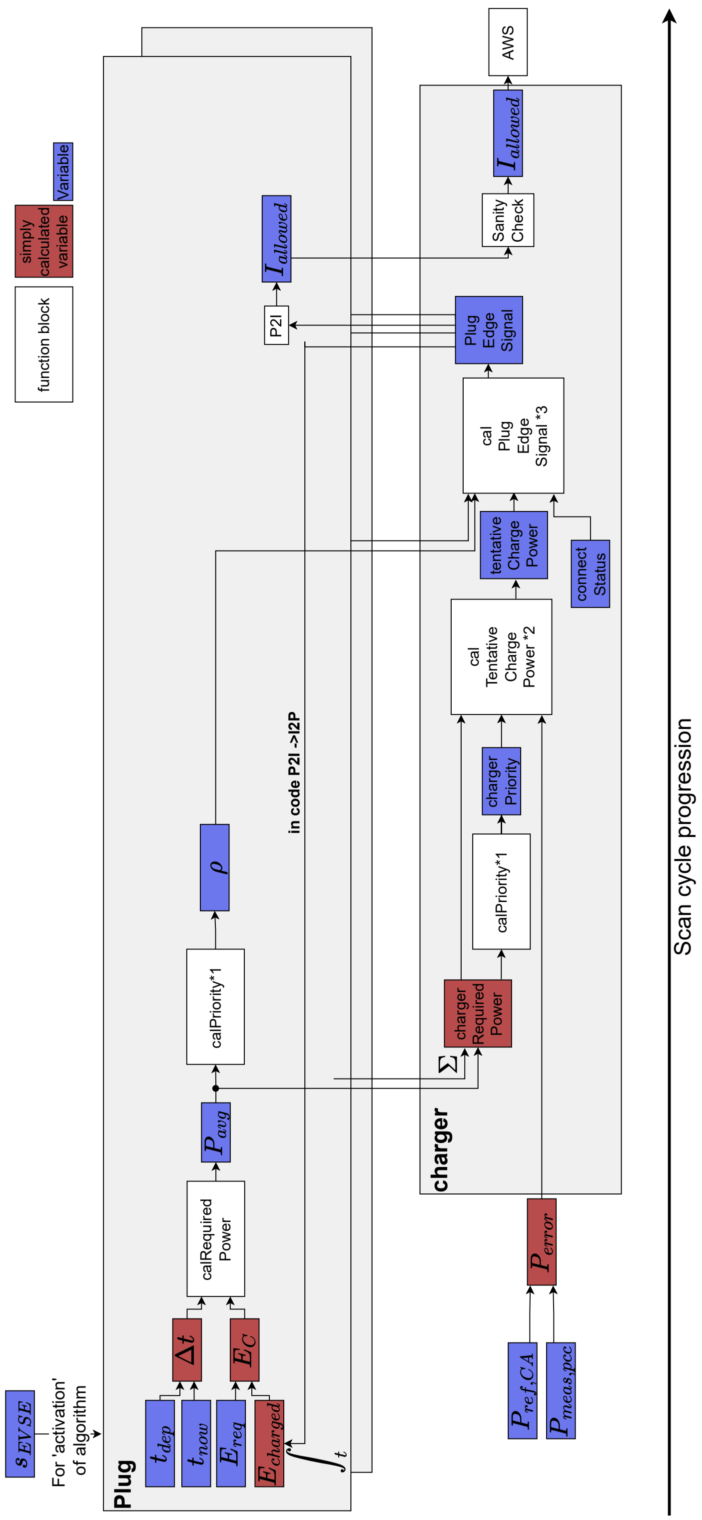


Figure 2.7: graphical interpretation of the algorithm made by Nissan. It resembles the control system. Names of parameters have been translated into the terminology of this thesis. Mark *1-3 is explained with Eq. (2.5), Figure 2.8 and Figure 2.9 respectively.

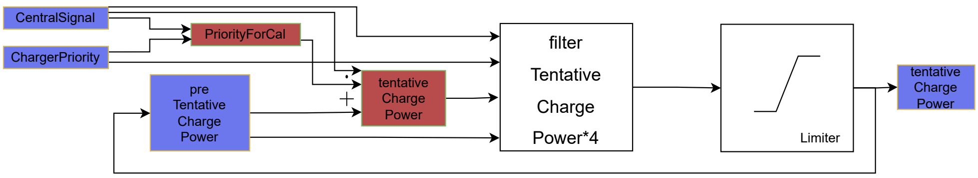


Figure 2.8: Calculator for Tentative Charge Power. Mark *4 is explained Figure 2.10.

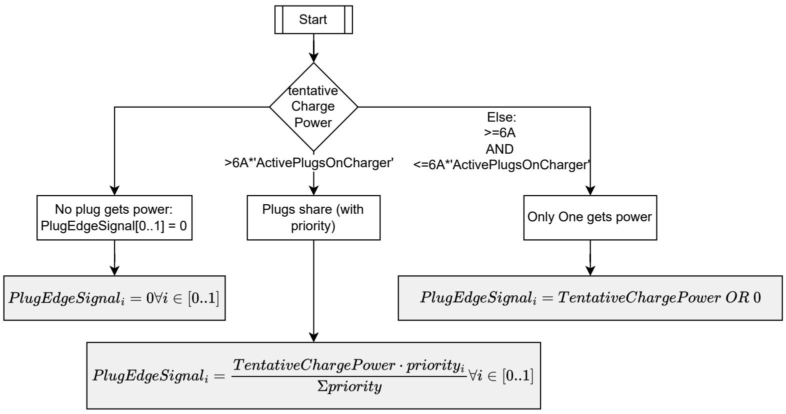


Figure 2.9: Decision tree for Plug Edge Signal.

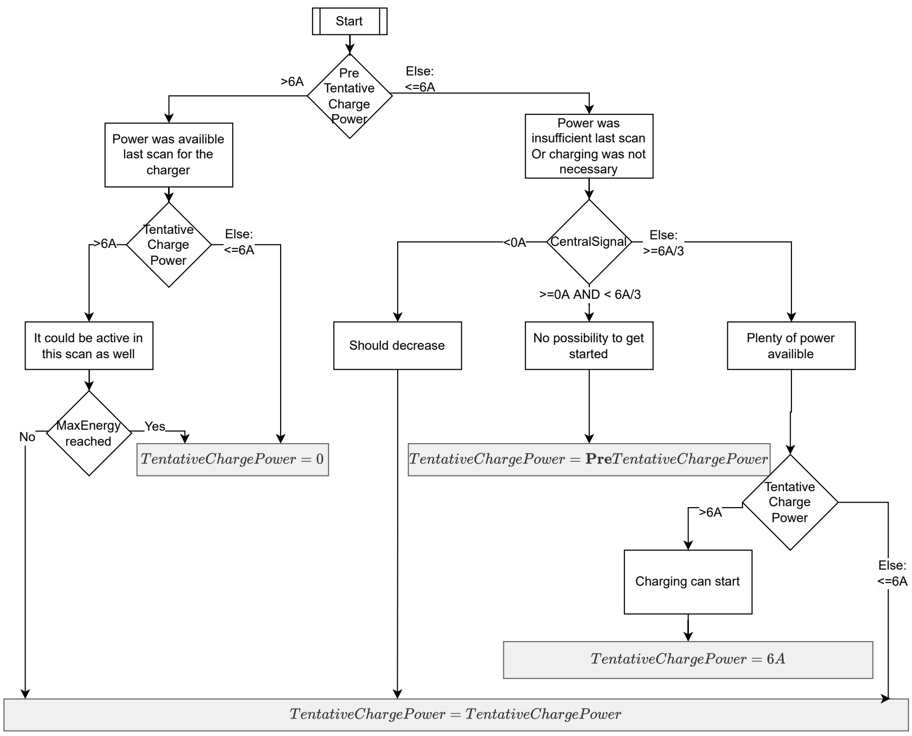


Figure 2.10: Decision tree for Tentative Charge Power.

3 Contribution

A distributed architecture is expected to have increased reliability and scalability when extending the perspective into the future with an increased EV population. The ACDC project has an architecture supporting this further investigation in a structure where changes are easily implemented. The project, which will be finalised in September 2023, aims to provide a real-life system with a distributed control strategy implemented, which further requires the tying of ends to be ready.

As described in Section 2.4.2, the code is implemented in a nonscalable control strategy but has been tested in a realistic confined environment. To prove the applicability in real-life scenarios, the control code should handle the random variety implicated by putting real users with EVs into the algorithm. In other words, the control code should go one step further toward robust real-life applicability. Additionally, the control and data structure is not designed to be split into separate units, i.e. not made for distributed control. It should, therefore, also be important in this project to ensure transparency of the solution to run on distributed units.

A further challenge that should be addressed is the need for full autonomy. A fault-tolerant system that can react simultaneously to inputs from all sides (CA and users) is needed. This will provide an insight into the dynamics which arise from the user interactions with a cluster that provides flexibility [39], [40].

As opposed to the above, the literature contains multiple implementations of CA and complete system control systems. This may be simulated or in real-life, and utilise model predictive control or optimisation (either simulated or on simple real-life systems), which provide model predictive control, optimisation or control on the CA level[41]. Further maturing of the distributed control architecture is necessary to prove its capabilities. A VA cluster system that provides easy and modular controllability by a CA should be investigated. This should be found before further research can be done into the algorithms of the CA and its application on real-life clusters[40]. Therefore this thesis will not focus on the optimisation or algorithms included in the CA but rather on how the VAs should react to the signals from it.

3.1 Research objectives

The gaps mentioned above have brought the author of this thesis towards solving the most crucial issues for further work within the field. A distributed autonomous control architecture for the base level of EV charging clusters should be built as it has advantageous features. It should operate with a user and CA interface to enable participation in flexibility services.

Through this project, a strategy for a real-life implementable distributed smart control system will be developed for a cluster of chargers sharing a connection point to the grid. The strategy should take into account the following objectives:

- Increase the capability to respond to a CA signal.
- Increase the efficiency of the charging process.
- Fullfil the needs of the users.

It is further the goal of the thesis to implement the strategy with a distributed control architecture to provide a real-life setup that can further examine its usability. To the possible extent, the implementation should utilise current standards and the communication limitations hereof.

A real-life implementation of the strategy on a small cluster should be made. As the novel technology of EV charging and its further capabilities has not fully developed, a demonstration platform hereof will serve with great value for further research[42]. A demonstration will provide novel insight into the barriers met when trying to control diverse EV charging from logic included in the EVSE and aid in defining the possible strategies.

The overall goal is to provide a technical view of how an easily controllable cluster of chargers may become a beneficial macroeconomic participant in both the energy and transportation sectors.

4 Method

As this thesis aims to generate a multi-objective strategy and provide a distributed architecture that supports this, the three mentioned objectives will first be analysed. The analysis will indulge in the range to which each objective can be reached, providing the foundation for deciding the strategy that will be a compromise between the objectives. The strategy which is wanted to fulfil is key to have defined before the necessary information sharing and decision making will be discussed as the architecture of the system. And lastly the complete way that each unit will behave is defined as the generic build of the system.

4.1 Analysis of objectives

The three objectives focus on three different ends of the system. The user wants a certain amount of energy delivered to the EV at a specific time. Efficiency focuses on the internal working of the process of taking energy from one place to another. And finally, the provision of flexibility disregards any of the two previously mentioned but purely on how the system may (as a blackbox) shift the energy consumption in time. Each objective will be analysed and consolidated into a formal objective function.

4.1.1 Providing flexibility

Providing flexibility with a generic parking lot as in Figure 2.1 can be considered a service to anybody in front of the point of common coupling (FTPCC). As mentioned in the background providing flexibility.

Within the distributed control architecture, the CA provides the control interface to any FTPCC. Within the CA, multiple different algorithms may be deployed to provide the services which, e.g. provides the best economic outcome for the charge point operator. The work of this thesis will not investigate the multiple algorithms but further investigate how the provision of flexibility may be communicated further to the EVSE. As the EVSE can control EV's upper current limit and if an EV should be charging as 1ϕ or if capable 3ϕ. The information from the CA would be sufficient to have a set of three power values, Φ, one for each phase, which the cluster should strive to consume if charging is possible. This will enable the CA to control the cluster's overall consumption by levelling all three values or have a skew alignment if the FTPCC service is to consume on a specific phase, e.g. due to local RES production in that particular phase.

The essence of this argument is, therefore, the notion that the CA will put the upper limit of the power it wants the cluster to consume at PCC, and the VAs should strive as a group to be always below but as close as possible at all instances of time. From the objective of the VAs as a group, the objective can therefore be formalised as:

$$\max_{P_{PCC,\phi,t}} \sum_{t} \sum_{\phi=L1}^{L3} P_{PCC,\phi,t} \tag{4.1}$$

Subject to:

$$0 \leq P_{PCC,\phi,t} \leq P_{ref,CA,\phi,t} \quad : \forall\phi, \forall t \tag{4.1a}$$

Where t denotes the discrete time instance and the phases from The objective function arises as there will be situations where the cluster cannot provide the consumption that the CA asks for as no EVs are connected.

4.1.2 Efficiency

The Internal charging process also impacts the decision-making for a charging strategy. As highlighted in Figure 2.4, the charging process does have the best efficiency when the OBC is allowed to charge at a power level close to the $P_{C,OBC}$. The extent to which charging efficiency should be considered is possible to debate as it is a question of a few per cent. However, implementing the strategy on larger clusters will add to a significant loss, worth considering. The objective function that the VA may consider for having a high efficiency may therefore be assumed as:

$$\max_{P_{i,t}} \sum_{t} \sum_{i=1}^{N_{EVSE}} P_{i,t} \cdot u_{i,t} \cdot \Delta t_t \tag{4.2}$$

Subject to:

$$u_{i,t} = \begin{cases} 1 & \text{: if: } P_{i,t} > \frac{P_{C,OBC,i}}{2} \\ 0 & \text{: Otherwise} \end{cases} \qquad : \forall i, \forall t \tag{4.2a}$$

In Eq. (4.2a) division by two is chosen from looking at Figure 2.4. A direct effect of this objective function is that with a limited amount of energy to charge (as is the case for V1G), maximizing the amount of energy set above a threshold minimises energy charged with power below the threshold. This objective function takes a high degree of assumption. However, for this thesis, it will suffice.

4.1.3 User needs

At the other end of the flexibility provision is another entity the VAs may consider: the users. The charging behaviour can be assumed at a workplace as visualized in Figure 4.1. The constraining elements of the charging capacity of the cluster are seen in an example where four EVs connect. $\sum_i P_{C,OBC,i}$ is the sum of the charging capacity of all the EVs connected, increasing as they connect and decreasing as they leave. The total capacity of the cluster is set at $P_{C,PCC,i} = 20$ kW.

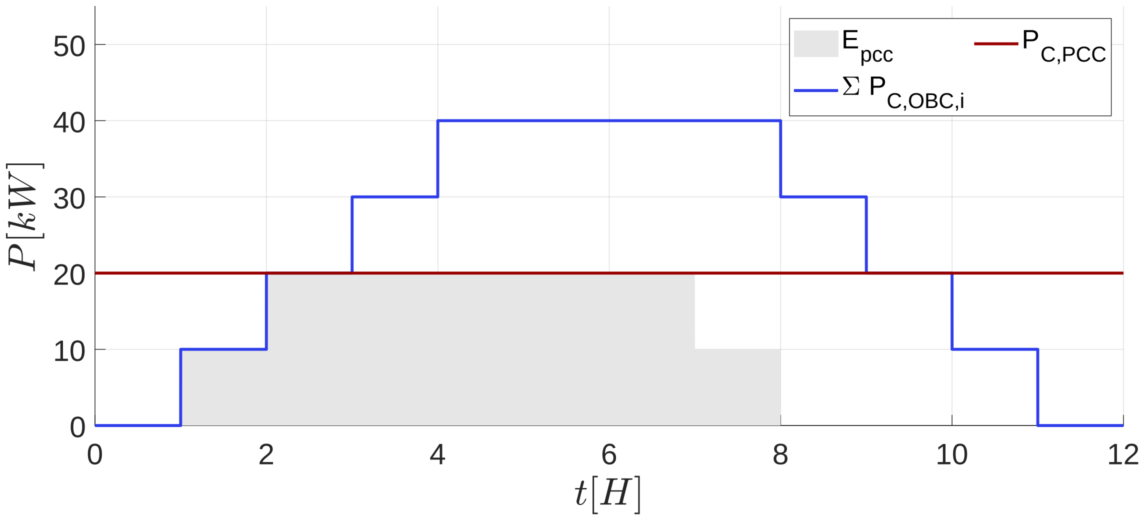


Figure 4.1: Generic user behaviour of workplace parking lot.

By integrating the resulting function of the binding constraint, the total consumption of the cluster can be found to be $E_{PCC} = 180$ kWh. However, as stated in Section 2.1, the incentive to provide flexibility comes from the realization that less energy is needed. For this example, the combined required energy of the users is $\sum E_{req,i} = 120$ kWh, which is shown as the grey-shaded area as $E_{PCC} = E_{req}$. It has been 'frontloaded' in the first part of the session, from the realization that further EVs may connect at any time. The further 60 kWh of energy available underneath both constraints but not part of the grey required energy, is what may be utilized for flexibility (hence, $P_{ref,CA}$ may, for this example, deviate downward from $P_{C,PCC}$ by a total of 60 kWh without compromising the need of the users).

It should now be apparent that the flexibility may only be provided given that it is known when the user departs again, and how much energy they want. Without this information, each VA could not determine if the EV connected could wait with charging for later. As a cluster, it is assumed that the information can be provided to the CA regarding forecasting. This forecasting is also necessary to project the price scheme for the users, as a high number of users wanting to charge will cause congestion. Thus the market mechanisms of the algorithm incentivise users to charge when no other EVs are there. It is further realized that the pricing cannot only be based on real-time data of EVs connected, as this would incentivise a 'first-come lowest price scheme' (Even though it may be of interest to the company next to the parking lot to have the employees coming in early for the lowest price). This also aligns with the idea of the ACDC project that the users should insert the data directly at the EVSE without the need to consult the cloud.

The proposed pricing scheme will also be mentioned to clarify the purpose. To incentivise the users also to participate in the flexibility services, they should be parking as long as possible and for V1G capable of charging an amount $0 < E_{req} < P_{C,OBC} \cdot t$. Usually, they should pay for the energy they consume from the grid. However, the price may be a function of their input when they negotiate at the initiation of the session:

$$C_\pi = E_{charged,\pi} \cdot c(E_{req,\pi}, \Delta t_\pi) \tag{4.3}$$

Where C_π is the total price of the entire session, and c is the price function which outcome is apparent to the, at the initial negotiation. After this agreement has been made (between the user and CPO), it is the assignment of the VA to secure that the negotiated power is reached. This brings us to the objective function of the user perspective, which the VA should consider:

$$\max_{P_{i,t}} \sum_t \sum_\pi P_{i,t} \cdot \tau_{i,t} \cdot \Delta t_t \tag{4.4}$$

Subject to:

$$P_{i\in\psi_\pi,t} \leq P_{C,OBC,\pi} \qquad : \forall t \forall \pi \tag{4.4a}$$

$$\sum_t P_{i\in\psi_\pi,t} \cdot \delta t_t \leq E_{req,\pi} \qquad : \forall \pi \tag{4.4b}$$

$$\tau_{i,t} = \begin{cases} 1 & : \text{if: } t_{arr,\pi} \leq t \leq t_{dep} \\ 0 & : \text{Otherwise} \end{cases} \qquad : \forall \pi, \forall t \tag{4.4c}$$

Where the subscript $i \in \psi_\pi$ indicates the VA indicies i which belongs to the session π It is assumed that the EVs charging capability, $P_{C,OBC,\pi}$, is a constant throughout the session. τ has been set to 0 for any time outside the user's given parking period, as charging may not be possible in that period of the given EV. If the EV stays for longer and E_{req} has not been reached it should of course still keep charging, though the objective function should not incentivise it.

4.2 A compromise of the objectives into a strategy

The three objective functions highlighted above are three different views but all with the cluster of VAs as the subject. They will now serve as the foundation for the strategy followed by the cluster of VAs.

4.2.1 Power division

When dealing with limited resources, a choice has to be made of who will get power and who will not. This could be treated for every instance in time, but also for the charging sessions; hence who will get the energy? Answering this may not be the exclusive choice of an engineer; however, an argument will now be made on this behalf. Throughout the project period, two schemes have been brought up; power scheduling and power sharing. Sharing is the democratic, fair option where the power is evenly distributed among the connected EVs. If one EV cannot consume some of the power distributed to it, this capacity of the PCC will still be available. If other EVs still can consume more, they can take over the otherwise wasted consumption possibility. The shared limited resource is distributed fairly for everybody at every time instance. Scheduling is a more market-based approach where the limited resource is distributed among several EVs to fulfil precisely their needs. If more EVs are connected than the capacity to provide power, some will be scheduled for later charging. When observing the power distribution at a specific instance in time, this option seems biased and unwanted from a democratic point of view. However, if the aggreement is met, the users disregard when the energy actually was delivered within the time window. As already discussed, the scheduling further suggests a market-based structure for the user needs in Section 4.1.3. From a scheduling perspective, the choice of who gets power can be decided by altering the economic dispatch into a ρ-dispatch illustrated in Figure 4.2. The 6 EVs are inserted with a decreasing priority. Their width represents their capability to consume power, $P_{C,OBC}$. For this specific time, t, EV 1 and EV 2 are allowed to charge at full capacity. EV 4, EV 5 and EV 6 have a too low ρ and will not be able to charge at time t as this would overload the PCC, $P_{C,PCC}$. EV 3 will then be the marginal consumer, and thus consume to the constraint of the shared capacity $P_3 = P_{C,PCC} - (P_{C,OBC,1} + P_{C,OBC,2})$. This equation is the ideal fit for the system and does not indicate any closed-loop controlling, which will be considered later. The two schemes have different foundations, but a strategy may still be founded as a mixture of the two. It is necessary to decide if the strategy should be based on democratic sharing or a market-based scheduling scheme.

To decide on the founding scheme, the two schemes are consolidated with the perspective of the technical objectives in Figure 4.3. The figure shows the performance of the two schemes under the following CA and user behaviour:

1. A constant CA signal: $P_{ref,CA} = 10$ kW
2. EV_1 Connects at $t = 1$ h and requests $E_{req,1} = 60$ kWh within $\Delta t = 10$ h.
3. EV_2 Connects at $t = 2$ h and requests $E_{req,2} = 40$ kWh within $\Delta t = 4$ h.

For the two EVs connected, their charging session is shown in terms of accumulated charged energy on the left axis and power consumption on the right axis.

The flexibility objective wants P_{PCC} as close to $P_{ref,CA}$ as possible. This is fulfilled in both schemes in $t = 1$ h to 9 h as the sharing has two EVs consuming 5 kW, in $t = 2$ h to 6 h. However, for the sharing scheme in Figure 4.3a, the energy charged to EV_1 in this period replaces the opportunity to charge it later. It is therefore observed that the scheduling outperforms the sharing in $t = 9$ h to 11 h where the $P_{ref,CA}$ is met with the consumption of EV1. The efficiency objective tends to the scheduling scheme equally, as the two EVs will be charging at half $P_{C,OBC}$ in $t = 2$ h to 6 h, which will bring the charging of both EVS

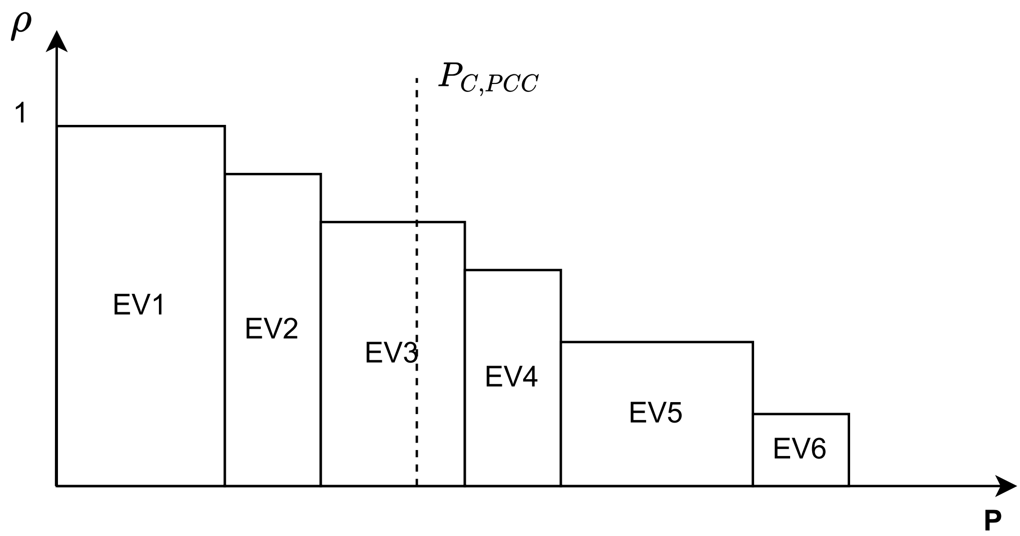


Figure 4.2: ρ-dispatch of 6 EVs at time t.

to a lower efficiency. Lastly, the user objective should also be taken into account. Here the goal is to charge the EVs at the user's request. When looking at the figure, it is seen that EV 2 disconnects at $t = 6$ h where it has reached $E_{C,left} = 20$ kWh for the sharing and $E_{C,left} = 0$ kWh for the scheduling.

Throughout the rest of this thesis, the scheme which will be at focus will therefore be the scheduling as it has the best chances of fulfilling the objectives.

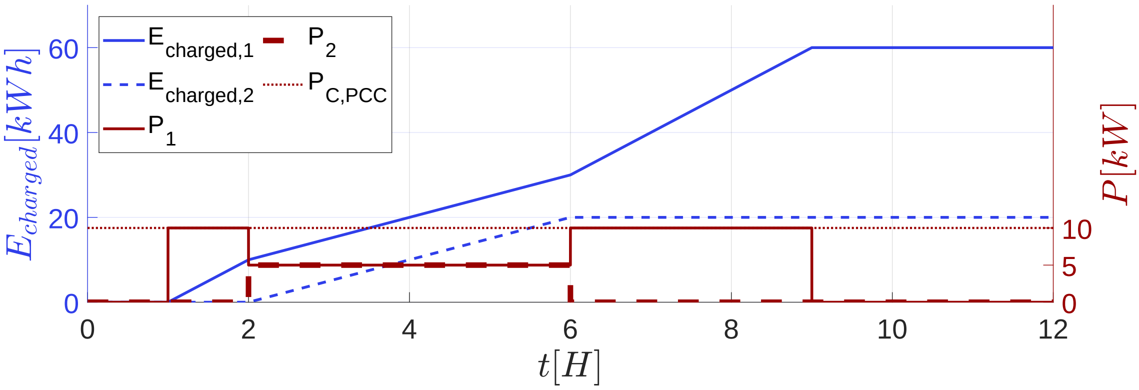
4.2.2 Neccessity for inter-VA communication

As it may have become apparent to the reader, the wanted strategy discussed above requires communication to let the other VAs evaluate if their priority allows them to charge. Another related issue arises from the non-linear initiation behaviour of a charging session. This makes it challenging for a VA where a new EV just has connected with high ρ to start charging without having other VAs making space.

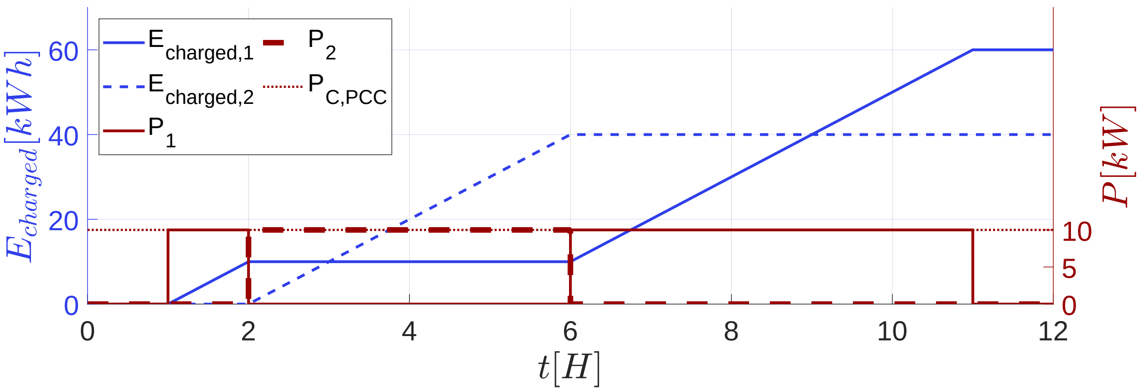
Real-life implementation does generate an increased number of scenarios to consider compared to simulations and laboratory tests. For a scheduling strategy, the case that requires the most pressure on the distributed control system is when a new EV is plugged in, and EVs are already charging at the capacity of the PCC. For this scenario, the new EV should be granted all the power it needs, as stated in Figure 4.2, and the marginal EV should decrease its consumption. The problem arises now from the large gap to start charging: The EVSE is only capable of controlling the EV charging to 0 A or ≥ 6 A $=$ 4.38 $kW_{3\phi}$. A distributed control, therefore, has four options to communicate between the new VA and the marginal VA that it should decrease its power:

- Constantly sacrificing a margin on the PCC capacity of 4.38 $kW_{3\phi}$.
- Every 15 minutes the marginal consumer momentarily drops 4.38 $kW_{3\phi}$.
- Overload PCC momentarily when starting up.
- Communicate a need to start charging via an independent communication line.

If neither of the options is chosen, the system will default to a first come, first serve strategy, which will not make the new EV charge within time. A constant sacrifice of the capacity is an unnecessary limitation of the system, which will affect the $P_{C,PCC}$ during steady state



(a) Sharing approach



(b) Scheduling approach

Figure 4.3: Two schemes for dividing the limited shared resource: $P_{C,PCC}$.

operation and therefore affect the total energy that may be delivered, $E_{cluster}$, as well. Letting the marginal consumer drop the power consumption every 15 minutes to allow for utilisation of the $P_{C,PCC}$ during steady state would increase $E_{cluster}$ from the previous option. When utilising this option, the operator should be aware of other dynamic mechanisms that may overlap with the momentary drops, as additional VAs charging may use it to charge even more. Overloading the PCC capacity from the startup of the new EV charging until the marginal VA react to the overload is also a viable option in cases where the $P_{C,PCC}$ is not a hard constraint. The last option to communicate it through an independent communication line will affect the $E_{cluster}$ least. Depending on the communication line delays, this option will have a $E_{cluster}$ very close to that of an ideal central control system.

The latter option of having the information in an independent communication line has been chosen for this thesis. The decision has been made to ensure that the fuse of the PCC will not open and further optimise the $E_{cluster}$ in alignment with the objectives.

4.2.3 Information being shared

For the strategy discussed so far, it should be clear that a certain amount of information is necessary to share between the VAs. To review, it should be shared when a VA wants to start charging, and further, it should be possible to compare the ρ to that of others. For a VA to decide its priority allows it to participate, it must be compared to the marginal VA. If its own ρ is higher, it may charge at its capacity, and conversely, if it is below, it should stop charging and wait for later. To define $\rho_{marginal}$ for all other VAs, there should be a distinction between those charging and those not charging. Lastly, it should be noted that if a VA wants to force itself into charging, it is unnecessary to share the ρ for the VA simultaneously. It is therefore suggested to have a single parameter being broadcasted between the VAs, ρ_{bc}, which takes a specific value if the VA wants to inform of its new entrance if it is charging shares its ρ, and otherwise, if it does not want to be charging (because its ρ is too low or no EV is connected).

4.2.4 Final remarks on the strategy

Multiple perspectives have been discussed throughout this section compromising into a strategy. They have provided each their argumentation to provide a single strategy. Changing slightly on one of the objectives or the tightness of the constraints may offer the possibility of going for a very different strategy. The strategy proposed in this thesis is primarily based on a ρ based scheduling which allows a market-based distribution of the limited resource $P_{C,PCC}$. Further, it secures that the VAs can provide a collaborative response to the $P_{ref,CA}$-signal. To increase the efficiency this can secondarily be a mutual response. There is now a foundation for sharing information between decision-making entities. The last objective of the thesis is to provide a robust distributed architecture to support the strategy this will now be discussed.

4.3 Architecture

As the objectives have been merged into a single strategy, the information-sharing and decision-making architecture is to be settled. As architecture is the backbone of communication and decision-making, it has, up until now, been confined and will now be presented explicitly. Some argumentation may seem redundant to previously made arguments but consolidates the decisions made for the architecture.

The point of having a distributed control for EV charging is to have as short control loops as possible without losing functionality. Fast both in terms of few nodes, distance to travel but most importantly reliant and short delays of time critical information.

Information needs to be propagated from those with a flexibility need: TSO, DSO, RES production or PCC measurements, to those providing the flexibility, specifically the EVSE. Decisions may be taken along the path of the information. However, to provide a simple, robust, private and fast-reacting system, data should be aggregated at all nodes, and only the necessary information should be shared with other nodes. This will secure an efficient system which is efficient even when scaled up. It should be mentioned that the architecture considerations defined here only focus on the information and not the topology of how the data is being shared, e.g. on a shared server, directly between all units or passed between physical units.

4.3.1 Information in and out of system boundary

To structure the architecture of a system, the most relevant parameters are where and how the periphery information is available to the system and where the outputs are that the system should control. Participation in flexibility provisioning requires data common to the entire electrical system within PCC can react to FTPCC signals. This may be signals from RES-production, transformer stations, DSO, or TSO. To enable the control loop of the system, its current performance should be provided to the system in terms of $P_{meas,PCC,\Phi}$ measured at PCC.

At the other end of the system, EVSE-specific data inputs $s_{EVSE,i}, i, P_{meas,i}$ are unique to each EVSE. Further, the user input ($E_{req,i}, t_{dep,i}$), which is π-specific, may also be considered to be addressed to each EVSE as $i \in \psi_\pi$. User input is therefore suggested within the ACDC project to have gathered directly at each EVSE. It is also within each EVSE that the only outputs of the system are as each EVSE can control the $\phi_{allowed}$ and $I_{allowed,i}$ again for all $EVSE_i$. It, therefore, suggests that information streams should all end within the EVSEs.

4.3.2 Aggregators

The information crossing the boundaries into the system may be picked up by any aggregator to be processed and further distributed to have the information ends at the EVSE.

As the background suggests, the CA is necessary to connect with the FTPCC interactions. This enables a single 'point of attack' where all FTPCC entities may communicate with the cluster. If the interface updates, the change only needs to be made at the CA point. Further, the calculations may be energy-consuming and require a timed response of the VAs and thus should not be in each VA.

The ACDC project has been presented in Section 2.4 with a Master VA role, which the first VA took with an EV connecting. The purpose was to organise the VA's specific setpoint values. This architecture, therefore, had both a Master VA and the VA as two separate aggregators within the control loop from the PCC. The role of a Master VA should be possible for every VA, so they all have the same information stream available. Lastly, the need for communicating between the VAs who had the role of Master VA was an unnecessary addition to the information flow. It has, therefore, for this thesis, been removed from the structure so that the CA communicates directly to each VA.

As stated above, all the EVSE and session-specific data is directly available at each EVSE. It is, therefore, very compelling to have an aggregator that can swiftly react to the information without the need for any communication. The resulting unit is the VA which controls precisely one set of outputs. It could also have been a VA for each charger, as the EVSEs would share the internal control hardware. However, as this project builds to be scalable, modularity is preferred. If an implementation has VAs residing on the same control hardware, a connection may be formed between those VAs to communicate with high reliability.

4.3.3 Internal information paths

As it has been found that decisions should be taken by two types of aggregators, CA and VAs, the intention is to share a minimum of information between the aggregators while still upholding the functionality. From the CA, it has therefore been determined that it broadcasts three values $P_{ref,CA,\Phi}$. This enables the system to react to any flexibility need it can provide. It has been a goal to avoid information sharing between the VAs. However, this was not possible, as the analysis has shown. It has, though, been possible to keep the information shared as low as possible, and this has resulted in just the parameter $\rho_{bc,i}$ for each $EVSE_i$, containing information if the VA wants to start charging, and in case it is setting; ρ_{int}.

Further, the PCC measurements should be broadcasted for the VAs . This information is specific to the cluster but is bypassed CA handling. This is first of all since the PCC is assumed to be part of the system and geographically closer to the VAs than the CA. It is further a time-critical control loop information where the shortest path possible is preferred, and information is therefore broadcasted directly from the PCC to the VAs.

4.3.4 Proposal for a distributed architecture

From the discussion above of the aggregators and the information streams necessary, the complete distributed architecture proposed for a working place parking lot is shown in Figure 4.4.

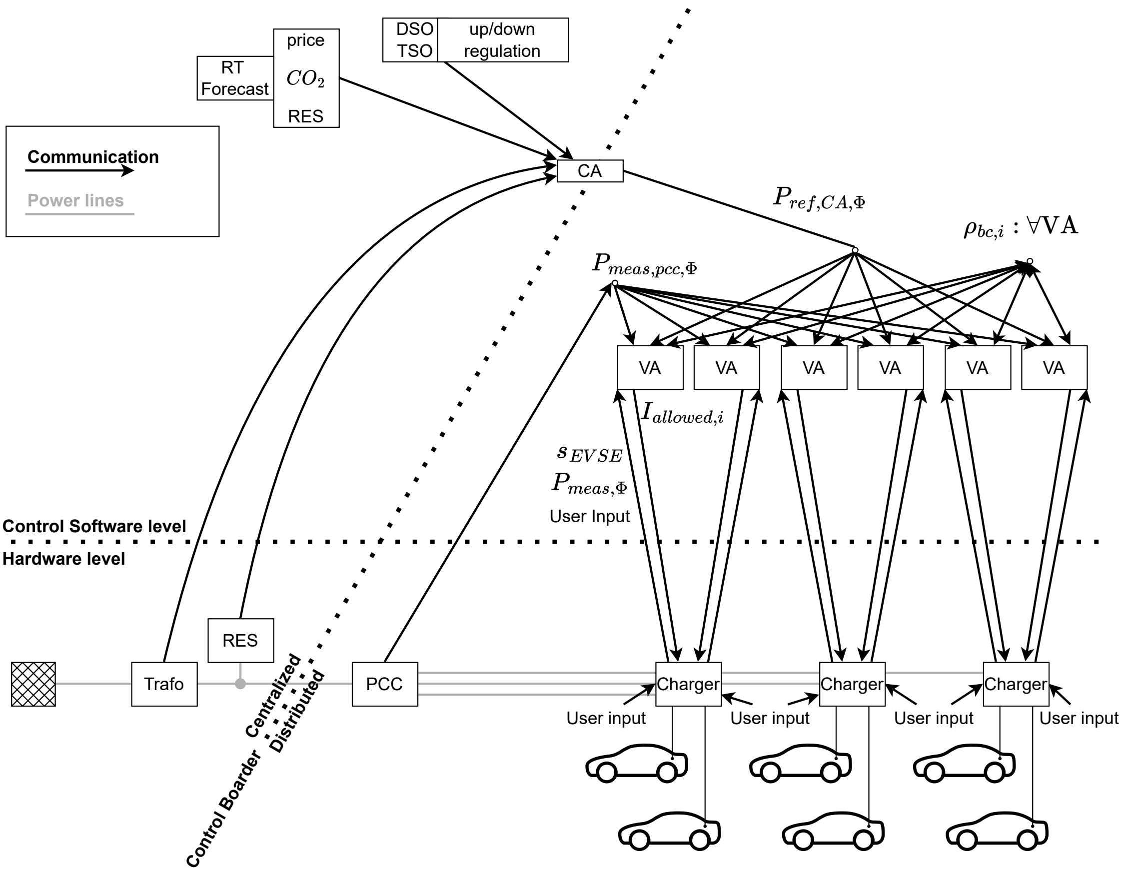


Figure 4.4: The architecture of the proposed system

The figure separates the hardware in the distribution grid from the control software controlling entities with the horizontal dotted line. The diagonal dotted line indicates where the central control domain is separated from the distributed control. The central control suggests that the units report to a single point from which power is individually set. The distributed control can only be extended to this border as the units RES and Trafo is not (yet) enabled for distributed controlling, where their information could be directly shared with the VAs.

As an architecture between the controlling units has been formulated, which supports the wanted strategy, the information available to each control unit has been defined, and the internal control of each unit can now be defined.

4.4 Build of strategy

As it has been settled on how the architecture should be for the system to satisfy the objectives, the internal decision-making of the different units should be defined. In other words, the logic of the entities in the control level of Figure 4.4 should be defined to describe how the strategy is obtained. The role of the CA, as has been discussed previously, is to aggregate the data from entities acquiring flexibility and determine a setpoint, $P_{ref,CA}$, that satisfies their needs. For these decisions, the CA should have a select few considerations and constraints of the cluster implemented in its decision-making. For this thesis, the goal is to operate with local decision-making in the VAs to liberate the CA from these considerations and still obtain the same purpose. The focus of this thesis is purely on the building of a VA control algorithm that is generic and independent of the number of EVs it should collaborate with.

A robust decision-making structure should be built where the possible combinations of inputs and states of the charging session should be considered. A finite state machine is specifically good at handling those and is therefore chosen to be at the heart of the decision-making.

The controller scan cycle is primarily adapted from Programmable Logic Controller and microcontroller architectures and is visualized in Figure 4.5. Each block in the diagram has exclusive rights to write to specific variables, which other blocks may read. One block primarily reads variables written by a block earlier in the scan cycle than itself. It, therefore, follows that the inputs are updated in the internal variables. Internal logic values are calculated, and the output is sent to the periphery output. This structure has high reliability directly in the design, providing a great sense of freedom to the programmer.

When the focus is on the scan cycle, the standard [19] states as normative that the OBC should react to changes in the CP PWM signal within 5 seconds. As different EVs have different response times within the $5\,$sec, it is suggested to keep a scan time for the VA at a minimum of $5\,$sec to free the control from any complexity arising from this random deviation.

The logic included in each block of the VA scan Figure 4.5 will now be described further. Especially the Finite State Machine (s_{VA}), priorities and Power reference are crucial to this thesis.

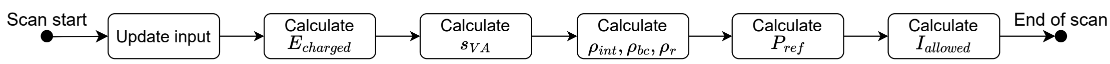


Figure 4.5: VA control scan cycle progress

4.4.1 Update input

Initially, in the scan of the VA, all the external parameters from other control entities or physical changes measured at the EVSE are retrieved and cached as internal variables. All of the necessary parameters for the VA are shown in Figure 4.4 where a separate function within the `update input` for each communication line ensures modularity of the build in terms of hardware and software independence, e.g. the communication line from the CA may change medium or from 3ϕ to Φ and can then be handled in a single explicit location. How each parameter is fetched depends on the hardware implementation and will be further discussed in Section 5.1.

4.4.2 Energy handler

As the first thing to calculate within the VA scan is pure calculations that update parameters dependent on multiple inputs from the physical system, hence the power should be integrated and added to the already charged amount of energy. For the discrete system, this is:

$$E_{charged} = E_{charged,prev} + P_{meas} \cdot \delta t \tag{4.5}$$

Where P_{meas} naturally is measured directly at the EVSE and δt is the time since the last update of $E_{charged}$.

The function here may be omitted in some implementations in case this is directly provided by lower levels of the EVSE system in parallel with P_{meas}, as the scan time of the VA will be at a minimum of 5 sec the precision of $E_{charged}$ may be undesirably low.

4.4.3 Finite state machine

The finite state machine is central to the behaviour of the VA as it defines the s_{VA}. In a dynamic control system as presented in Section 2.4.2, the multiple VAs have similar responses differing by their ρ. Different reaction patterns are necessary to allow new EVs to enter charging sessions and, more importantly, to enable elevated controllability of the scheduling. For different reactions a FSM is introduced in the VAs . s_{VA} is specific to the VA, and any transition between states depends primarily on its input parameters. The particular state of the VA thereby sets deterministic the behaviour of the output of the VA depending on the history seen by the VA.

Figure 4.6 visually explains all the states and their transitions. The states are organized in groups which firstly is based on the usual sequence of the states through a charging session and secondly is based on regions. The three regions, Active, Powered and Enters, indicate states with substantial relations. The Enters-region is explicitly the three states where a VA broadcasts to the other VAs that it needs more power. This broadcast will make all VAs in the Powered-region transition to one of the two making space states. For any non-clarified points in the figure, the purpose of all states and the transitions out of each state will now be further described.

0: Idle

The Idle state is the default state the VAs will take whenever a system restart is initiated. In this state, the VA will be looking for a valid combination of user inputs (E_{req} and t_{dep}) and an EV being present ($s_{EVSE} = \{\texttt{Connected, Charging}\}$). How the user input may affect an ongoing charging is also an implementation-dependent decision, should a user be able to update the to a sooner t_{dep} in case something immediate comes up in their plans. However, for this thesis, it is assumed that the user only inputs data at the beginning of the session and will be constant parameters until the end. The VA will proceed to `starting point` when both conditions are present.

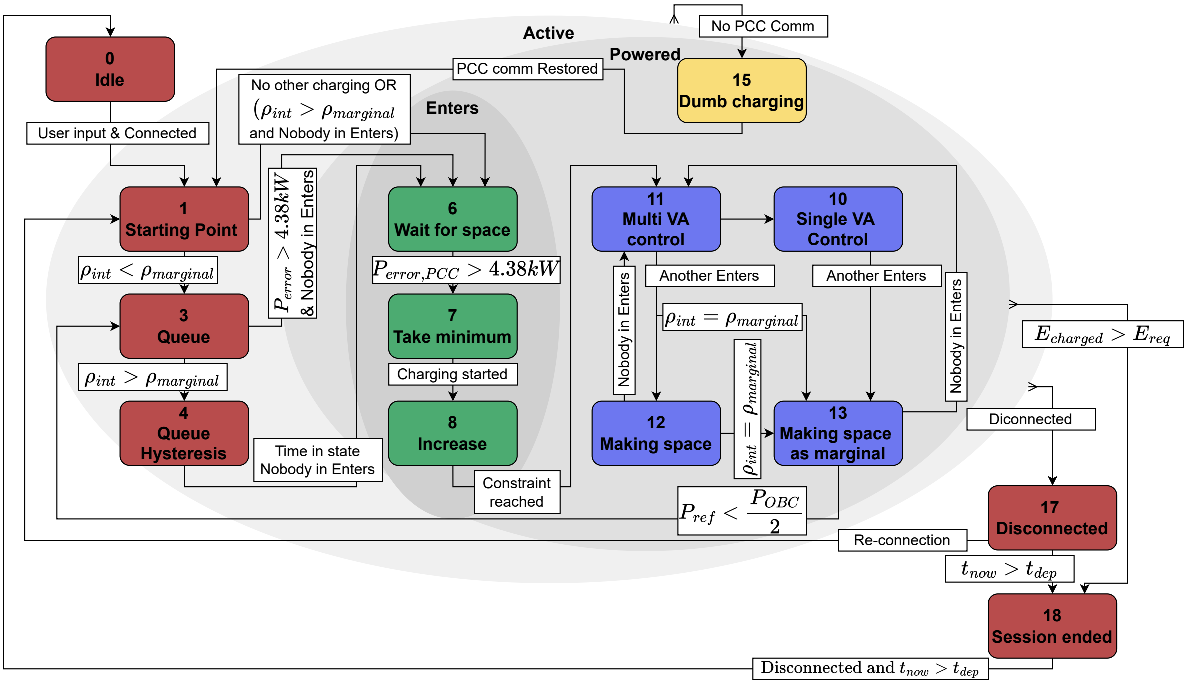


Figure 4.6: FSM, s_{VA}, states and transitions between different states. The grey regions indicate groups with some similar transitions. The colour scheme is further utilized in the result section.

1: Starting Point
The starting point is a decision state where the VA decides how to initiate the charging session depending on the newly specified user inputs and the information available from the other VAs and the PCC. At this state, the VA evaluates the charging status of all other VAs through their broadcasted priority, ρ_{bc} (The parameter will be further detailed in Eq. (4.8), here the information extracted is presented). It evaluates three conditions that may bring this VA to start charging:

1. If no other VA is charging
2. If no other VA is currently entering and this VA has a higher priority than the marginally consuming VA

No other VA may be entering as the system is built only to have one VA starting its charging session at a time. If non of the conditions are satisfied, then the VA may remain in the state, waiting for the entering VA to transition to a steady state charging state. The VA will more likely transit to the queuing state as the internal priority, ρ_{int}, is less than the marginal consuming VAs .

3: Queue
The queuing state is intended for scheduling VAs where immediate charging is not urgent enough to let them charge immediately. This may be both new VAs joining a charging session and VAs that have been 'pushed out' of the Powered-region. In this state, the VA is still active as an EV with proper user input is present; however not powered. When a VA is queued, it constantly seeks any opportunity to charge again. This may come from two conditions. Either the VA sees that the VAs in the Powered-region cannot consume the power requested by the CA, and it will transit to `Wait for Space` (which only is to ensure that it is the only one doing so). The other option is that charging at this VA over time has become urgent as those charging may get a lower priority, and those in the queue will get

a higher priority. If this happens, it will transit into the `Queue Hysteresis` state.

4: Queue Hysteresis
Whenever a VA is queued, there will be a time when the ρ of it has surpassed those already charing. This happens naturally as the EVs not charing will come closer to their departure time without getting any power, whereas those charging will lower their ρ as they charge. When a non-charging VA suddenly changes to have a higher priority than the marginally consuming VA, it should decide when to enter charging. Entering immediately would cause two VAs to have a constant battle to be charging. This would highly impact the overall $E_{C,cluster}$ as the switch will have the power consumption drop-down momentarily. Therefore a hysteresis is implemented, which allows the currently marginally charging VA to charge for a given period before the VA in the queue goes to `Wait for Space`.

The transition out of this state could take many different forms, leading to a more 'true' scheduling or higher security of reaching E_{req} in time.

6: wait for space
This state is the only entrance to allow an actual PWM signal to be sent on the CP line. In this state, the VA has decided that it wants power and broadcasts a signal in the ρ_{bc} that it wants power. This state is also included to ensure that multiple VAs are not simultaneously in the Enters-region. Therefore, the minimum time in this state needs to be one scan time; for the others to know, they should also not go to Enters-region. There is only one transition out of the state, which will be when the VA observes that the PCC has space, namely when the error between the reference and the measured power of the cluster is is large enough to allow starting to charge:

$$P_{error,PCC} = P_{ref,CA} - P_{meas,PCC} \leq 4.38\,\text{kW}_{3\phi} \tag{4.6}$$

7: Take Minimum
When entering this state, the VA has assured that it is the only VA allowed to increase its power consumption and that the PCC has power space to initiate the charging. Therefore, the EV will not be allowed to consume any power until this state. When the EV has responded to the allowance and started charging, the EVSE gets a signal back $s_{EVSE} =$ `Charging`, which is utilized as a transition towards the `Increaser` state.

8: Increaser
In the increaser state, the VA continuously allows the EV to charge with increasing power. The increase of the P_{ref} naturally depends on the power decrease made by the other VAs in response to the broadcast of a need for power. The VA may secondarily utilize this state to conduct empirical evaluations of additional OBC parameters such as 1ϕ or 3ϕ charging and $P_{C,OBC}$. This functionality will, however, not be utilized for this thesis but discussed in the Section 5.1.

When gradually increasing the P_{ref}, other constraints will end as the binding constraint of the charging. When this is the case and the P_{ref} no longer is met by the P_{meas} of the EVSE itself, then the VA has reached the empirically charging limit and no longer needs exclusive access to increase P_{ref} it will therefore make the transition into the normal charging operation state.

10: Single VA Control
Specific parameters can be omitted from the control loop whenever a single VA charges. This will further be explained in Section 4.4.5. Therefore a separate state is included that conducts this behaviour. Therefore, the only specific transition out of this state is if another VA is in Enters-region. Suppose a VA is in this state and another is in Enters-region. In that case, it has already been evaluated that the other VA has a higher ρ, and this VA becomes $VA_{marginal}$ and transits directly to making space marginal.

11: Multi VA Control
This serves as the most steady charging state where the VAs , in collaboration, will be controlling their consumption to the need of the CA. Again the specific control loop is explained in Section 4.4.5. The first VA that has entered or is in a situation where all VAs charging has reached their requested energy, except this VA, will make an immediate transition as it is the only one in the Powered-region. When steadily charging in this state, another event that can cause a transition is the need for a new VA to Enter. If another VA broadcasts a requirement to enter, all VAs in this state will evaluate if they are the marginally consuming VA, hence the VA charging with the lowest $\rho_b c$. If that is the case, the transition will be to the state of `Making Space as Marginal`. Otherwise, it will transit to the `Making Space` state.

12: Making space
A VA will only find itself in this state when another wants to enter, and another VA already charging will be in the `Making Space as Marginal`. Hence the total number of VAs in the Powered-region is larger than 3. In this state, a VA will keep a steady charging power and let the VA entering and the VA in `Making Space as Marginal` handle any necessary control. However, the VAs in this state will still survey if they suddenly become the marginal consumer and then transition to `Making Space as Marginal`. When the VA who was entering no longer broadcasts that it needs the power, a change may again be made back to `Multi VA Control`.

13: Making space as marginal
If another VA is entering, the VA with the lowest priority and charging will be the $VA_{marginal}$ responsible for ensuring that the new VA entering is given the necessary power. Therefore only one VA will be in this state at any given time. As the marginal consumer P_{ref} will steadily decrease, described in Section 4.4.5. If the lower limit of what is accepted as efficient charging power is breached, the VA will transition to the `Queue` state as this VA no longer has priority to participate in charging. Whenever there is no longer a VA broadcasting it enters, a transition back to the steady charging in `Multi VA control` is made.

15: Dumb Charging
Any communication failure will, for this build, lead to a situation where the strategy is impossible to fulfil. Therefore they will lead to this state where the VA will initiate a charge without any input considerations. The VAs caught in this state may return to the regular smart charging operation when the communication is re-established. All VAs will then proceed to the `Starting Point` state as the distributed control units need a renegotiation.

17: Disconnected
If the EVSE finds the cable has been disconnected, it will transit to this state. This may arise from many outside circumstances and may, in most cases, result in a terminated charging session; however, if it were a fault, the charging would still be possible to restart within the same session. If a reconnection is made, the VA will transit to a new decision-making of how to proceed in the state `Starting Point`. If this does not occur, a transition will be performed out of this state again when the departure time given by the user t_{dep} will cause a transition to the `Session Ended` condition.

18: Session ended
The final state that a VA will take within any charging session is to finalize the session after all power has been shut. All variables are reset to default values, and specifically for this build, the VA waits until both the EV is disconnected and t_{dep} is reached. These will be the last conditions of the session and enable the VA to go back to `Idle`, where a new session may start.

General transitions

In addition to all the transitions specific to certain states, The VA needs a few transitions with a broader perspective. From all states in the Active-region, abnormal hardware situations may interfere. For now, two transitions are possible. Firstly a persistent communication failure may cause a shift to the `Dumb Charging` state. Secondly, a stop of the charging session, i.e. $s_{EVSE} = \texttt{Idle}$, cause a transition to the state `Disconnected`. From the more confined Powered-region, there is the apparent transition that the charging may have ended as the $E_{charged}$ have reached E_{wanted}, hence $E_C = 0\,$kW.

4.4.4 Priority

The priority as P_{avg} was already introduced in Section 2.4.2 and is a convenient measure of how urgent charging is for the user. The concepts of a broadcasted ρ_{bc} and an internal ρ_{int} priority have also been introduced in the section above and will now be elaborated upon. The internal priority is, to some extent, inherited from Section 2.4.2. The difference is that ρ_{int} only is an operational parameter when the VA is actively participating in the smart charging:

$$\rho_{int} = \begin{cases} \frac{E_{req} - E_{charged}}{t_{dep} - t_{now} \cdot P_{C,EVSE}} & \text{if: } \texttt{Starting Point} \leq s_{VA} \leq \texttt{Making Space as Marginal} \\ 0 & \text{otherwise} \end{cases} \tag{4.7}$$

Remarks that the two values E_{req} and t_{dep} are constants for the charging session, but t_{now} continuously increases to increase ρ_{int} and whenever the EV is charging $E_{charged}$ increases to lower ρ_{int}. From the implementation in Section 2.4.2, a lesson learned is that power is shared (making those with very high priority get suboptimal power as a sharing strategy). Moreover, the strategy was implemented on a first come, first serve. With the FSM, sharing has now been turned towards a higher emphasis on scheduling. The concept of making space for a new VA has been discussed in Section 4.2, which requires that it broadcast information that it needs to get into the market. This information will be integrated into the priority broadcast to the other VAs :

$$\rho_{bc} = \begin{cases} 0 & \text{if: } s_{VA} \leq \texttt{Queue Hysteresis} \\ 0 & \text{if: } \texttt{Dumb Charging} \leq s_{VA} \\ 1 & \text{if: } \texttt{Wait For Space} \leq s_{VA} \leq \texttt{Increase} \\ \rho_{int} & \text{otherwise} \end{cases} \tag{4.8}$$

As may be seen above, the priority is broadcasted as 0 also when it is in the $s_{VA} = \{\texttt{Queue}, \texttt{Queue Hysteresis}\}$. This makes it possible to distinguish those getting power from those not charging. This differentiation brings forward the ρ_{bc} of the VA, which is at the margin of not being allowed to charge, namely $VA_{marginal}$ and its $\rho_{marginal}$, which also has been discussed with the FSM. That the VAs in the queue does not broadcast their ρ_{int} does, however, come with the downside that they lose the capability to determine which should be the next to enter when capacity is available. This feature is not considered for this implementation as it would be trivial to implement on top, but for long charging sessions it will not be important who gets into charging first.

An additional priority-related parameter is introduced for the power calculations to determine how much responsibility the individual VA has for minimizing $P_{error,PCC}$. A high-priority VA should be eager to increase its power consumption when needed but less willing to decrease its consumption if required. To ensure that the right amount of responsibility is taken, the parameter relative priority, ρ_r, is introduced:

$$\rho_r = \frac{\rho_{int}}{\sum_{i=1}^{N_{cluster}} \rho_{bc,i}} \tag{4.9}$$

Where $N_{cluster}$ is the number of EVSEs in the cluster. Therefore, ρ_r yields the part for which this VA can take responsibility when increasing. And when decreasing $P_{cluster}$ the part which it should not take responsibility of, but rather all the others.

The three parameters ρ_{int}, ρ_{bc} and ρ_r are, therefore, three dependent variables that, in each their way, aid the VA in making decisions that are in alignment with the other VAs who also takes part in the control.

4.4.5 Power reference

The reader should realize how the VA has been prepared to participate in the cluster's behaviour to control the power consumption, i.e. make $P_{cluster}$ to align with $P_{ref,CA}$. The participation depends firstly on s_{VA}, e.g. VAs with no EV connected or in the queue cannot participate. The control loop from the setpoint of the CA has been presented in Figure 4.7. The figure relates to the communication lines in Figure 4.4, but with a focused view on the internal components.

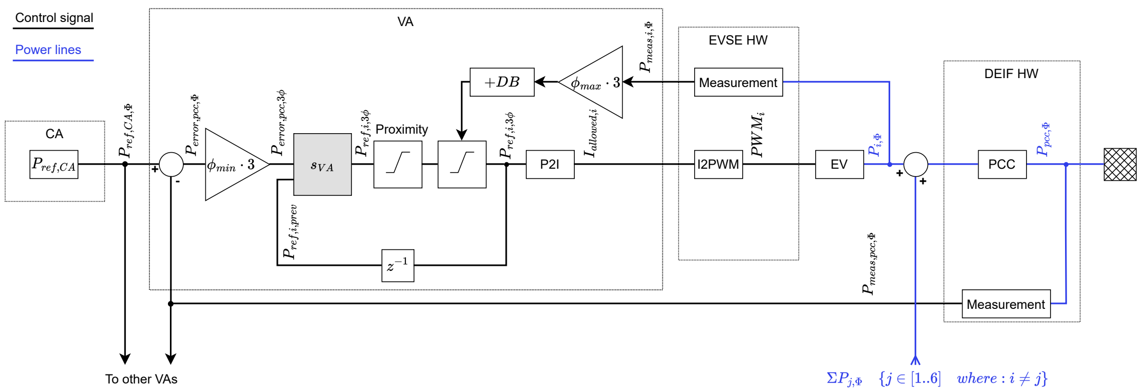


Figure 4.7: The main control loop of a VA.

The CA decision-making provides a continuous data stream of three setpoints values for the cluster, $P_{ref,CA,\Phi}$. One for each phase. This signal is fetched by each VA and subtracted by the measured power of the cluster to yield $P_{error,PCC,\Phi}$. The minimum error is then found and multiplied by 3 to indicate the total amount of power that may be addressed with the output handle availible for the VA (setting $I_{allowed}$). This assumes 3ϕ charging. However, if already charging with $\phi_{allowed} = 1\phi$, it may utilize the specific phase instead. The $P_{error,PCC,3\phi}$ is then fed into the $P_{ref,i}$ block, which has s_{VA} specific behaviour. The two most interesting cases are highlighted in Figure 4.8, where the other states' behaviour may be seen in appendix A.

When a VA has $s_{VA} = \texttt{Single VA Control}$, it knows that it is the only VA controlling the P_{PCC}. Hence it may act as a normal single controller. The selector box in Figure 4.8a has the following outcome:

$$P_{ref,i} = \begin{cases} P_{ref,i,prev} & \text{if: } 0\,\text{kW} \leq P_{error,PCC,3\phi} \leq P_{db} \\ P_{ref,i,prev} + P_{error,PCC,3\phi} & \text{otherwise} \end{cases} \tag{4.10}$$

(a) $s_{VA} =$ `Single VA Control` (b) $s_{VA} =$ `Multi VA Control`

Figure 4.8: $P_{ref,i}$ blocks for the two steady state s_{VA} states. The rest of the states are placed in appendix A.

This indicates that the control system is satisfied with the current power consumption if it is within a deadband below the setpoint from the CA. And if not, this VA will take full responsibility for adding the error to its setpoint. When the case is that a group of VAs is stationary and powered, they will have the state s_{VA} = `Multi VA Control` seen in Figure 4.8b, where:

$$P_{ref,i} = \begin{cases} P_{ref,i,prev} & \text{if: } 0\,\text{kW} \leq P_{error,PCC,3\phi} \leq P_{db} \\ P_{ref,i,prev} + P_{error,PCC,3\phi} \cdot \rho_r & \text{if: } P_{db} \leq P_{error,PCC,3\phi} \\ P_{ref,i,prev} + P_{error,PCC,3\phi} \cdot (1-\rho_r) & \text{otherwise} \end{cases} \quad (4.11)$$

The selector box utilizes the $P_{ref,i,prev}$, when $P_{error,PCC,3\phi}$ is within the deadband, the ρ_r gain when it is otherwise positive and $(1-\rho_r)$ when it is negative[1].

An architecture with deterministic actions has now been developed where the VAs as a cluster are able to respond in accordance with the three objectives for the VA. It is thus time to test it out in real-life implementation.

[1]After testing it has been theoretically detected that the equation will overcompensate when more than two EVs are connected. It should therefore more correctly be: $\rho_r = \frac{(1-\rho_r)}{(N_{powered}-1)}\ N_{powered} > 1$. This does not affect the tests performed for this thesis as it is never tested with more than two EVs in this state.

5 Implementation

To test the build described above, the test setup described in Section 2.4.1 has been used as the foundation; changes have been made as this is a new iteration on the setup that seeks to be a more confined distributed architecture. As the first section title indicates, this is not entirely true to the proposed build of Section 4.4. The discrepancy has been necessary from hardware constraints, which will be highlighted throughout the section, to guide work on the subsequent iterations of the ACDC project. A section then describes the extra testbench functionalities implemented to ensure that the tests can be performed and appropriately visualised. The documentation provided further highlights considerations to establish the best foundation for testing the build's functionality with the setup.

5.1 Emulation of a distributed system

This section will concurrently describe how the implementation of the build has been performed and adapted to the existing hardware. Much of the generic design has been described above and will not be additionally described here. The implementation of this control is mainly produced in Python. The code is stored in a git repository but contains confidential matter. It is, therefore, not reported in this thesis but may become publicly available at a later point.

5.1.1 Central controller emulating distributed control

As also seen in Section 2.4.1, the architecture resembles a central controller, as all code to control is positioned in one unit, giving individual setpoints for each EVSE. This structure has neither been possible to change nor wanted for this first trial of having a distributed strategy controlling multiple chargers. It has not been desired since the central control provides a platform where changes in the control code are easily implemented, and changes in the firmware of the EVSE require too heavy involvement of Circle Consult.

The architecture of the code has been completely transformed from the implementation in Section 2.4.2. A resemblance of distributed architecture with object oriented programming (OOP) was drawn, which provides vital usability. In OOP, the programming is built from the perspective of objects. A key aspect of OOP is encapsulating data and functions into objects (Python: `Classes`). The data is private to each object, and the functions are shared for objects of the same type. The modularity of OOP makes it very convenient for emulating distributed systems.

The control logic of the chargers has therefore been implemented as the `ControlCode.py` code in Figure 5.1 where the controlling part of a charger is emulated as an object, `CH`, and with two `VA` child objects (one for each EVSE). The emulated architecture, therefore, has no impact on the build of the VA in Section 4.4 as they live inside the chargers and only may change the input/output formats, i.e. the object of a CH and VA may be taken directly from the control code and inserted within a hardware charger and function there.

The emulation thereby seeks to have code which inherits that data is only explicitly shared among different units and therefore controlled to the data detailed in Figure 5.1.

5.1.2 Scan cycle and multithreading

However, a compromise of the emulation is made as the distributed control is made single-threaded. An aspect that has to be considered with the method is that `ControlCode.py` puts all the control into a single thread to be run on with a single kernel of the server. With

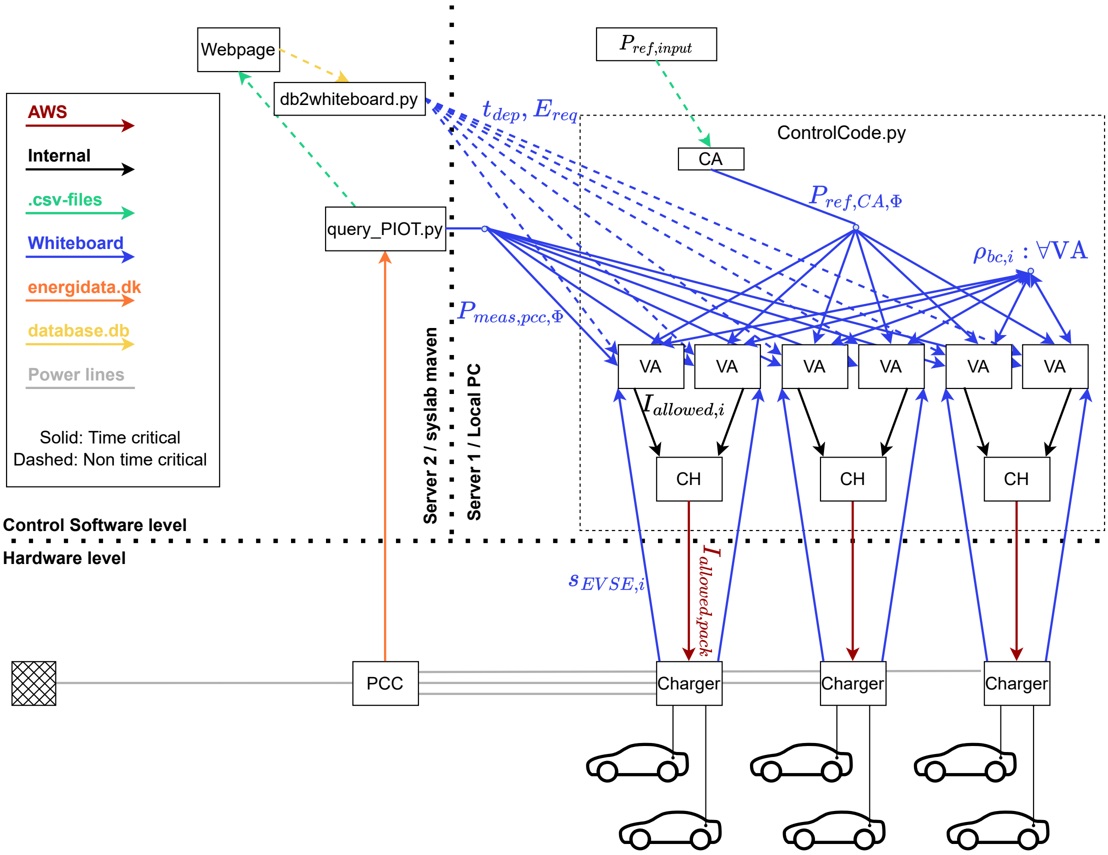


Figure 5.1: The system communication lines with the ControlCode containing objects for chargers and VAs. Only hardware and logic-containing elements are mentioned. Mediums of communication are shown as arrows of different colours.

a distributed architecture, the controllers will run their scan cycle asynchronically and even out of phase. This may cause issues that will not be sighted with this testing method.

The scan cycle of the `ControlCode.py` has further been set to 10 sec plus an additional 0.1 sec per charger to allow time between sending packages to AWS. This will not stress the system from the control engineering perspective as the controlled real-life system should respond to changes within 5 sec. It was in the preliminary tests found that the communication to AWS was interrupted when running below 10 sec. It is a parameter that could later be an optimization investigation.

Therefore, the combination of the two aspects mentioned above assures unintendedly that approximately 10 sec pass after the last change of any PWM signal until the following scan of the VAs is initiated.

5.1.3 Communication lines

It can further be seen in Figure 5.1 that all communication of inputs to the VAs has now been transferred to propagate through Whiteboard. During the building of the architecture, it has been an ongoing issue to get through firewalls with publicly accessible data, such as user input and visualization on the one side and connection to AWS on the other. As the final system is thought to have user inputs directly at the chargers, this is not seen as a problem of priority. All ControlCode communication has been made as links in Whiteboard to work around the firewall. The ControlCode has been liberated on the input side and may be positioned in any domain dependent on the AWS needs. The modular implementation which has been described in the Build Section 4.4 enables to replace of the inputs to more secure connections from the CA, PCC and other VAs when the control functions have shown its applicability and should be prepared for further implementation.

5.1.4 EVSE measurement feedback

Another deficit impacting the implementation is the direct feedback on the charging process. As may be seen in Figure 5.1, the VAs only gets s_{EVSE} as feedback from the EVSE. The parallel development within the hardware has not been able to provide measurements directly of the power flow through the EVSE. It is a critical issue for the current strategy but is expected to be implemented later as it is essential information for users' billing. For the implementation, the feedback of the $P_{meas,i,\Phi}$ has therefore been omitted and does not provide a limit of the $P_{ref,i}$. The control loop in the VA, thus, may unintendedly operate with an unwanted large error between the $P_{ref,i}$ and the actual $P_{i,\Phi}$. This will generate a slower response to a lowering of its power consumption, which may cause other VAs to respond before this VA provides any response on the $P_{PCC,\Phi}$. The case further disables the VA to evaluate the $P_{C,OBC}$ and whether it is a 1ϕ OBC as sought in Section 4.4.3 $s_{VA} = \texttt{Increaser}$. Without this information, the VA may get stuck in $s_{VA} = \texttt{Increaser}$ as the expected power consumption is not reached, which would make the VA transit to the Controlling states.

5.1.5 User input from webpage

Another difference seen between the proposed build in Figure 4.4 and the emulating system in Figure 5.1 is the user input. Again, the hardware is not currently able to communicate with the users. The user communication is therefore provided by the ACDC webpage Section 2.4.1. The script, `db2whiteboard.py` developed within this thesis runs on the webpage's server. The script runs every $10\,$sec to search the database for any valid entry and send the E_{req} and t_{dep} to Whiteboard for each VA to react upon.

5.1.6 Continuity of the runtime

Another issue caught in the preliminary testing was the code's continuity. In the first implementations that included a changing $P_{ref,i}$ $i \in \{1..6\}$, the code stopped after a period of up to $2\,$h. For the ACDC project, it is essential to have a system that can also run when it is not supervised with operators ready to restart the code.

As code seldom crashes from internal errors, it was found that the issue was within the communication with other entities. Bugfixing showed that when the data was sent to AWS, it required feedback from the AWS that the message was received; otherwise, the third-party functions would cause the code to stop. Therefore, every location with inputs or outputs has been enclosed in an exception-handling routine. The output communication drops a message in the terminal of which communication is lost, and the code may continue. A default value (usually a specific negative value) for the input has been set for the parameter. This enables the following program to know that communication is lost and may react to it, e.g. by going to $s_{VA} = \texttt{Dumb Charging}$.

5.2 Testbench functions

In addition to the developed system described above, a few extra functions have been made to surround the system with an environment where it is possible to perform all the tests. As the tests are performed on real hardware and with real EVs and a beta setup for taking user input, this is all at a point where it should be. However, the generation of the signals that the CA broadcasts to the VA and the data output are testbench parts necessary to test but should be kept separate from the implemented code. Further development has also been done to ensure smooth debugging throughout the testing.

5.2.1 Debugging of system

The whole setup on which the strategy tests have been performed has multiple parallel development tracks, and faults have been shown to occur throughout the control loop. This brought up the need for a simple open loop controller in which an individual $I_{allowed}$ could be sent through AWS to the EVSE hardware from the control code. This open control allowed for fast testing of the hardware, if it was able to charge and able to react to a change in the $I_{allowed}$.

The other way arround the code was also made to enable debugging of the software. This was simply implemented with a question for the operator when starting the script if the output of the code should be published to AWS. This option was utilized when running a new function for the first time and check if it had an expected behaviour.

5.2.2 Emulation of CA signal

The script `Gen_P_ref_for_CA.py` has been produced to generate the power reference signal, which may be the output of any computation of the CA. The script creates a series of timestamps and $P_{ref,CA,3\phi}$ values representing a constant, steps or sinus power setpoint signal. The steps and sinus have a maximum and minimum power setpoint and sampling time (time between steps), and further, the step function has the step size in kW. These essential functions enable simple tests which provide great insight into the system's behaviour. The script may be run on a different kernel parallel to the ControlCode.py of the Local PC to generate/overwrite the file P_ref.csv-file. This enables the test system operator to change the setpoints, directly affecting the running control code. The `CA` will then read the P_ref.csv-file for each scan, take the most recent value from the time series, and broadcast it to the VAs in Whiteboard. The most recent value ensures that the CA still has a value to broadcast even if the file has not been updated with new fitting time series. However, it will just be running with the constant of the last value in the time series. It is also be noted here that the P_ref.csv file contains 3ϕ-values- where the only logic inside the CA is to distribute the power equally into each phase for a Φ-signal, a power reference for each phase.

5.2.3 Data logging

Lastly, the emulation of the system requires data to be extracted. This has been one of the arguments for keeping the single-threaded emulation and reporting this thesis. With all the code running in `ControlCode.py`, the data logging has been possible to implement as a non-intrusive and straightforward part of the code. Non-intrusive as it is completely separated from the controlling code and only takes the object's stored variables at the end of each scan and extracts them into its data structure, a `dict`. This way, the data logging is inherent in the control code and will not be passed on when the `Charger.py` and `VirtualAggregator.py` code is passed to an actual implementation. When the code is implemented, a different method for data logging needs to be developed. The logging implemented in the Conctrolcode is stored in a `dict` which is stored in the file CCLog_<final_timestamp>.csv-file (CC, in this case, referring to ControlCode, and the <> is a placeholder) as a timestamp time series when the code is stopped. The same file format is utilized with the data logged in prova2.csv by `query_PIOT.py`, developed before I initiated the project. This file both contains the PCC measurements and s_{EVSE} and is logging at approximately 1 sec sampling time. With the two .csv-files mentioned above and the manual control input file P_ref.csv from the emulation of the CA signal, all the necessary data for evaluation of the cluster's behaviour is gathered and ready to be utilized for the tests.

6 Results and Discussion

6.1 Overview of tests

In this section, an overview and introduction to reading the results of the tests conducted are provided, followed by a detailed analysis of five different tests that offer valuable insights into the system's functionality.

Tests have been selected and designed to provide insight into the dynamics of a larger cluster, the relative drop may seem high when an ev goes to zero for another to take over, however, the relative drop of the cluster will be less as the cluster increases. Throughout the tests, it is the intention to test all the significant transitions in the FSM Figure 4.6 by letting one VA pass it.

All the tests described below have been performed on the same code. It is, therefore essential to highlight that no manual settings have been necessary to switch between different modes for different tests to showcase the abilities.

The first two test shows how the system reacts to different user and EV behaviour. Test three and four show how the system responds to changes in the $P_{ref,CA}$ signal with a single VA and two competing VAs controlling, respectively. The final test shows how the system will react to a communication failure. The test cases will be described with the purpose of the test, the testing procedure and thereafter the actual outcome of the performed tests will be displayed and discussed. Some tests have time intervals of particular interest, which will be further highlighted.

6.1.1 General conditions for the tests

For the tests, a few conditions have to be satisfied by the EVs to get a For all tests, EVs are utilized with $SOC = 15$ % to 85 % as the EVs charging behaviour is assumed constant in this region. The upper limit will therefore be considered when entering the user input data.

Furthermore, the tests will only be carried out with 3ϕ EVs as the system is unable to determine if an EV only charges 1ϕ and will therefore not be able to react accordingly.

6.1.2 Introduction to reading the test result figure

A short introduction to how the result plots are read should be made. The plots gather many parameters that will dynamically affect each other. Each pair of VA, EVSE, plug, and its connected EV will have the same ID number and colour code throughout the plots in this Results section (one EV may be connected to different EVSEs and thereby have an other ID). Refer to the first test Figure 6.1 for this introduction. s_{EVSE} refers to the published by the EVSE to Whiteboard and is closely related to the voltage level of the CP (see: Section 2.1.2). EVs may be in `connected` either because charging has not started yet, as user input needs to be present, they are in the queue, or charging has ended. Which of the three may be seen in the plot below: s_{VA} is also a digital state variable and thus can take any value from Figure 4.6. The plot only has labels for a select number of states. The background colours of the figure refer directly to the colours of the state machine in Figure 4.6 and should give the reader a good understanding of the immediate behaviour of the VA. The following plot of the priority ρ also indicates much of the behaviour and both have the internal, ρ_{int}, and broadcast, ρ_{bc}, where the internal is utilized for its own decisions and the broadcast states how others should react to it. The reader may be reminded by this figure that $\rho_{bc} = 1$ for any VA in the green `Enters` group of s_{VA}. The last plot shows the actual results of the system's performance in power consumption. All values are on a 3ϕ base, hence the sum of the three phases. By looking at the control loop in Figure 4.7 it may be observed that the minimum error, ϕ_{min} is utilized therefore being a source of the discrepancy between $P_{ref,CA}$ and $P_{meas,PCC}$ as some EVs have an unbalanced consumption on the 3 phases. Also, keep in mind that the $\sum_{i=1}^{N_{cluster}} P_{ref,i}$ ideally should match $P_{ref,CA}$ and thereby also $P_{meas,PCC}$ however as there is no feedback for this system it will not always be the case.

As we have been through the basic interpretation of the figures, the reader is assumed to know the dynamics represented in the result figures.

6.2 Making space

As mentioned in the method, the users' perspective should be considered and instantly allow a user with high priority to start charging immediately. To showcase this, a cluster with $P_{ref,CA} = 21$ kW has been set up where three EVs connect, with new EVs always connecting with a larger priority than the prior. After charging the high-priority EV, the others should regain the power to charge until they have fulfilled the $E_{req,i}$ given by the user.

For this test, the following procedure was followed:

1. Set a constant reference signal from CA: $P_{ref,CA} = 21$ kW
2. **Plug 3:** Connect BMW i3 with user input: $\Delta t = 1$ h, $E_{req,3} = 5$ kWh,
3. Wait for steady consumption.
4. **Plug 4:** Connect Renault Megane with user input: $\Delta t = 0.75$ h, $E_{req,4} = 5$ kWh,
5. Wait for steady consumption.
6. **Plug 5:** Connect Peugeot 208e with user input: $\Delta t = 0.5$ h, $E_{req,5} = 5$ kWh

The energy needed for the entire cluster is therefore 15 kWh within 1 hour, which scheduling enables to reach. The input for the Peugeot 208e is, however more critical with a $P_{avg} = 10$ kW which is close to the OBC capability of 11 kW.

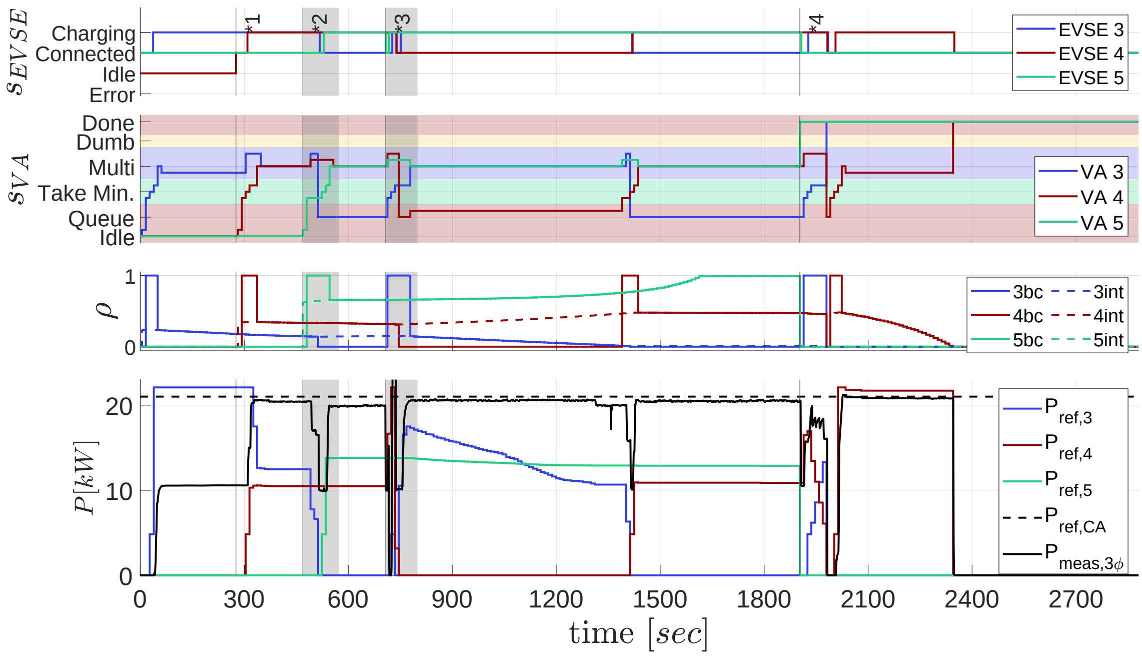


Figure 6.1: Results of the ability to make space. At mark *2 and *3 is further described in Figure 6.2 and Figure 6.3.

It is seen in figure Figure 6.1 that charging starts when the first EV connects and is given more power on $P_{ref,3} = 22$ kW than the EV can consume (seen on $P_{meas,PCC} = 10.5$ kW). When the second EV connects at mark *1 and starts charging VA 3 assures that it gets the requested power by decreasing $P_{ref,3}$. As $P_{ref,3} > P_{EV,3}$ this has no real effect on the power consumed by EV 3. Now after mark *1 the two EVs have a combined consumption close to $P_{ref,CA}$ and when EV 5 connects it overtakes the power consumption at mark *2. The dynamics of the overtaking are further discussed below with Figure 6.2. After mark *2, we have the wanted situation where the two EVs with the highest ρ are charging, namely EV 4 and 5. This should be a steady charging until one reaches a lower priority than VA 3 in the queue. However, a situation occurs at mark *3, which is further discussed with Figure 6.3, which shuffles the charging and suddenly VA 3 and 5 is charging where VA 3 has a lower priority than VA 4 in the queue. Therefore observed that $s_{VA,4} = \texttt{Queue\_hysteresis}$, where it stays for 10 minutes before it again takes over charging.

In the period where all 3 EVs are connected, between mark *3 and *4, it is further observed how the priority of VA 5 is increasing to 0.99. The total time given for VA 5 from the start of charge to t_{dep} is 22 min as charging has to be initiated with the key present for the Peugeot. Therefore the $P_{avg} = \frac{5\,\text{kWh}}{22\,\text{min}} = 13.6$ kW which is more than the the Peugeots $P_{C,OBC}$ and therefore impossible to reach within t_{dep}. In other words, the priority increases as the denominator increases faster than the numerator in Eq. (4.7). As the result shows the VA keeps charging with $\rho = 0.99$ from 1613 sec to 1903 sec to ensure that the negotiated energy is reached. This could represent a pricy option chosen by a user who wants to leave as soon as possible but needs a certain amount of energy to reach their next charge point.

As the PCC has a $P_{C,PCC} = 22$ kW, any combination of user input that combined goes above this should be avoided. For this system where $P_{C,PCC} = P_{C,EVSE}$ which normalizes the ρ function, a sum of all priorities should never be above 1. If that is the case then the average power wanted by the users is higher than the power the cluster may provide and some users will not be charged. This should be considered when designing the pricing function in Eq. (4.3).

6.2.1 *2 Zoom: Taking over power

A deeper dive into the dynamics when one VA takes over power is highlighted with Figure 6.2 where the full-time scale is 100 sec just after the takeover is initiated at mark *2. The process is initiated as user input becomes present for VA 5, and it seems that its $\rho_{int,5} > \rho_{bc,j}\ \forall j \neq 5$, and therefore goes to $s_{VA} = \texttt{wait\_for\_space}$ and broadcasts $\rho_{bc,5} = 1$. In the next scan cycle of the centralized control format, all other charging EVs adapt. VA 5 goes to the stationary power output state $s_{VA} = \texttt{Making\_space}$ and VA 3 with the lowest ρ_{bc} transits to $s_{VA} = \texttt{Making\_space\_as\_marginal}$. The latter therefore now takes the role of gradually scaling down $P_{ref,3}$. As it reaches below the efficient charging limit it stops charging and transits to $s_{VA} = \texttt{Queue}$. When the marginal consumer stops charging the $P_{error,PCC}$ is sufficient for VA 5 to initiate charging and $P_{meas,PCC}$ increases back up to the control deadband of 1 kW within the $P_{ref,CA}$. All in all, the manoeuvre to take over power functioned as intended with a total energy transfer loss of approximated as the integral between $P_{meas,PCC}$ and the steady consumption of $P = 20$ kWh:

$$\text{section 1:}\quad qE_{loss,1} = 4\,\text{kW} \cdot \{495\,\text{sec to } 515\,\text{sec}\} = 4\,\text{kW} \cdot 20\,\text{sec} = 0.022\,\text{kWh} \tag{6.1}$$

$$\text{section 2:}\quad E_{loss,2} = 10\,\text{kW} \cdot \{515\,\text{sec to } 545\,\text{sec}\} = 10\,\text{kW} \cdot 30\,\text{sec} = 0.083\,\text{kWh} \tag{6.2}$$

$$\text{total:}\quad E_{loss} = E_{loss,1} + E_{loss,2} = 0.11\,\text{kWh} \tag{6.3}$$

6.2.2 *3 Zoom: Overcompensating scenario

In this short timescale, the input acts unexpectedly for the algorithm forcing it to generate an unintended output. The outcome has already been discussed above that a VA with lower priority pushes the marginal consuming EV down into the queue. As may be seen in Figure 6.3 the trigger is when EVSE 5 with the Peugeot suddenly changes from charging to connected. This is caused by the behavior of the Peugeot that immediately stops charging when the keys are brought near the vehicle, as if 'now the user needs the EV and charging should stop'. The VA has not implemented any logic to react to this behavior and stays

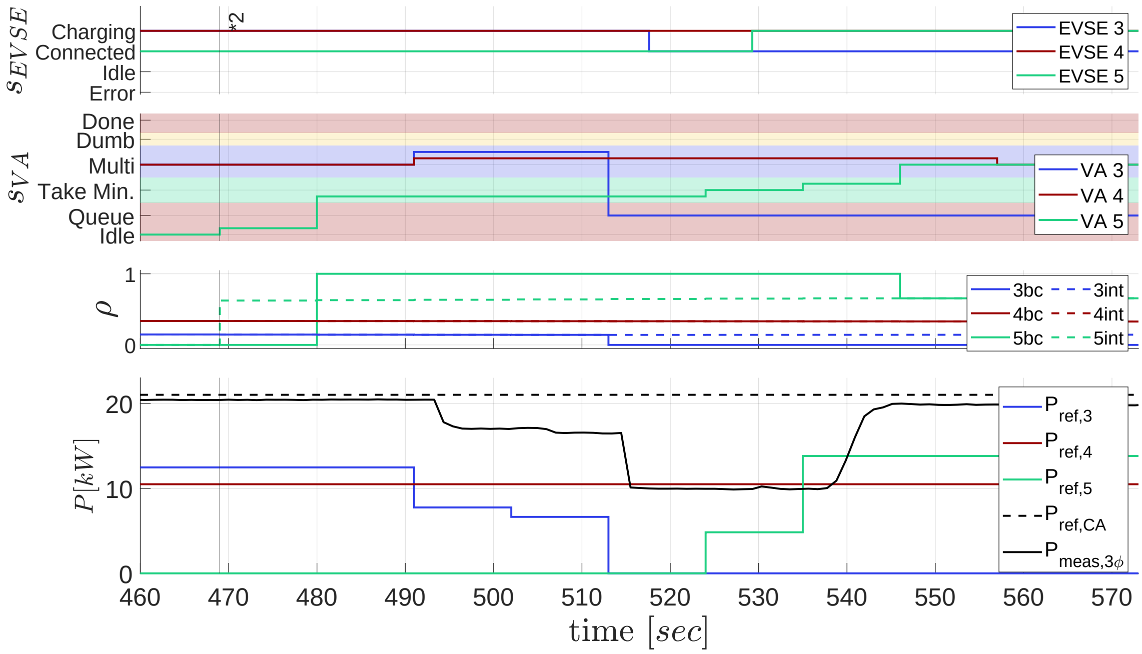


Figure 6.2: Zoomed in view on mark *2 to highlight the dynaics in the switch.

in s_{VA} = `Multi_VA_Control`. This leaves a $P_{error,PCC} = 10$ kWh which is seen by the other two VAs . VA 4 with the Renault that has a $P_{C,EV} = 22$ kW ramps up the $P_{ref,4}$ to close the gap. VA 3, who is in the queue, reacts by entering the charging market and starts charging as it still sees a positive $P_{error,PCC}$. To sum up, at 725 sec consumption is at 0 kW, leaving VA 3 and 4 to ramp up. And simultaneously the Peugeot at EVSE 5 is restarting its charging. Leaving all EVs in a ramp-up state. It is therefore seen that $P_{meas,PCC}$ reach 33.5 kWfar above $P_{ref,CA}$. When the cluster still is in the states to allow another to enter, the marginal consumer (VA 4) and the VA entering (VA 3) are those reacting to the $P_{error,PCC}$, and both react by bringing charging to a stop. At 746 sec VA 4 transits to the queue as it assumes no power is available for it any longer, and VA 3 can take over as usual again.

This case is surely something that can and should be prevented in any commercial implementation. A recommendation to EV producers is that EVs should aim at a more continuous charge pattern. Similarly, the VA control should be allowed a certain period of instability of the error between the $P_{ref,CA}$ and $P_{meas,PCC}$ before VAs initiate the transition from the queue to actual charging. A simple note also is that it should be prevented with less aggressive control algorithms.

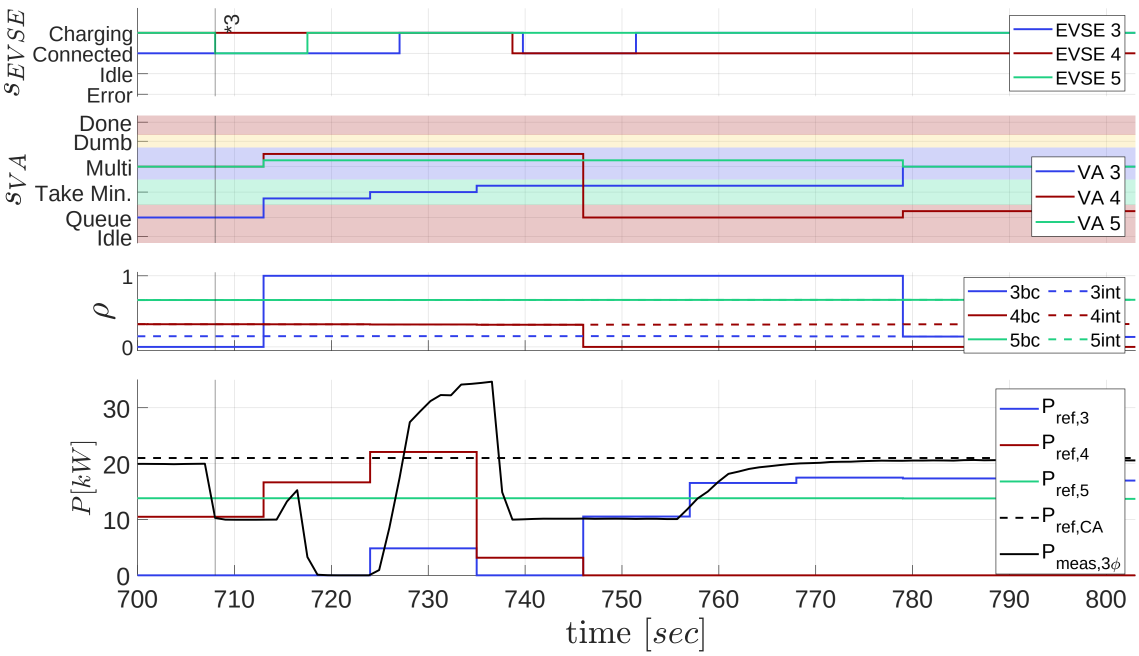


Figure 6.3: Zoomed in view on mark *3 to highlight a case of overcompensation.

6.3 Scheduling of long term charging

This test will showcase the dynamics of priority and scheduling by having two EVs with long-term charging sessions. The two EVs will have the same departure time but with different energy demands and should showcase how they both end their charging within a short time of each other.

1. Set a constant reference signal from CA: $P_{ref,CA} = 11$ kW
2. **Plug 3:** Connect Volvo XC40 with user input: $\Delta t = 3$ h, $E_{req,3} = 20$ kWh,
3. Wait for steady consumption.
4. **Plug 5:** Connect Renault Megane with user input: $\Delta t = 3$ h, $E_{req,5} = 10$ kWh,

$P_{ref,CA}$ is set below $E_{C,cluster}$ as this brings the PCC constraint down to the same as for one EV. This helps showcase the scheduling and makes the algorithm more reliable when the EVSE has no 'private' power measurement feedback. As the PCC is set to not consume more than 11 kW the two EVs should be able to charge within: $t = \frac{30\,\text{kWh}}{11\,\text{kW}} = 2.72$ h.

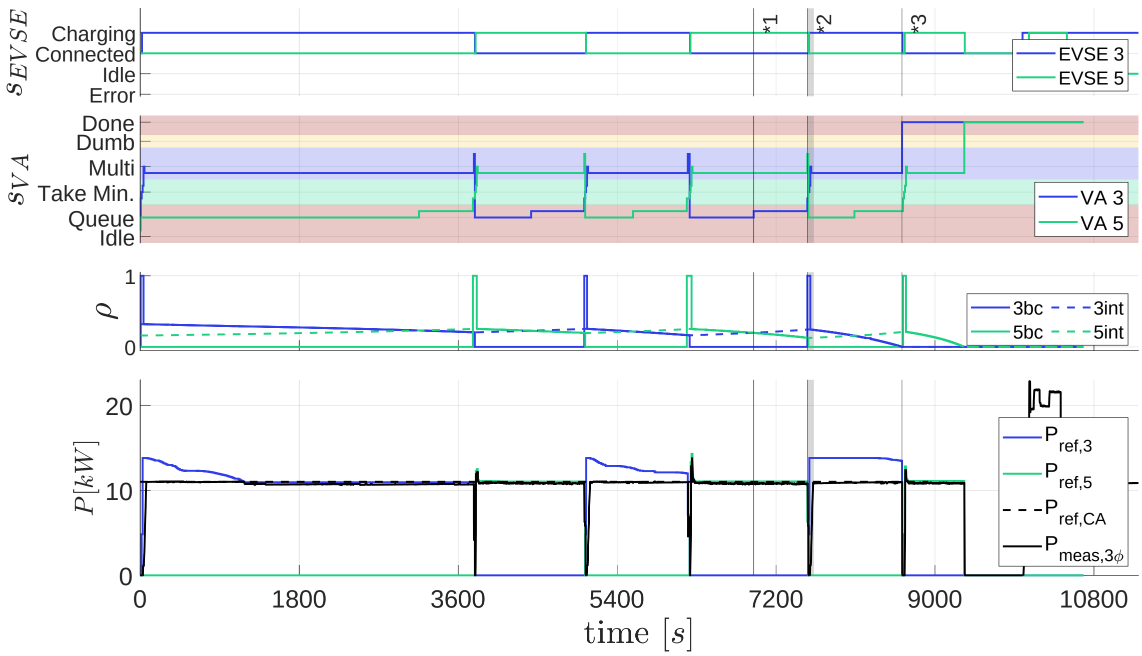


Figure 6.4: Results of long term charging. Mark * 2 is zoomed in in Figure 6.5

It can be observed in Figure 6.4 how the test with the above recipe has been performed. For the first hour, EV 3 is changing steadily at the 11 kW power set by the CA. VA 5 can be seen in the queue as it immediately found that $P_{error,PCC}$ could not allow a VA with lower priority than those already charging to intervene. After the first hour follows two hours with a distinct charging pattern. Mark *1 and *2 showcases two consecutive events of the pattern and have been chosen in the finishing part as the control parameters are more apparent. At mark *1, it is observed that VA 3 transits to s_{VA} = `Queue_Hysteresis` as it now has a larger ρ_{int} than the marginal charging VA broadcasts. VA 3 then waits in the hysteresis for 10 minutes until mark *2 which is more elaborate in Figure 6.5. At mark *2 VA 3 has determined that after waiting for the 10 min it should start its charge and goes into the `Entering` region where it broadcasts a $\rho_{bc,5} = 1$. VA 3 reacts by going directly to s_{VA} = `making_space_as_marginal` and puts down its power consumption. First to a $P_{ref,5} = 6.3$ kW. Then at the next scan, the `cal_state` sees that $P_{ref,5,prev} < 6.9$ $\text{kW}_{3\phi} = 10$ A, and therefore puts the VA into the Queue and charging stops. When VA 5 has stopped a normal initiation sequence is performed by VA 3, where the OBC connected exhibits a smooth ramp up of the power consumption which is approximately 35 sec.

In Figure 6.5 a loss of energy transfer is observed. 40 sec of 10 kW power lost for every switch, which gives a lost energy transfer of 0.111 kWh. Which has less impact on $E_{C,cluster}$ than the other options discussed in the method section for detecting new users. However, it could be better with a more true scheduling algorithm where any VA is parked in the queue.

In order to reach real scheduling the transition criteria from the queue could be altered from having higher priority than one charging to just putting itself in the back. This does however require that the P_C of the EV is known as it is essential for this calculation. Otherwise, it becomes a gamble of 'how long do I trust I can be not charging before I need to get back in'. And further, any 'miscalculation/misestimation of EVs would hit customers very unevenly.

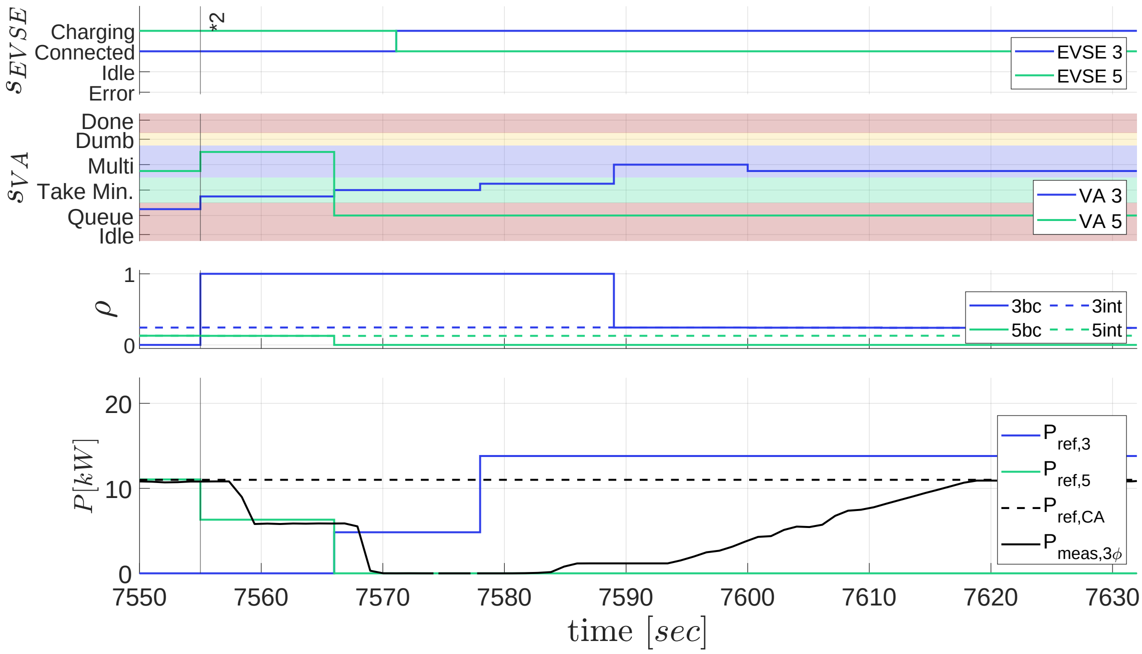


Figure 6.5: Zoomed in view on mark *2 to highlight the dynamics in the switch.

6.4 Varying CA reference signal with a single EV

Above it has been shown how the system functions with respect to distinct user behaviours and satisfies their needs. The focus will now move to how the system reacts in regards to the grid, more specifically, the $P_{ref,CA}$ signal. As the system operates under two different modes, if there is a single or multiple EVs connected a test of both will be performed. First, a test with a single EV will be conducted where a generated step down and up signal is imposed by $P_{ref,CA}$. The procedure is as follows:

1. Set a constant reference signal from CA: $P_{ref,CA} = 21$ kW
2. **Plug 4:** Connect Renault Megane with user input: $\Delta t = 1$ h, $E_{req,4} = 5$ kWh,
3. Wait for steady consumption.
4. Change to a constant reference signal from CA: $P_{ref,CA} = 14$ kW
5. Wait for steady consumption.
6. Change to a constant reference signal from CA: $P_{ref,CA} = 21$ kW
7. Repeat from step 4 a couple of times

For this test, the Renault Megane is utilized which first of all deviates by having $P_{C,OBC} = 22$ kW, but also has in preliminary results shown to be very aligned on the consumption of all

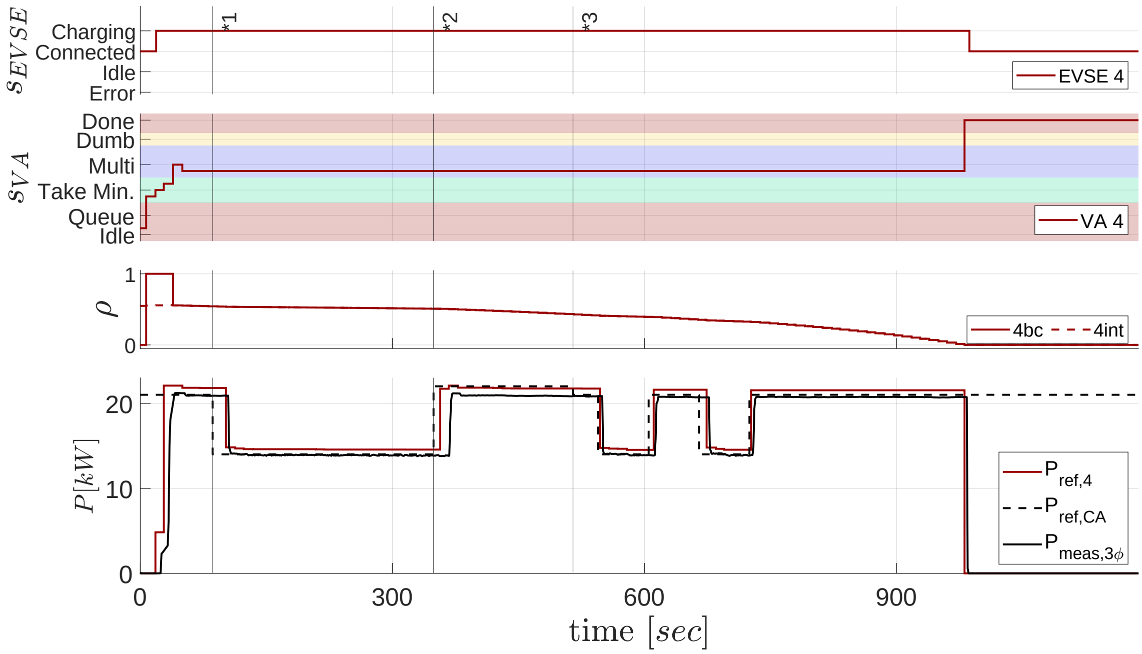


Figure 6.6: Result of a single VA response to changing $P_{ref,CA}$.

It should be reminded here that this only tests one VAs ability to adapt the power output and therefore does not test the collaborative decisionmaking as the VA is steadily working in $s_{VA} = \texttt{single\_VA\_control}$. Throughout Figure 6.6 it can be seen that the VA and EV in collaboration alter the control signal and thereafter the $P_{meas,PCC}$ to accommodate the reference signal from the CA. Explicitly at mark *1 the $P_{ref,CA}$ changes from 22 kW to 14 kW which is followed by the VA reference signal 16 sec later and the measurement again reacts 2 sec after that and stabilizes at the new setpoint within 3 sec more. The `ControlCode.py` is set to run the code every 10 sec $+ 0.1 \cdot N_{chargers}$, and can therefore not explain the 16 sec delay alone. But a communication failure is suspected as the change at mark *1 is the only change with a delay more than 10.2 sec. The most likely is that the CA could not read the `.csv` file, which could have been non-readable during the write of the new values. In this case, it defaults to the previous value stored in the CA internal memory. Another point could be when the CA writes its internal value $P_{ref,CA,\Phi}$ to Whiteboard for the VAs to read them. At mark *2, the step is in the other direction, which from the control perspective has no effect, but the OBC reaction may be observed slightly slower as the ramp-up time should be more controlled where the ramp-down acts to be below the allowed current as fast as possible.

Mark *3 in Figure 6.6 highlights a slight change in the power reference which is caused by an operator mistake to have inserted 22 kW in the first place. The $P_{ref,5}$, therefore, ends higher than the OBC is capable of. No immediate response is therefore seen at *mark 3 as $P_{meas,PCC}$ still is below the new $P_{ref,CA}$

Related to this test is a theoretical observation. This system is later tested if a communication fault occurs between the PCC and all VAs . However, a much worse scenario could play out for this system if every VA loses connection to the other VAs and therefore would conclude that they should be in $s_{VA} = \texttt{single\_VA\_control}$. This would cause an extremely overcompensating system and should be avoided with the same measures as when PCC communication is lost.

As a single VA, it is capable of providing flexibility within its abilities. The time delay currently depends primarily on the scan cycle time of the VAs . The scan cycle time should be possible to get down to 6 sec (5 sec for EV to react according to [19] and 1 sec to sample the measurements at PCC and provide it for the VA again) without causing oscillation.

6.5 Varying CA reference with two competing EVs

As mentioned in the previous section, the more interesting case in relation to distributed control should also be tested. Namely when multiple EVs charges simultaneously and reacts in collaboration to changes in $P_{ref,CA}$. This will be tested through both a step response and a triangular step sequence as follows:

1. Set a constant reference signal from CA: $P_{ref,CA} = 22$ kW
2. **Plug 4:** Connect Renault Megane with user input: $\Delta t = 1$ h, $E_{req,4} = 5$ kWh,
3. **Plug 5:** Connect Peugeot 208e with user input: $\Delta t = 0.5$ h, $E_{req,5} = 5$ kWh
4. Wait for steady consumption.
5. Change to a constant reference signal from CA: $P_{ref,CA} = 14$ kW
6. Wait for steady consumption.
7. Change to a constant reference signal from CA: $P_{ref,CA} = 21$ kW
8. Set an triangula step signal from CA: $P_{ref,CA} = \{21$ kW to 15 kW : 2 kW every 20 sec$\}$

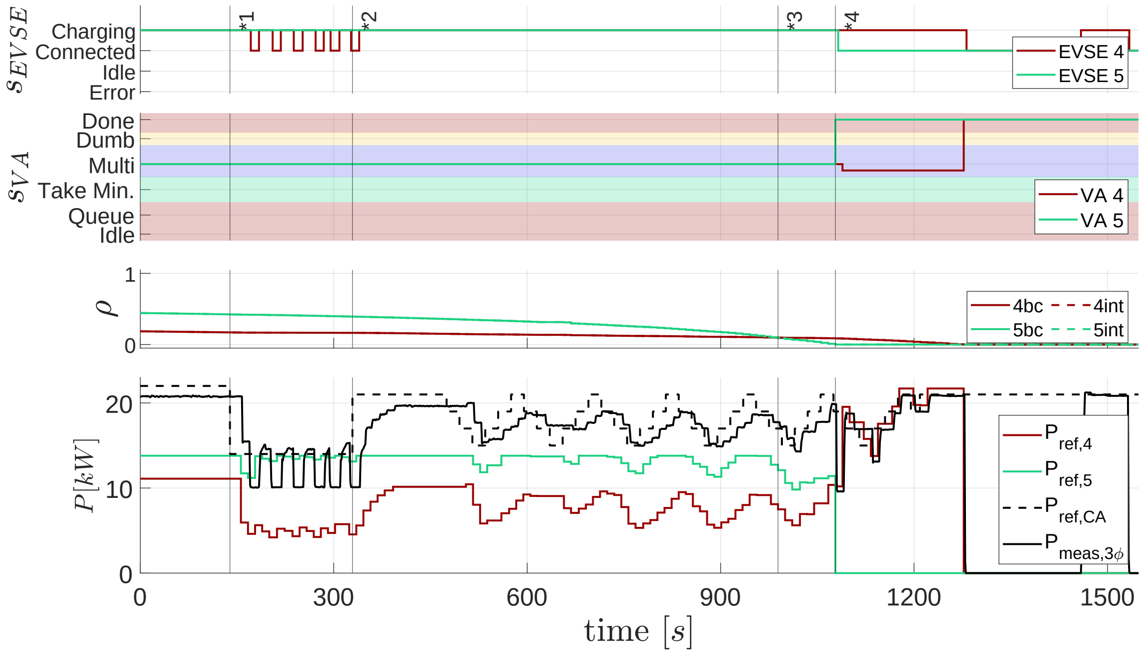


Figure 6.7: Result of two VAs response to changing $P_{ref,CA}$.

In Figure 6.7 $t = 0$ sec is set when both VAs charges at steady state in s_{va} = `multi_VA_control`, and hence the startup is not shown. They have different P_{ref} initially as VA 5 was activated last with the highest priority and thereby able to take all the power it wanted (13.8 kW given by the proximity). At mark *1, the step down is performed and causes the two EVs to lower their P_{ref}. VA 5 responds by reducing $P_{ref,5}$ by 2 kW, and VA 3 with the lower priority responds with 5 kW, as their response is dependent on their relative priority $\rho_{relative}$. For this response, it is observed that an additional response is required to reach $P_{meas,PCC} < P_{ref,CA}$. This comes the discrepancy $P_{C,OBC,5} = 11$ kW $< P_{ref,5} = 13.8$ kW and therefore its respons has no effect on the $P_{meas,PCC}$. That VA 4 has to go further down in $P_{ref,4}$ to 4.68 kW has the effect that the EV itself stops charging immediately (seen both in its s_{EVSE} and $P_{meas,PCC}$ dropping to the 10 kW consumed by EV 5). the two controllers then enter an overcompensating control scenario as EV 4 is in an ON/OFF state. As this does not showcase the system from the best sides we swiftly move to the step up at mark *2. Here again, the actual participation of VA 5 is not seen in the $P_{meas,PCC}$. The system does, however recover to a consumption within the control dead band of $P_{ref,CA}$ as VA 4 for each scan cycle minimises $P_{error,PCC}$. In the section where the system responds to the triangle step signal, it is shown that two EVs follow nicely but have issues reaching the peaks, which only last for 20 seconds. On the bright side, as the priorities' relative magnitudes change and are equal at mark *3, it is possible to spot a significant system enhancement. When VA 5 suddenly has a lower priority than VA 4, it tends towards a control where the $P_{C,OBC,5} = 11\,\text{kW} > P_{ref,5}$ and the control reactions are more true to the output.

It could be that the EVs reaching their negotiated energy should have a milder transition towards not charging. This will, of course, only help in these situations, not if the user suddenly stops charging. As it is observed that an EV stops charging when it is allowed less than $\approx 5\,\text{kW}_{3\phi}$, it should be taken into account that the manufacturers of the EVs and OBC already have implemented the efficiency considerations of Section 4.1.2.

When a step down is experienced, the EVs use $(1 - \rho_{relative})$ as the gain for their scaling. This works very well for a two-EV system as they will 'take the other VA's part and step down. This should be overcome by utilising a less aggressive control in Section 2.4 or having a different gain function for the negative P_{error} case. It should maybe be explored to have the same gain for all Powered VAs which is a function of the actively charging EVs, and loosen more on what the VAs decide to do. As we see in Figure 6.7 after *1, VA 4 might want to stay above a certain threshold when participating in the charging, and the others will still take responsibility for removing the excess power. However, this approach would probably require more information to be shared.

Variations in the reference signal from CA cannot theoretically be met if it goes below $n \cdot 6\,\text{A}$ to $7\,\text{A}$ as EVs would have to stop charging or go into the queue. In other words: There is a constraint from the EVs that they cannot provide more variation flexibility than from $n \cdot 6\,\text{A}$ to $7\,\text{A}$ to their upper limit often $P_{C,OBC} = 11\,\text{kW}$.

6.6 Communication failure

Communication failures are an important aspect when preparing for real-life implementation, which has had little consideration throughout the thesis. With the emulated system, the test should still reflect the distributed control system's most critical and probable lost connection. Returning to Figure 4.4, this can be identified as the communication of $P_{meas,PCC}$ from the PCC to the VAs. The connection to the CA is also meaningful, but in case of loss, it should be considered constant from the last trusted value, as this is a safe estimation that loses the participation in the control code.

For this test, the following procedure was followed:

1. Set a constant reference signal from CA: $P_{ref,CA} = 21$ kW
2. **Plug 3:** Connect BMW i3 with user input: $\Delta t = 0.5$ h, $E_{req,3} = 3$ kWh,
3. Wait for steady consumption.
4. **Plug 5:** Connect Peugeot 208e with user input: $\Delta t = 0.5$ h, $E_{req,5} = 2$ kWh
5. stop the code `QueryPIOT.py`
6. Make manual readings on the PCC with timestamp reference of changes in the power
7. Wait for steady consumption.
8. Restart the code `QueryPIOT.py`

For this test, the data acquisition is going to deviate slightly as an intended lost communication between the PCC and VAs requires that the power is not automatically tracked by the code that both makes $P_{meas,PCC}$ available in Whiteboard and logs it in the `.csv` file. However, manual readings are still possible directly on the PCCs hardware display.

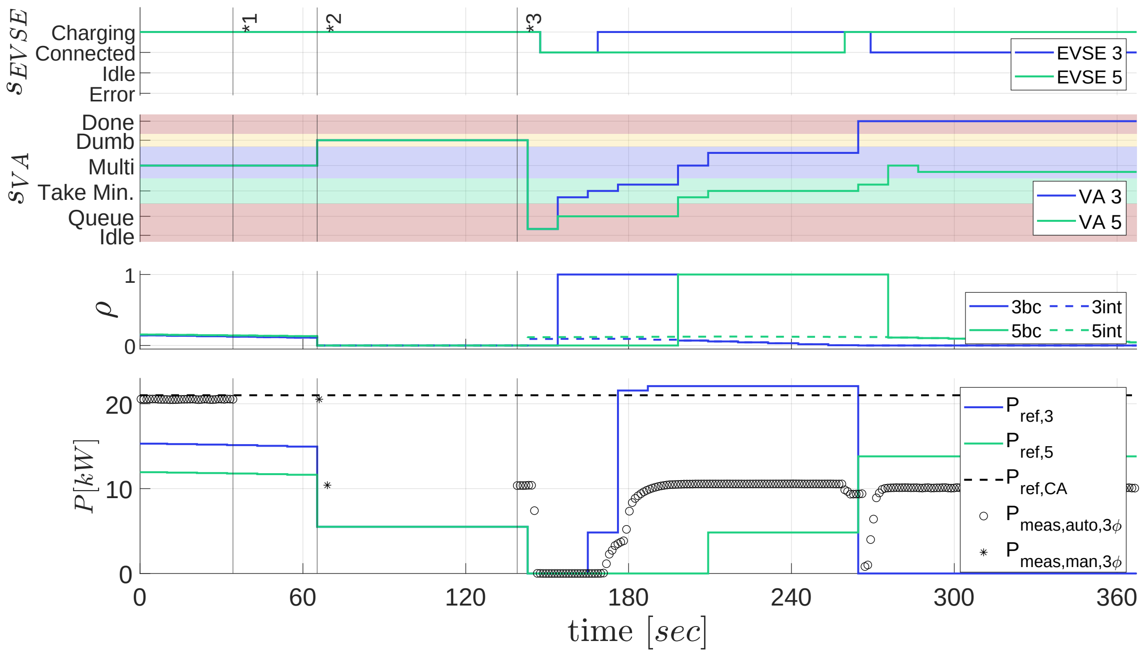


Figure 6.8: Result of lost communication with PCC.

For this test, the timeframe of Figure 6.8 has been scaled to show the critical part of reacting to the fault and restarting regular operation. The test indicates that the communication is lost at mark *1 and 31 sec later at mark *2. Both VAs react as the timestamp of the last reading in Whiteboard is more than 30 seconds old. They respond by going immediately to $s_{VA} = \texttt{dumb}$ where their reference is a hardcoded fraction of cluster capacity: $P_{ref,i} = \frac{P_{C,PCC}}{N_{EVSE}} = \frac{22\,\text{kW}}{4\,\text{EVSEs}} = 5.5$ kW for $i = [3, 5]$. This is a safe consumption for this parking lot as the state may be utilized for all communication loss, and the VA assumes no communication is present; therefore, every other charger may charge with the same power without violating the $P_{C,PCC}$. The manual readings confirm the consumption drop: $P_{meas,PCC} = 10.4$ kW, which is half the $P_{C,PCC}$ as only two EVs are charging. After steady consumption, at mark *3, the communication is intentionally restored, and the VAs transit from $s_{VA} = \texttt{dumb}$ to restart their smart charging. One VA by the other, as only one can be in the Entering states concurrently.

The restarting sequence could be optimized as the entire system intentionally consumes 0 kW. Letting the chargers go directly back into their previous charging state should be considered for such an implementation. Further optimizations would include that the communication within the charger should be regarded as not failing. One VA in dumb charging may, in that case, borrow power from the other if it is in an inactive state: ($s_{VA} = \{\texttt{Idle}, \texttt{Disconnected}$ or $\texttt{Done}\}$). These considerations are all application dependent, and this thesis has, therefore, only considered one scenario, which serves to showcase the general method of the system.

7 Conclusion

7.1 Key findings

This thesis has developed and implemented a charging strategy based on a distributed control architecture. The aim was to autonomously make the VAs take three perspectives into account, each having its objective; provide flexibility, be energy efficient and accommodate the user requirements. The strategy was implemented and tested in an emulated state with a real-life charging system. The key findings are highlighted within each field as the thesis has brought together the domains of distributed autonomous control, strategies and real-life implementation.

For the strategy, the objectives provided an unexpectedly high preference towards scheduling. It was realized that flexibility is only possible if user needs have been acquired (or boldly assumed). With the user needs available, it was discovered that equality of power is secondary to 'equality' of energy for the users. Therefore, a scheduling scheme based on the user needs has provided the strategy's foundation, which theoretically yields the highest systemwide energy throughput at high efficiency. Hence satisfying both users, flexibility acquires and ensures an efficient system.

For a distributed control architecture, this project has brought the foundation for a modular build system. The focus has been on the control level of the VAs and how much self-governing they may perform. It was found that the cluster of VAs autonomously could adjust to a common periphery signal in collaboration while making individual decisions that enable charging those with the highest priority. This was obtained while PCC measurements and the VA's priority was broadcasted for the VAs to evaluate. The critical finding is that the VAs can control their common consumption with a single cluster-specific setpoint being shared down from the CA; no need to share data with the CA or include a local central control unit with redundancy requirements. As the architecture has been emulated with a small parking lot, the minimal need for sharing information between the lowest level of VAs suggests good scalability capabilities.

Some barriers have been observed within EV controllability for real-life implementation and testing. With the testing platform encouraging testing iterations, the strategy was incrementally developed to overcome the smart charging of real EVs. Outside the scope of the charging protocols, the manufacturers may develop the EV's behaviour freely. Some are biased towards the user objective, elegantly stopping charging when the user is assumed to use the EV. Others with a supposed bias on the efficiency objective have included their constraint to stop the charging if the allowance from the EVSE forces a low-efficiency charging session. Such behaviours may bring challenges to a clustered dynamic control system. Therefore, looking at further confinement of EV's charging behaviour is recommended for progress within the field.

The thesis has thus provided a surge towards distributed control of smart charging as results have provided valuable first insights into the barriers and possibilities that arise from coupling the parallel transitions of the transportation and electric generation sectors. Clusters of EV chargers where the user needs are requested may provide flexibility. It requires a back-end charging structure where the modular Cloud Aggregator, Virtual Aggregator, has intrinsic advantages.

7.2 Future work

The work of this thesis serves new experimental insight, which should be a base for future research. Focus has been on the control capabilities of the VAs , which is part of a more extensive unanswered system. The distributed control architecture has not been functionally implemented. These two perspectives will now be discussed, and finally, a recommendation for the immediate work necessary, which could be considered in the subsequent iterations of the system.

A cluster of VA controllers and their dynamics has been pivotal for this thesis. It has been developed as a modular control system module to provide simple interfacing from the Cloud Aggregator. However, it should be coupled with a Cloud aggregator responsible for multiple EV clusters and other flexibility providers to offer a complete system assessment. With the simple interface, it is believed that Cloud Aggregator may be developed with Model Predictive Control or Optimization schemes to provide the necessary real-time system behaviour. It should be coupled with a pricing scheme for the negotiation process with the users, which could be calculated simultaneously at the CA and broadcast daily to the VAs for their complete real-time independent behaviour.

This project has been on a path towards proving the applicability of distributed architecture. A few steps are still necessary to come to the point of a fully functional distributed architecture. Firstly the emulated system should detach the different control units in time by making multi-threaded control. Then thoughts should be put into the desired topology for the architecture sharing of information (Utilizing a local server, broadcasting or subscription-based). Thirdly the VA structure may be directly implemented in VAs with the appropriate information and communication technologies applied. At that point, it will be possible to optimize the control loops and further investigate the impact of the delays in the system. Then it should be finally possible to examine the full scale of advantages of the distributed control architecture.

The final remark goes to the most immediate actions which arise when the available information for the VA increase. The internal power measurements of the EVSE are expected to be available for the VAs soon. This has been a significant control barrier in this thesis. When the hardware has it implemented, the FSM and control loop may need a revisit. When the VA can evaluate the performance of the OBC connected, it may provide phase balancing with 1ϕ EVs. And most notably, it enables a shorter control loop where the VA knows the response of its control output.

Bibliography

[1] The Danish Government and Radikale Venstre and Socialistisk Folkeparti and Enhedslisten. *Grøn omstilling af vejtransporten*. 2020.

[2] J. Ostergaard, C. Ziras, H. W. Bindner, et al. “Energy Security Through Demand-Side Flexibility: The Case of Denmark”. In: *IEEE Power and Energy Magazine* 19 (2 2021), pages 46–55. DOI: 10.1109/MPE.2020.3043615.

[3] M. Muratori. “Impact of uncoordinated plug-in electric vehicle charging on residential power demand”. In: *Nature Energy* 3 (3 2018), pages 193–201. DOI: 10.1038/s41560-017-0074-z.

[4] J. Engelhardt. “Reconfigurable Batteries in Electric Vehicle Fast Chargers: Towards Renewable-Powered Mobility”. In: *Downloaded from orbit.dtu.dk on 2023/05/20* (2022). DOI: 10.11581/dtu.00000254.

[5] S. Striani, K. Sevdari, L. Calearo, P. B. Andersen, and M. Marinelli. “Barriers and Solutions for EVs Integration in the Distribution Grid”. In: *2021 56th International Universities Power Engineering Conference (UPEC)* (2021), pages 1–6. DOI: 10.1109/UPEC50034.2021.9548235.

[6] K. Sevdari, L. Calearo, P. B. Andersen, and M. Marinelli. “Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives”. In: *Renewable and Sustainable Energy Reviews* 167 (2022), page 112666. DOI: 10.1016/j.rser.2022.112666.

[7] A. Thingvad, P. B. Andersen, T. Unterluggauer, C. Træholt, and M. Marinelli. “Electrification of personal vehicle travels in cities - Quantifying the public charging demand”. In: *eTransportation* 9 (2021), page 100125. DOI: 10.1016/J.ETRAN.2021.100125.

[8] J. Ramsebner, A. Hiesl, R. Haas, et al. “Smart charging infrastructure for battery electric vehicles in multi apartment buildings”. In: *Smart Energy* 9 (2023), page 100093. DOI: 10.1016/j.segy.2022.100093.

[9] A. Bowen, J. Engelhardt, T. Gabderakhmanova, M. Marinelli, and G. Rohde. “Battery Buffered EV Fast Chargers on Bornholm: Charging Patterns and Grid Integration”. In: *2022 57th International Universities Power Engineering Conference (UPEC)* (2022), pages 1–6. DOI: 10.1109/UPEC55022.2022.9917690.

[10] J. Engelhardt, J. M. Zepter, J. P. Sparssø, and M. Marinelli. *Real-life demonstration of a hybrid EV fast charging station with reconfigurable battery technology enabling renewable-powered mobility*. 2023.

[11] J. Engelhardt, J. M. Zepter, T. Gabderakhmanova, G. Rohde, and M. Marinelli. “Double-String Battery System with Reconfigurable Cell Topology Operated as a Fast Charging Station for Electric Vehicles”. In: *Energies* 14 (9 2021), page 2414. DOI: 10.3390/en14092414.

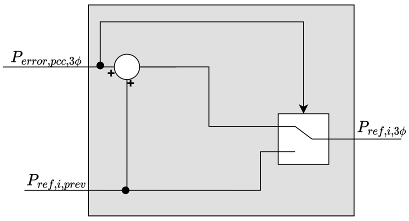
[12] J. Engelhardt, T. Gabderakhmanova, G. Rohde, and M. Marinelli. “Reconfigurable Stationary Battery with Adaptive Cell Switching for Electric Vehicle Fast-Charging”. In: IEEE, 2020, pages 1–6. ISBN: 978-1-7281-1078-3. DOI: 10.1109/UPEC49904.2020.9209774.

[13] J. Engelhardt, J. M. Zepter, T. Gabderakhmanova, and M. Marinelli. “Energy management of a multi-battery system for renewable-based high power EV charging”. In: *eTransportation* 14 (2022), page 100198. DOI: 10.1016/j.etran.2022.100198.

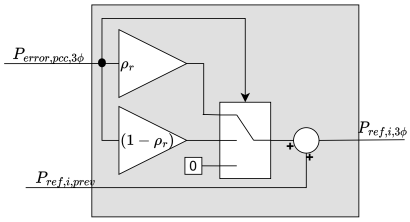
[14] N. Erdogan, S. Kucuksari, and J. Murphy. “A multi-objective optimization model for EVSE deployment at workplaces with smart charging strategies and scheduling policies”. In: *Energy* 254 (2022), page 124161. DOI: 10.1016/j.energy.2022.124161.
[15] K. Fauziah, Y. Astriani, D. A. Renata, et al. “Design of AC Electric Vehicle Supply Equipment based on Safety Standard”. In: *2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)* (2021), pages 425–430. DOI: 10.1109/ICHVEPS53178.2021.9600963.
[16] X. Han, K. Heussen, O. Gehrke, H. W. Bindner, and B. Kroposki. “Taxonomy for Evaluation of Distributed Control Strategies for Distributed Energy Resources”. In: *IEEE Transactions on Smart Grid* 9 (5 2018), pages 5185–5195. DOI: 10.1109/TSG.2017.2682924.
[17] K. Sevdari, S. Striani, P. B. Andersen, and M. Marinelli. “Power Modulation and Phase Switching Testing of Smart Charger and Electric Vehicle Pairs”. In: *2022 57th International Universities Power Engineering Conference (UPEC)* (2022), pages 1–6. DOI: 10.1109/UPEC55022.2022.9917660.
[18] Dansk Standard. *IEC 62196-2:2020: Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 2: Dimensional compatibility requirements for AC pin and contact-tube accessories*. 2020.
[19] Dansk Standard. *IEC 61851-1:2019: Electric vehicle conductive charging system – Part 1: General requirements*. 2019.
[20] L. Calearo, M. Marinelli, and C. Ziras. “A review of data sources for electric vehicle integration studies”. In: *Renewable and Sustainable Energy Reviews* 151 (2021), page 111518. DOI: 10.1016/j.rser.2021.111518.
[21] M. Marinelli, L. Calearo, J. Engelhardt, and G. Rohde. “Electrical Thermal and Degradation Measurements of the LEAF e-plus 62-kWh Battery Pack”. In: *2022 International Conference on Renewable Energies and Smart Technologies (REST)* (2022), pages 1–5. DOI: 10.1109/REST54687.2022.10023130.
[22] A. Zecchino, A. Thingvad, P. B. Andersen, and M. Marinelli. “Test and modelling of commercial V2G CHAdeMO chargers to assess the suitability for grid services”. In: *World Electric Vehicle Journal* 10 (2 2019). DOI: 10.3390/wevj10020021.
[23] M. Marinelli. *https://www.linkedin.com/posts/mattiamarinelli_a-while-ago-i-presented-the-efficiency-curves-activity-7055816423318642690-w7t_?utm _source=shareutm_medium=member_desktop*. 2023.
[24] Z. J. Lee, T. Li, and S. H. Low. “ACN-Data: Analysis and Applications of an Open EV Charging Dataset”. In: *Proceedings of the Tenth ACM International Conference on Future Energy Systems* (2019), pages 139–149. DOI: 10.1145/3307772.3328313.
[25] H. W. Bindner and O. Gehrke. *System control and communication*. Risø DTU - National Laboratory for Sustainable Energy, 2009. ISBN: 9788755037540.
[26] Z. López, I. Saviuc, A. Puskas, K. Rollert, and P. Bertoldi. “Explicit Demand Response for small end-users and independent aggregators Status, context, enablers and barriers”. In: (2022). DOI: 10.2760/625919.
[27] J. Hildermeier, J. Burger, A. Jahn, and J. Rosenow. “A Review of Tariffs and Services for Smart Charging of Electric Vehicles in Europe”. In: *Energies* 16 (1 2022), page 88. DOI: 10.3390/en16010088.
[28] J. García-Villalobos, I. Zamora, J. S. Martín, F. Asensio, and V. Aperribay. “Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches”. In: *Renewable and Sustainable Energy Reviews* 38 (2014), pages 717–731. DOI: 10.1016/j.rser.2014.07.040.
[29] A. Thingvad, C. Ziras, G. L. Ray, J. Engelhardt, R. R. Mosbæk, and M. Marinelli. “Economic Value of Multi-Market Bidding in Nordic Frequency Markets”. In: *2022*

International Conference on Renewable Energies and Smart Technologies, REST 2022 (2022). DOI: 10.1109/REST54687.2022.10023471.
[30] Energinet. *https://energinet.dk/El/Systemydelser/Introduktion-til-Systemydelser/Oversigt-over-systemydelser/*. 2023.
[31] C. Dharmakeerthi, N. Mithulananthan, and T. Saha. “Impact of electric vehicle fast charging on power system voltage stability”. In: *International Journal of Electrical Power & Energy Systems* 57 (2014), pages 241–249. DOI: 10.1016/j.ijepes.2013.12.005.
[32] M. Tveit, ; Halldis, K. ; Sevdari, et al. *Behind-the-meter residential electric vehicle smart charging strategies: Danish cases*. DTU, 2022.
[33] J. M. Zepter, J. Engelhardt, T. Gabderakhmanova, and M. Marinelli. “Re-Thinking the Definition of Self-Sufficiency in Systems with Energy Storage”. In: *2022 International Conference on Smart Energy Systems and Technologies (SEST)* (2022), pages 1–6. DOI: 10.1109/SEST53650.2022.9898436.
[34] S. Striani, K. Sevdari, M. Marinelli, V. Lampropoulos, Y. Kobayashi, and K. Suzuki. “Wind Based Charging via Autonomously Controlled EV Chargers under Grid Constraints”. In: *2022 57th International Universities Power Engineering Conference (UPEC)* (2022), pages 1–6. DOI: 10.1109/UPEC55022.2022.9917883.
[35] X. Han, H. W. Bindner, J. Mehmedalic, and D. V. Tackie. “Hybrid control scheme for distributed energy resource management in a market context”. In: *2015 IEEE Power & Energy Society General Meeting* 2015-September (2015), pages 1–5. DOI: 10.1109/PESGM.2015.7286000.
[36] S. Lai, J. Qiu, Y. Tao, and J. Zhao. “Pricing for Electric Vehicle Charging Stations Based on the Responsiveness of Demand”. In: *IEEE Transactions on Smart Grid* 14 (1 2023), pages 530–544. DOI: 10.1109/TSG.2022.3188832.
[37] M. R. B. Khan, R. Jidin, and J. Pasupuleti. “Multi-agent based distributed control architecture for microgrid energy management and optimization”. In: *Energy Conversion and Management* 112 (2016), pages 288–307. DOI: 10.1016/j.enconman.2016.01.011.
[38] DTU. *https://www.acdc-bornholm.eu/*. 2020.
[39] A. Malkova, S. Striani, J. M. Zepter, M. Marinelli, and L. Calearo. *Laboratory validation of electric vehicle smart charging strategies*. 2023.
[40] X. Cao, S. Striani, C. Ziras, and M. Marinelli. “A semi-distributed charging strategy for electric vehicle clusters”. In: *8th International Conference on Sustainable and Renewable Energy Engineering.* (2023).
[41] J. Hu, H. Morais, T. Sousa, and M. Lind. *Electric vehicle fleet management in smart grids: A review of services, optimization and control aspects*. 2016. DOI: 10.1016/j.rser.2015.12.014.
[42] T. Gabderakhmanova, J. Engelhardt, J. M. Zepter, et al. “Demonstrations of DC Microgrid and Virtual Power Plant Technologies on the Danish Island of Bornholm”. In: *2020 55th International Universities Power Engineering Conference (UPEC)* (2020), pages 1–6. DOI: 10.1109/UPEC49904.2020.9209853.

A Calculation of reference power in states



$s_{VA} =$ `Single VA Control`



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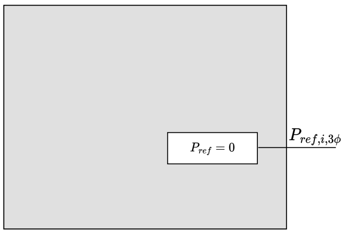
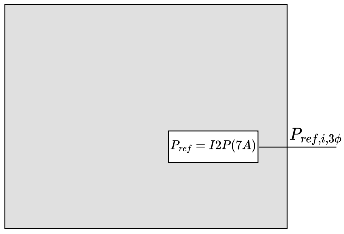
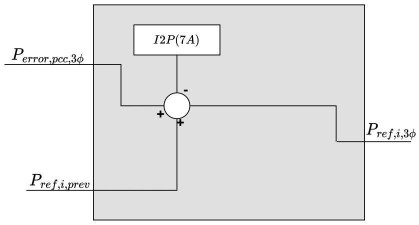


$s_{VA} =$ Not powered

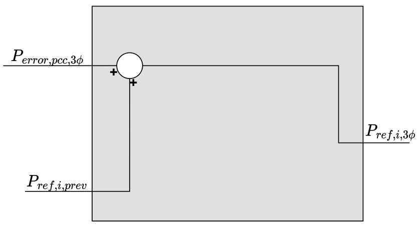


$s_{VA} =$ `Take Minimum`

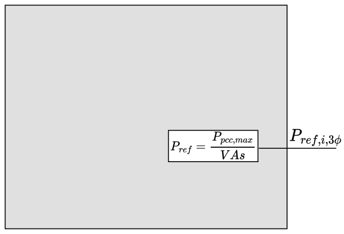
$s_{VA} =$ `Making Space`



$s_{VA} =$ `Making Space as Marginal`



$s_{VA} =$ `Increase`



$s_{VA} =$ `Dumb Charging`

B Preliminary tests

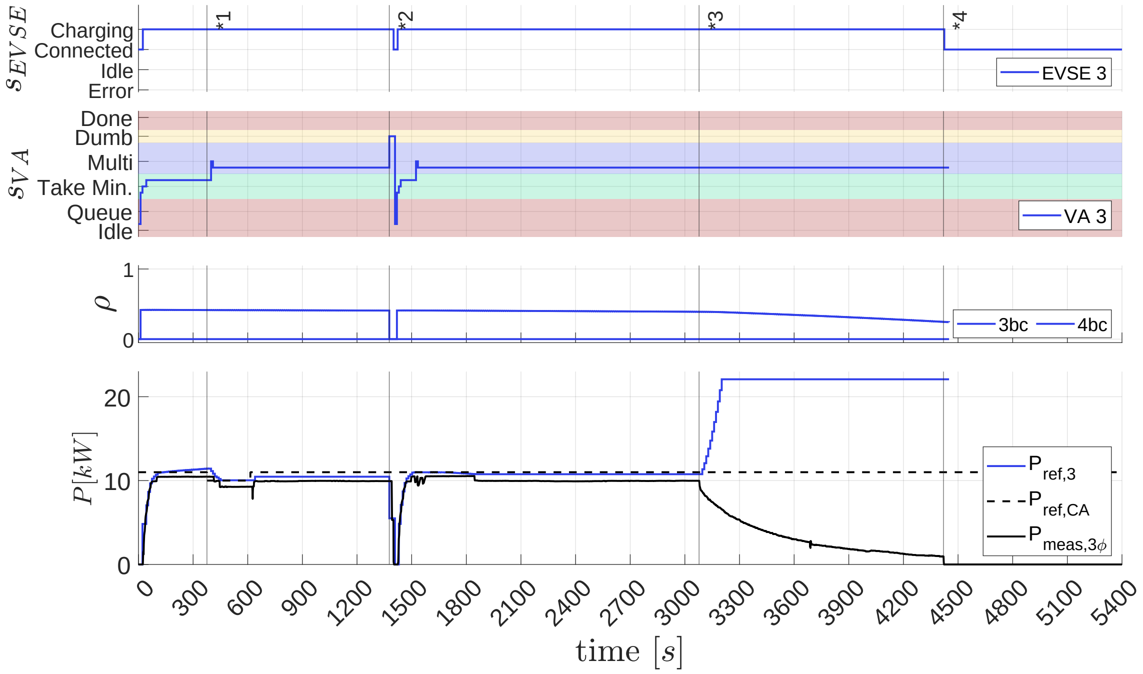


Figure B.1: The BMW charging at charger 3 at mark *3 the Constant Voltage power curve initiates and the EV reach SOC = 1 at mark *4 where charging stops.

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