Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Electric Power Engineering

Teis Kloster Skogland

Charging flexibility from electric vehicles via autonomous chargers in a workplace

Juli 2021

Master's thesis in Innovative Sustainable Energy Engineering - System Integration of Wind Power
Supervisor: Mattia Marinelli
Co-supervisor: Kristian Sevdari, Lisa Calearo, Simone Striani, Venkatachalam Lakshmanan, Kenta Suzuki
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Lade fleksibilitet fra elbiler via autonome ladere på en arbejdsplads.

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Abstract

As a part of the ongoing project Autonomously Controlled Distributed Chargers (ACDC), This thesis have designed an autonomous charging controller, with a distributed control architecture incorporating virtual aggregator capabilities.

In order to limit global warming, as stated by the Paris agreement 2015, decarbonising of the energy sector is key. Large scale electrification, and reduction of fossil fuel bases energy production is needed. To enable high penetration of uncontrollable renewable energy sources, demand side flexibility is needed. Sector coupling is also suggested as a solution. This could be done by integrating the transportation sector into the power sector. The idea is to use the storage capacity from Electric vehicles (EV) to benefit the electrical power system.

Electrification of the transportation sector is also necessary. To enable high penetration levels of EVs, it is important to integrate them to the grid in such a way that they could be of benefit to the system, instead of increasing peak loads and becoming a burden. The way of doing this is by use of smart charging.

This thesis have been focused on designing an autonomous charging controller, by use of a distributed control architecture. The model is capable of coordinating the charging of 18 EVs connected via nine chargers, with two outlets each, which is typically found in a workplace parking lot. The model uses historical EV data from 18 Nissan LEAFs. The idea is that by use of a distributed control architecture will enable high penetration of EVs in a cost-effective and simple manner. The controller could operate independently, but also contribute with flexibility by responding to demand-response signals, such as power limitation, and load balancing. A virtual aggregator is incorporated in every charger which distributes a dynamic power signal. This signal can be changed to provide flexibility to the grid operator, or to provide behind-the-meter services.

The model have been developed in MATLAB Simulink. The model utilises historical EV data consisting of arrival time, departure time and State of Charge (SOC). The model autonomously coordinates charging of the 18 EVs, while keeping the power within desired limits.

To analyse the results, a total of 3 different cases with smart charging have been analysed, in addition to a base case utilising uncontrolled, dumb charging. By distributing the demand throughout the day, and with times of surplus power, the smart charger reduces peak loads. The result show that smart charging can reduce the required charging power by a factor of three, compared to dumb charging, and still deliver satisfying results when considering the total charged energy, and the SOC for every EV. From an economic perspective, taking this power difference into consideration could make the total investment of smart chargers cheaper compared to dumb chargers.

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Teis Kloster Skogland, MSc Innovative Sustainable Energy Engineering - System Integration of Wind Power,NTNU DTU

Although this thesis have been completed during a world wide pandemic, I look back full of gratitude for the people I have met, and the experiences I've been enriched with during these times of at uncertainty.

I am very grateful for the opportunity and the support from my supervisors, Mattia Marinelli, Kristian Sevdari, Lisa Calearo, Simone Striani, Venkatachalam Lakshmanan and Kenta Suzuki helping me through this MSc thesis. They have provided unconditional support and kind words throughout the entire five month period.

I would also like to thank my family, friends and loved ones for believing in me.

Contents

1 Introduction

According to the Paris Agreement from 2015, countries are legally obliged to limit global warming to well below the 2° target [1]. More recently in 2019, this has been further confirmed by the European Commission (EC), after they launched the European Green Deal, which sets out how to make Europe carbon neutral by 2050 [2]. This is looked upon as our times biggest challenge. To achieve carbon neutrality, decarbonisation of the energy sector is key. Today most of the energy comes from fossil fuels sources, such as coal, oil and natural gas. These are utilised in many different sectors, such as industry, transportation, heating, electricity and more. The most prominent solutions to decarbonise the energy and transport sector are electrification and renewable energy sources (RES).

It is expected that the annual share of electricity in the final energy consumption mix for all energy applications will increase from 19% in 2016 to 49% in 2050, as displayed in Figure 1.1 [3]. In Terawatt-hours (TWh), this corresponds to approximately 22 000 TWh today, out of 110 000 TWh in total, too 48 000 TWh out of 97 500 TWh.

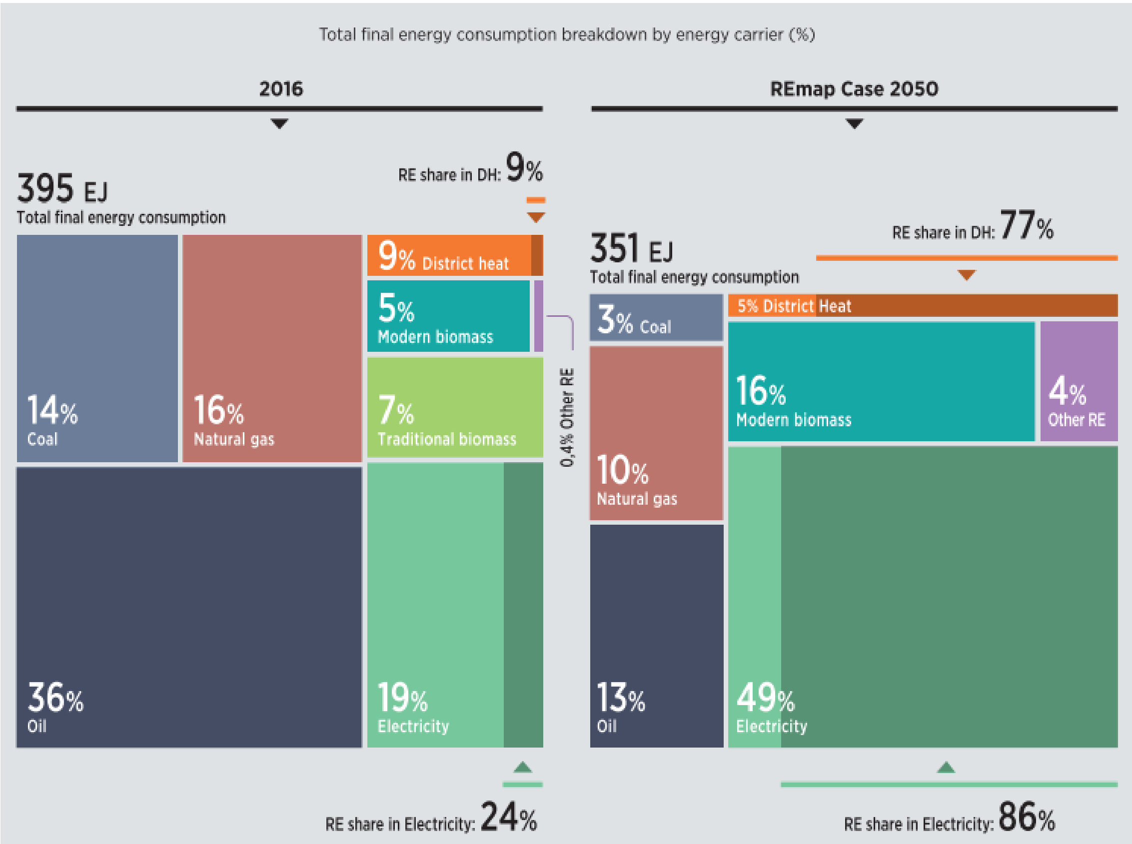


Figure 1.1: Breakdown of total final energy consumption by energy carrier in 2016 and REmap Case 2050, EJ = exajoule [3].

One of the reasons for electrification to grow is that electricity is one of, if not the most efficient energy carrier today. It has a wide range of end-use applications, and can be generated from renewable energy sources (RES), such as hydro power, biomass, photovoltaics (PV) and wind power. Here, the electrification needs to go in parallel with decarbonising the power sector. Doing the first without the second will only shift the emissions from one sector to another, even though with the increased efficiency of electricity as a fuel source this could still decrease total energy consumption and overall emissions. However, the society demands energy as people are not likely to accept a decrease in living standards. Thus, RESs are key to keep welfare level high, and emissions low. In 2016 only 24% of the worlds electricity mix was produced from RES. To fulfil the share of 86% RES in 2050, a radical increase in renewable production is required. More specifically from today's 5280 TWh, to 41 280 TWh. In first quarter of 2020, global RES share of electricity increased to 28% from 26% in 2019 [4]. Another sector with great challenges is global transportation, which accounts for around 25% of the worlds CO_2 emissions, with cars and trucks accounting for 75% of these [5]. More than 20 countries have electrification targets or are planning to ban purchases of new internal combustion engine (ICE) vehicles, within the next decade [6], [7], [8]. Most of these cars will be replaced by electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEV), and in 2025 global EV stock is expected to exceed 50 million, and furthermore almost 140 million vehicles by 2030 [9]. Successfully reducing fossil fuel consumption in the transportation sector will not only reduce CO_2 emissions, but also reduce air pollution and noise [10], [11]. More EVs will naturally increase the overall demand for electricity, and could also increase loads during peak hours [12]. This comes on top of the ongoing electrification of other sectors, phase out of fossil power plants, and a tenfold increase in renewable energy sources (RES), which are naturally intermittent [13].

1.1 Paradigm shift

Historically the power system has been a centralised system, where power flows from producer to consumer, as shown in Figure 1.2.

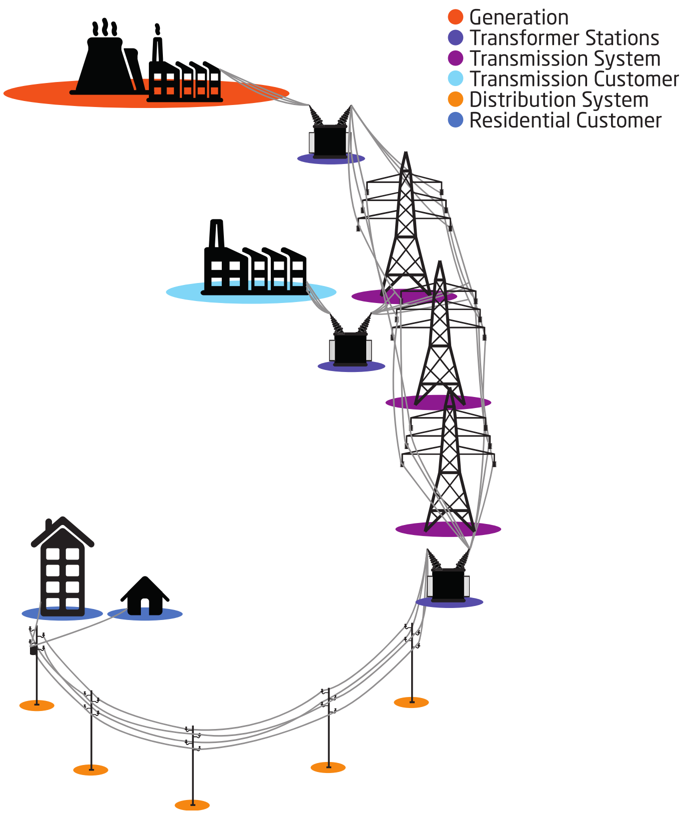


Figure 1.2: The traditional power system [14].

The transmission system operator (TSO) is responsible for balancing the power system (production matching consumption) at all times. Here, traditionally by use of large generating units.In addition, the TSO is also responsible for the electrical grid and for the transmission of the the energy. The grid is interconnected but split into a transmission system and a distribution system. The high voltage system (over 100kV) is owned by the TSO, while the medium, and low voltage systems are owned by distribution system operator (DSO). Construction and maintenance of electrical grids are expensive and in Europe, the distribution business is still regulated as a natural monopoly, even though the sector was privatised and liberalised during the 1990s [15].

The Danish energy system has changed from a centralised to a distributed system in the past decades [16]. Central large-scale fossil fuelled power plants have been replaced by distributed energy sources such as wind power plants, PV and combined heat and power plants. Denmark with its high penetration of RES, makes a good example of a future power system. In addition, the Danish island of Bornholm resembles a Danish distribution system where multiple smart grid themed projects related to the topic of EV integration and demand response have been, and are carried out. From the ACES [17], ECOgrid 2.0 [18], and now the ongoing ACDC-research project which this thesis is a part of [19].

The phase out of controllable fossil power plants and increase in non-controllable RES creates a control-vacuum. This calls for controllable demand side flexibility, and EV demand response is part of that. A centralised control approach of the vast number of smaller units that could provide flexibility, would require a complex and expensive information and communication technology (ICT) infrastructure [20].

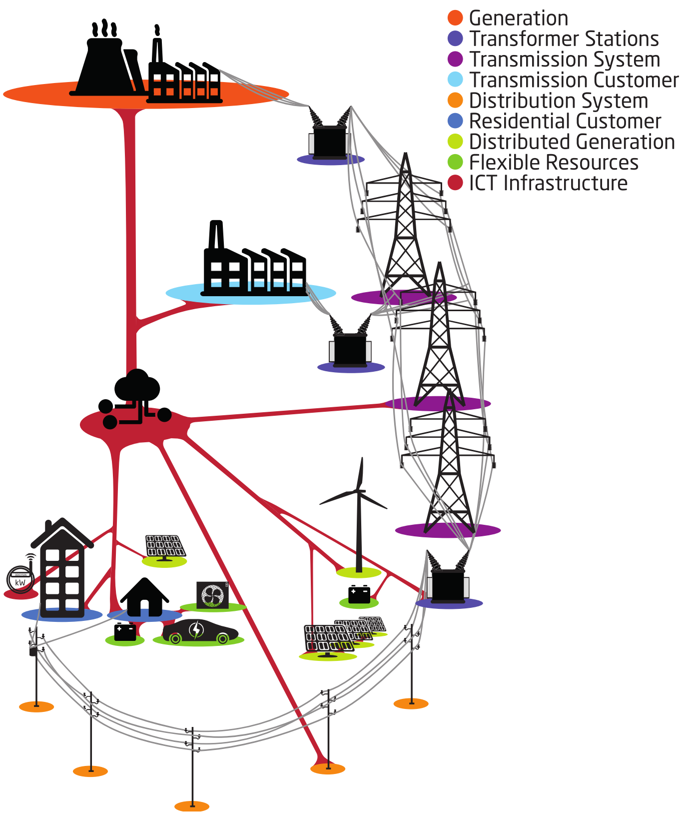


Figure 1.3: The future smart grid paradigm [14].

Therefore a distributed control approach seems more promising towards distributed energy technologies coordination. Furthermore, sector coupling is suggested as part of the solution [3]. This could be coming from power-to-heat, power-to-hydrogen, and electrification of the transport sector, that could be shifted, increased or reduced in a period of time to provide demand-side flexibility. More specifically by reshaping load profiles to match generation from RES, reduce peak loads and adapt to price signals.

According to user patterns for several countries, personal vehicles are on average utilised less than 3% of the day [21]. As EV penetration increases, unexploited storage resources emerge, which could potentially reduce the non-controllable solar and wind power issue. Nevertheless, EVs do come with a self-inflicted adverse effects, for example grid loading that could cause congestion issues [12]. Therefore, it is important to coordinate charging to reduce potential negative impacts.

Furthermore, to enable demand side flexibility from EVs, coordinated charging infrastructure is key. And as EV penetration increases, so does the need for charging infrastructure. One of the focus areas of the EC is sustainable mobility, and they expect 1 million public charging stations to be needed by 2025. If we assume 40% EV penetration by 2030, Denmark alone, with 380,000 EVs in 2025 and 1 million EVs 2030, would require an infrastructure investment of 1.1 billion DKK in 2025, and 3.4 billion DKK to cover the expenses needed to deliver the needed energy [22]. If the installation of chargers is done in a smart way, 1 million EVs could provide large flexibility to the power system, and support the integration of RES.

1.2 Overall Thesis Objectives

Thesis work will focus on coordinated and autonomous charging control of EVs for the provision of behind the meter services of an aggregation of EVs in a workplace parking lot. Grid services include responding to demand-response signals with the aim of providing services such as power limitation, PV production matching or frequency control. Another aspect to be investigated is the assessment of grid services flexibility of EVs based on different constraints such as SOC, battery capacity and charging availability. A techno-economic analysis for different investigated cases and the recommendation following the investigated charging modes will complement the work.

The thesis is part of to the ongoing ACDC (Autonomously Controlled Distributed Chargers) project. The proposed control approach at ACDC distinguishes from the centralised approach, as there will not be a single centralised charging control unit receiving and distributing the signals [23]. On the contrary there will be a distributed approach with every charging unit incorporating virtual aggregator capabilities, which could switch between acting as the leading or the following unit. This way redundancy would be preserved, along with other advantages and disadvantages which will be outlined at chapter 2. The investigation will be limited to the context of a workplace parking lot. The thesis is also limited to unidirectional smart chargers.

Other elements to be considered are individual constrains such as system control response time, state of charge (SoC), battery capacity, charging availability, maximum charging rate, and grid constrains. These constrains are both effected by technical limitations, and user behaviour.

The **techno-economic analysis** will investigate how the different operational modes could be both beneficial and challenging. Could this control approach fulfil frequency market requirements? A recommendation of charging strategy will follow the investigation along with analysis of the charging modes. Thus, the research questions can be summarised as follows:

- **How is it possible to design a coordinated and autonomous charging controller?** The goal is to design a realistic coordinated and autonomous charging control that could provide behind the meter services such as power limitation, load balancing by use of a virtual aggregator responding to demand-response signals. The virtual aggregator would also autonomously coordinate the responds from other inputs such as PV electricity production, and priority between the EVs themselves and between chargers to provide the desired charging operation.
  - Which are the main inputs, outputs and processes to consider?
- **How feasible is the smart charger utilisation on a workplace parking lot?** Assess the smart charger deployment and controlling techniques to fulfilment of energy demands and system safety.
- What is this flexibility for an EV aggregation in a workplace parking lot?
- How can different operational models be designed?
  - What are the inputs, outputs and main processes?
- Could this control approach fulfil frequency market requirements?

1.3 Report outline

The thesis is organised in 5 chapters. It starts with a description of EV charging framework and grid constrains. Next step is explaining the methodology for the design and implementation of the Simulink model. Finally the results from the different cases investigated are presented along with a techno-economical analysis and some suggested future work.

- **Chapter 2** starts with an introduction to EV charging control architecture and grid constrains. In addition to an introduction of the distributed approach.
- **Chapter 3** starts with explaining the design of the EV charging model. It also gives an schematic overview of the system and finally the realised model in Simulink along with the description of the implemented logic.
- **Chapter 4** shows the historical EV driving pattern. The different charging control cases are introduced and results from the simulations are shown.
- **Chapter 5** concludes the thesis by summarising the most important findings, answering the questions raised in Chapter 1, and suggests the future work.

2 EV charging framework

This chapter introduces the EV charging infrastructure and the behaviour accompanying the charging process. Most of the charging process is thought to happen on the low-voltage levels, hence it is prior to experience a higher overloading as described 2.5. It concludes with a description of different control approaches for smart chargers.

2.1 EV stock increase and charging infrastructure

The transportation sector is going from fully reliant on petroleum, towards a massive electrification. As mentioned in section 1.1, EV penetration is expected to increase almost exponentially, and as shown in the left side in figure 2.1, from 2010 and until today, it has already started. From less than 1% of the European passenger vehicle fleet in 2020, to between 10% to 20% in 2030. Running vehicles on electricity instead of petrol, will shift demand from petrol stations to charging stations. A massive investment in charging infrastructure is required, however deciding the charging technology and location is still a challenge for investors and policy makers.

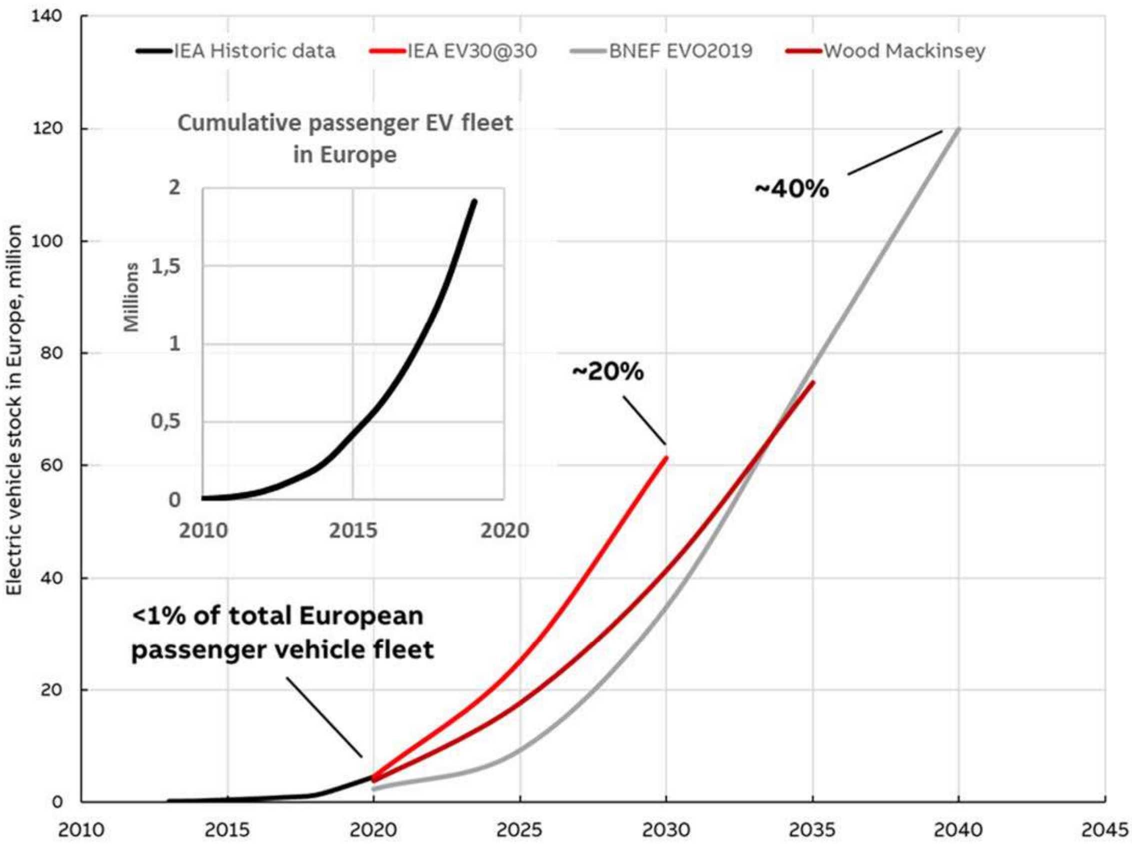


Figure 2.1: Projections of EV stock in Europa [24]

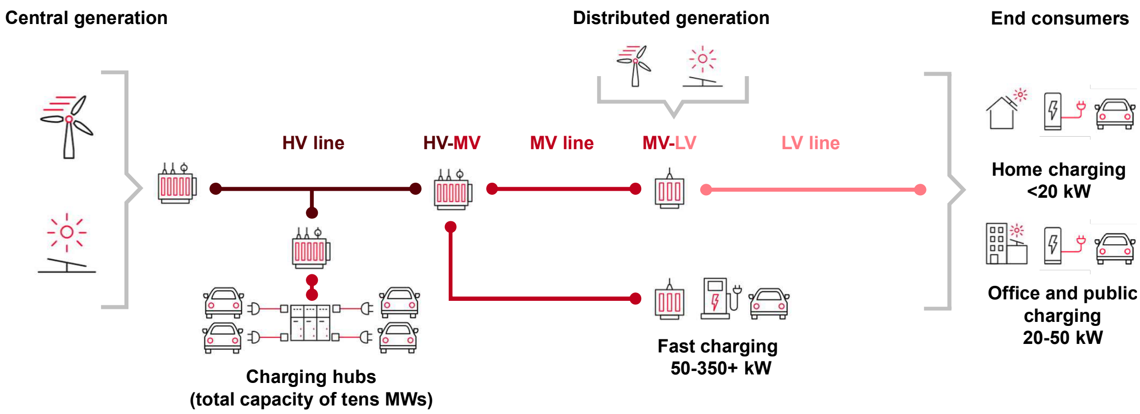


Figure 2.2: EV charging area of impacts on the power system [24]

For sparse populated areas, such as the Nordic regions, a higher share of EV charging is expected to occur at home. Especially in semi-urban and district areas, because higher share of residents have their own parking space, with access to power. People resident in more urban areas, are more likely to park on public roads without access to private chargers. For example, in the greater Copenhagen area 53% of households in Lyngby-Taarbæk municipality have access to parking on own property, compared to 12% of households in Frederiksberg municipality [19]. A significant part of the EV stock is therefore dependent on public or office chargers. A common attribute to home, office and public chargers is that they are all located at the low-voltage distribution grid side, as seen on the right side in figure 2.2.

This is often far away from where large central generating units are located, thus more power need to be transported through the grid, which again could lead to premature upgrade of existing transformers and cables. The exact amount of power needed is hard to predict, but an estimate, depending on total vehicle driving distance per capita and its average energy consumption per capita, for some countries, is provided in Figure 2.3.

An rough idea of the demand increase as an effect of electrification of the transport section lies between 10-30%. Two outliers, Singapore and Norway have an estimated lower demand increase around 5%. For Singapore it is assumed that the reason is due to the small geographical size of the country, and therefore short driving distance. For Norway it is more likely related to the fact that electricity consumption already accounts for the greater part of the total energy consumption. Although the 10-30% total electricity demand may not sound that much, the problem is usually not with the amount of energy that the grid can transport over time, but rather the peak load sustained by the grid during high demand periods. A typical load profile dependent on charger location can be seen in figure 2.7.

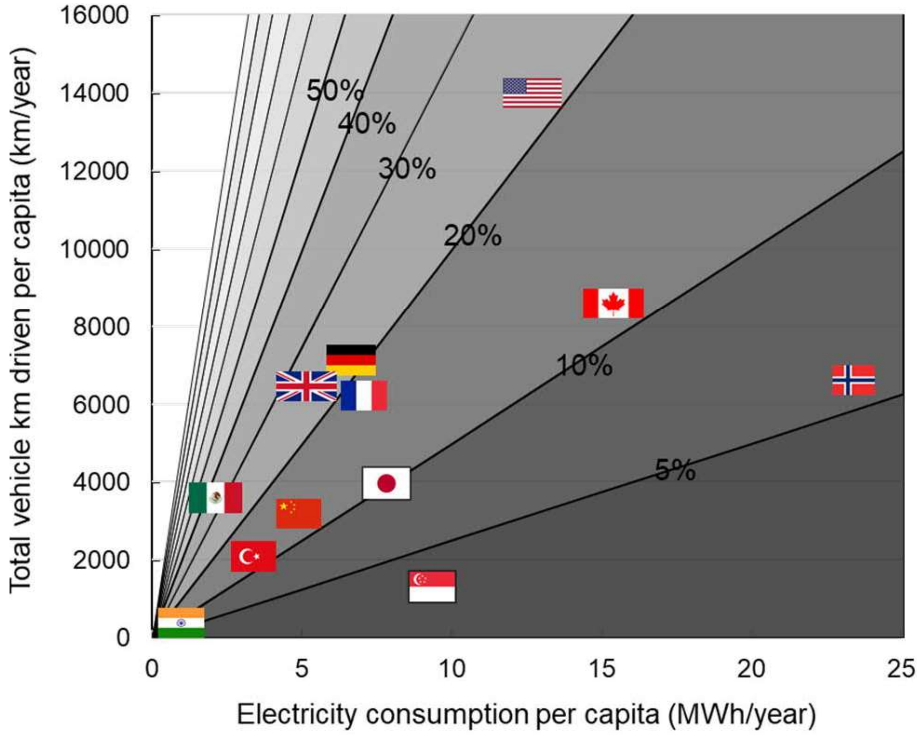


Figure 2.3: Charging demand increase as a percentage of the total demand per country, assuming 100% electrified passenger car fleet [24]

2.2 Distribution grid loading and EV adverse effects

Historically the electricity systems have been built to handle peak loads during the high demand season in a year. Usually, in the afternoon between 17:00 to 20:00 during the coldest winter months. Transformers and cables are the components that tends to get overloaded. Transformers have a long lifetime, often 25-35 years, but some more than 40-50 if not severely loaded [25]. A requisite for long lifetime of transformers is making sure they are not being overloaded, as even short periods of overloading tends to reduce their lifetime. 30 years is a long period in times when technology rapidly evolves and demand changes. For these two reasons, when deciding the size of a new transformers, it is common practice to over-size it.

In the distribution grid, the grid is less stiff at the outermost radials of the low voltage electrical system, and keeping voltage levels within limits are more difficult. The harbour town of Tejn, on Bornholm is a good example. More specifically terminal 4379 as seen in figure 2.4 next to the capital letter B. In [12], station 29 of Tejn is analysed. Further, the grid layout of Tejn can be seen in figure 2.4. In the above mentioned paper, the authors show that EV charging could pose problems in term of congestion issues when considering very high EV penetration. The main problem related to one-phase charging is voltage unbalances. Despite the chargers being distributed evenly across the three phases, charging patterns still affects it. The resultant voltage analysis of terminal 4379 in Tejn can be seen in figure 2.5. Under-voltage outliers are observed from 50% EV penetration and above, but are still within the EU standard, which is the reference voltage level $\pm 10\%$.

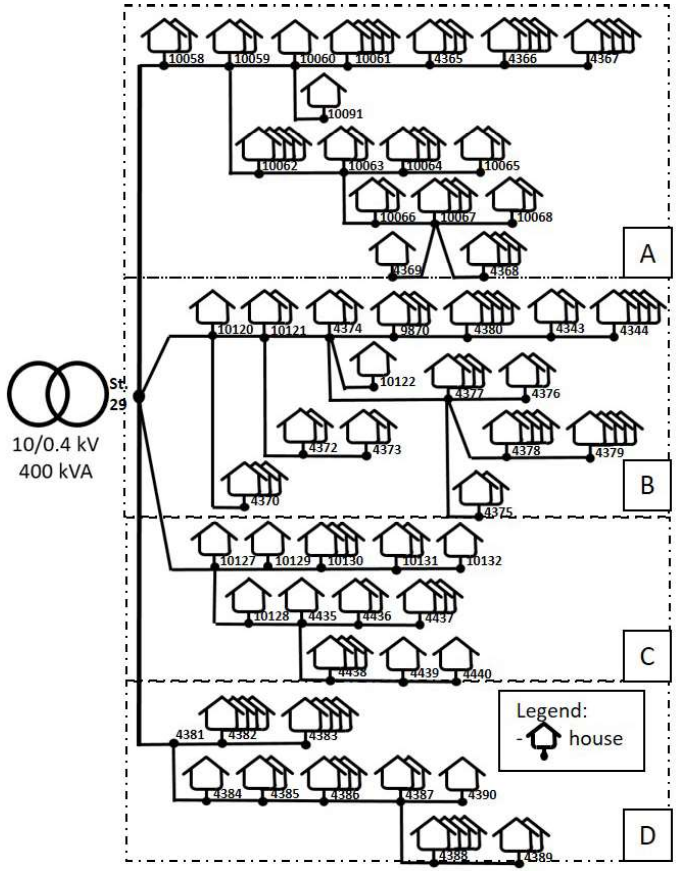


Figure 2.4: Tejn grid layout [12]

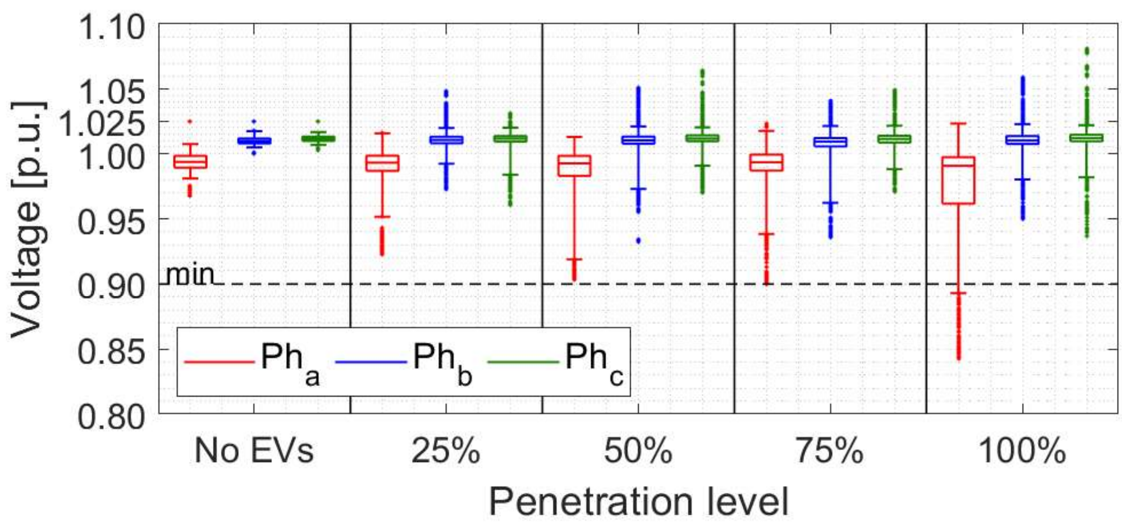


Figure 2.5: Phase-to-neutral voltages for junction 4379 for EV penetration levels between 0 and 100% [12]

In conclusion, the authors describe that even though the energy consumption is the same, when considering three-phase charging, charging power is tripled, but simultaneous charging time is lower. Therefore the combined peak only increases 50%. This can be seen in figure 2.6. The system is also more balanced. This indicates that in three-phase charging, problems tend to relate more to transformer and cable congestion when compared to single-phase charging. Result of three-phase charging shows that only 100% EV penetration actually initiates problems in terms of congestion. However, authors at [12] consider only home charging, but point out that in the future, with more workplace and public chargers this could affect the total charging profile. An estimate of future charging profiles and their share of EV charging in 2020, 2030 and 2040 depending on location can be seen in Figure 2.7. The share of workplace and public charging is expected to increase, while the share home charging is expected to decrease. The trend is expected to continue towards 2040 [26].

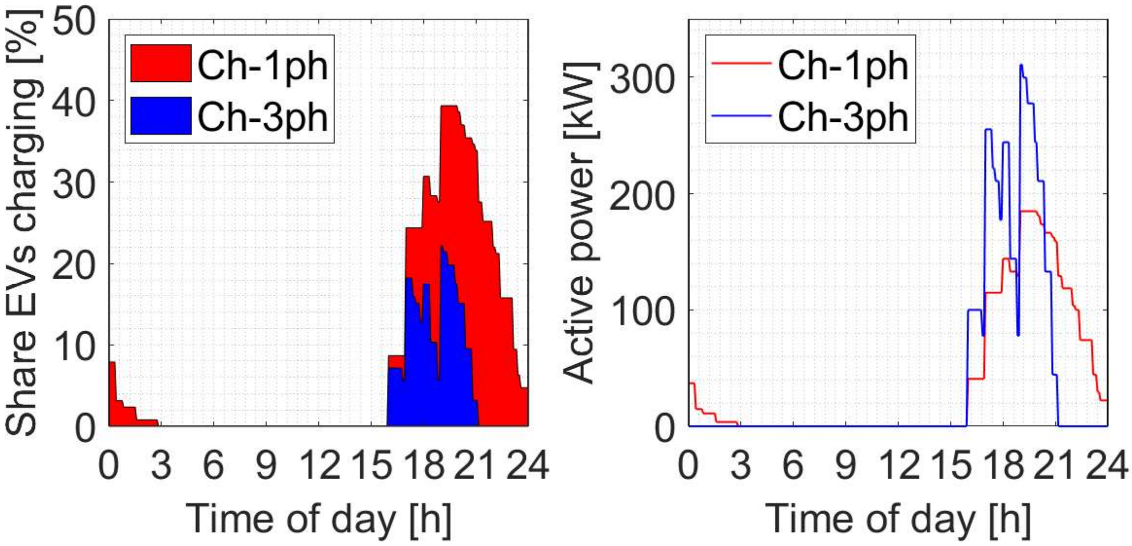


Figure 2.6: Comparison single-phase and three-phase charging with 100% EV penetration: on the left the share of EVs charging, on the right active power during one-day period [12].

In an investigation done in [24], the distribution transformer is overloaded at 26% EV penetration, during a winter evening. Given the following assumptions: previously peak load corresponded to 90% of rated power, a PV penetration level of 32%, 70% of EV charging share occurs every night, 30% twice a week, annual household demand 3100 kWh, charger size of 7.7kW, and PV size 6m^2, also assuming the charging profile location share in figure 2.7.

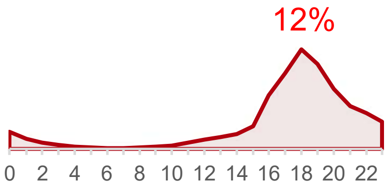
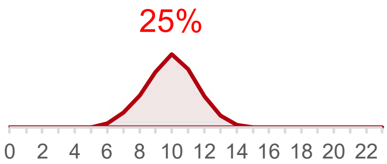
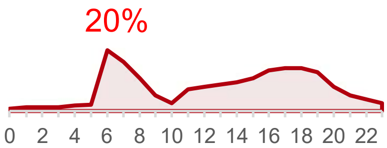
Location	24h profile	2020	2030	2040
Home		85%	60%	50%
Work		10%	20%	30%
Public Fast		5%	10%	20%

Figure 2.7: Predicted charging profiles and their added share in demand for different locations in 2020, 2030 and 2040 [24].

2.3 Uncontrolled and controlled charging

When discussing EV charging we normally distinguish between uncontrolled and controlled charging. Uncontrolled charging, also known as ”dumb” charging, is when EVs charge at maximum power as soon as connected to the grid. Nowadays it is normal to have a passive (dumb) charging strategy. The most common passive strategy is to charge at night. The incentive for this from an EV owner perspective is a lower electricity price during night time. There are several companies providing EV home charging solutions with smart charging capabilities, an overview of models and capabilities is given in [27]. However, EV owners who do not have the luxury to charge at home, or company owned EVs, rely on other options such as public chargers or workplace chargers.

Smart charging allows EV owners and grid operators to optimise charging to get economic and technical benefits. This could be achieved by e.g. schedule charging to reduce peak consumption, price or CO_2 emissions. Ideally this should be coordinated autonomously, without the need for other inputs than the desired SOC and departure time. This thesis focuses on autonomous controlled unidirectional charging in a workplace parking lot utilising a distributed control architecture.

Unidirectional charging is by far the most common way EV charging is adopted. Unidirectional charging delivers power from the grid, to the EV battery, when plugged into the socket. One-phase charging usually ranges between 6 - 16 or 32 Amps, or 1.4 - 3.7 or 7.4kW, depending on the size of the fuse. Three-phase charging range can go all the way up to 11, or 22 kW depending on the fuse size, assuming that the EV is capable of delivering this power to the battery. Figure 2.8 shows a technical categorisation of EV chargers, which are moving from grid connection to grid integration.

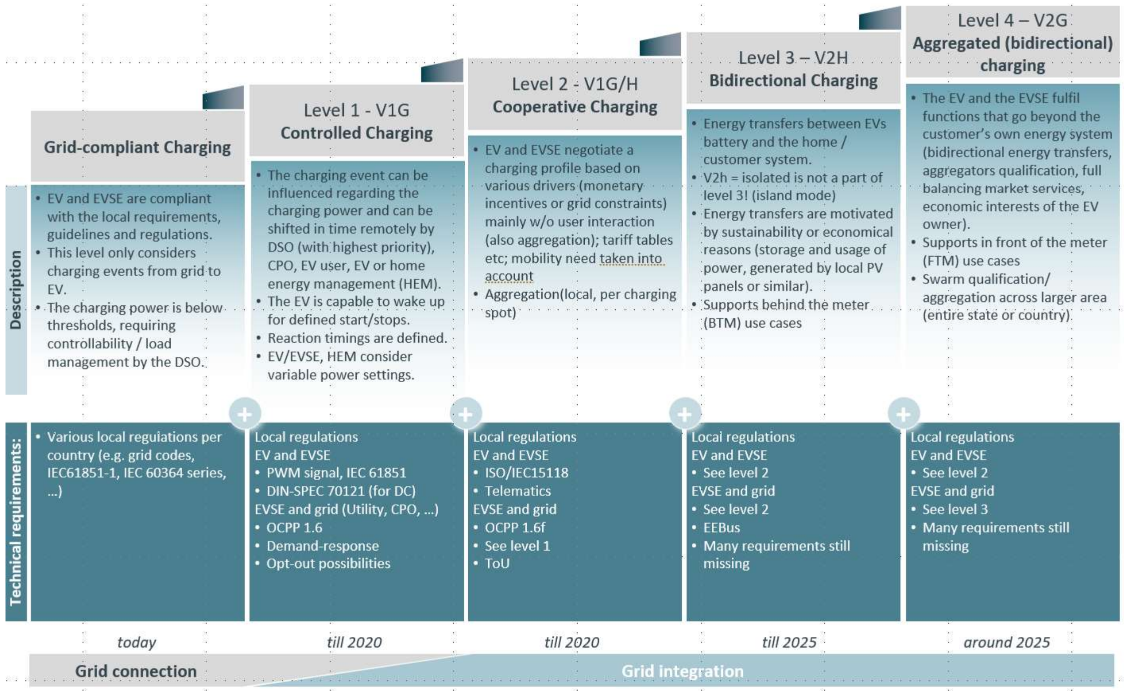


Figure 2.8: EVSE - electric vehicle supply equipment CPO - charge point operator. Chargers grid integration levels- definitions after focus group survey [28].

This thesis is considering Level 1 - V1G and Level 2 - V1G/H to enable high EV penetration integration. Now the question arise of which control architecture one should aim for. There are pros and cons with a centralised, decentralised and distributed control architecture, which are discussed in the next section.

2.4 Control architecture

There are several definitions of centralised, decentralised or distributed control architectures. This leads to difficulties when comparing and describing control strategies and it is therefore important to distinguish one term from another. A definition based on control architecture is proposed in [29]. The definitions are suggested as the following.

- **Centralised:** One central control element collecting information from remote sites and deciding set-points for remote actuation

- **Distributed:** Multiple control elements organised in a common architecture jointly responsible for decomposing objectives and deciding actuation.

- **Decentralised:** A central (common) control objective is decomposed and delegated to independent local control elements; the local control elements only use local measurements and actuators.

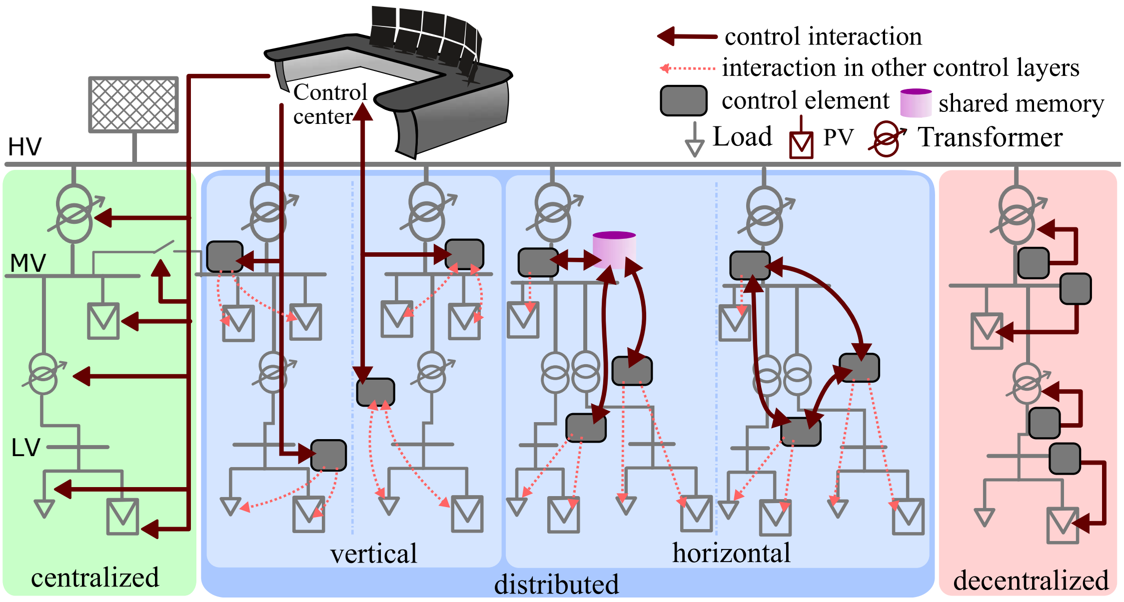


Figure 2.9: Illustration of different control architectures. "The graphic does not account data acquisition subsystems. Large, solid arrows describe interactions within the control layer that are classified while small arrows denote interactions in other local control layers which are out of scope for the classification. The control center represents central control of the system operator (e.g. the SCADA/EMS/DMS functionality)." [29].

Advantages and drawbacks of centralised control, distributed control and decentralised, or local control have been outlined in several papers, and a summary is provided in Table 2.1 below [20], [23], [30]. Although most of these characteristics still apply, the area is developing rapidly. In 2019/2020, for the first time in Norway, demand was automatically activated in the mFRR-market. A total of 7.95MW from panel heaters, EVs and industrial loads was delivered [31].

As elaborated in Table 2.1, there are pros and cons with every control architecture. However, distributed control approach is the most attractive solution for high levels of EVs integration, with the aim of keeping the system cost-effective, reliable and simple, .

This thesis will utilise a control based on a distributed manner, where chargers individually maximise the charging rate of the EV connected, subject to the allocated power limit at the point of common coupling (POCC), or a reference power allocated by a virtual aggregator. More specifically how this can be realised is further elaborated in chapter 3.

Table 2.1: Comparison of control approach.

Control architecture	Advantages	Drawbacks
Centralized	Monitoring from single observation point. Better utilization of network capacity. Better anchillary services provision. Well known architecture. Compatible with current market setup. Operational transparency.	A complex and expensive communication infrastructure is required. A central controller and a backup. Complexity increases with number of EVs. Large amount of data to process. Possible privacy violation. Limited resilience to cyber attacks.
Distributed	Increased privacy. Decreased communication cost. Increased autonomy and scalability. Compatible with market setup	Suboptimal solution. Limited operational transparency. Non-mature architecture. Limited resilience to cyber attacks.
Decentralized	Scalable and autonomous. Improved fault tolerance. Less communication infrastructure is required. Charge control remain in the user. Higher consumer acceptance.	Uncertainty in the final result. Limited ancillary service provision. Necessity of predicting of forecasting the reaction of consumer. Avalanche effects of simultaneous reactions may happen. Non-compatible with current market setup.

3 Methodology

The main objective of the thesis is to design a coordinated and autonomous charging controller. This is important to be able to assess the flexibility that an aggregation of EVs could provide in a workplace parking lot. Furthermore it is also important do define the characteristics of the system, such as assumptions, inputs, outputs and processes in the model to reflect a realistic model that the novel control architecture can be verified.

3.1 Model inputs

3.1.1 EV driving patterns

A secondary dataset was provided containing driving pattern focused on EV availability in a parking lot. The data consisted of arrival time, state of charge (SOC), and departure time for 20 EVs for 24 hours as shown in table 3.1.

Table 3.1: AT - Arrival time, DT - Departure time. EV driving patterns

EV	EV1	EV2	EV3	EV4	EV5	EV6	EV7	EV8	EV9	EV10
SOC [%]	25	17	33	59	58	67	50	58	67	92
AT1	08:47	09:31	08:24	12:22	08:36	08:24	07:47	08:15	07:56	10:40
AT2		14:41	10:40	17::02			12:53			
AT3							16:24			
AT4										
DT1	18:08	12:29	08:52	03:10	20:29	19:25	12:15	18:10	18:03	16:23
DT2		18:00	17:40	16:07			16:06			
DT3				21:34			17:18			
DT4										
DT5										
EV	EV11	EV12	EV13	EV14	EV15	EV16	EV17	EV18	EV19	EV20
SOC [%]	42	33	33	75	67	17	42	83	92	50
AT1	07:25	07:35	06:46	08:31	08:55	06:28	08:01	08:56	06:37	09:52
AT2			08:51			11:41			14:35	
AT3			14:38							
AT4			15:11							
DT1	17:01	19:55	05:52	17:12	22:16	09:15	21:49	19:17	11:50	18:04
DT2			08:31			17:06			17:06	
DT3			14:15							
DT4			14:39							
DT5			20:26							

It was assumed that the SOC, was recorded when the EVs arrived for the first time, and that during the time parked, the SOC would not be reduced. Based on the data, some EVs leave and return several times during the day, for simplicity, and since only 1 SOC was provided, it is assumed that the EV returns with the SOC it had when it left. All EVs are assumed to be a Nissan Leaf with a 24kWh battery. Another two of the EVs arrived with the SOC goal already fulfilled, EV10 and EV19, but was decided to be included. The dataset was analysed to derive an aggregated load profile, shown in figure 4.1. A theoretical total energy charged was calculated, given the constrains of 1 phase charging, and 18 available chargers. This was to enable comparison with other cases investigated.

In the realised model, each EV has a reserved charging spot in the parking lot, which it keeps during the day, even if it leaves and returns several times. The assigning of charging spots is not optimised for maximum delivered energy at the end of the day, and could lead to two EVs parked at the same charger, while both two sockets at another charger remain unused. However this may reflect the unpredictable user behaviour of those who not know about the simultaneous charging constraint.

3.1.2 PV production and Office load profile from Risø Campus

Historical PV production from Risø Campus was provided along with the buildings load profile. This raw data was collected from the Smart-meter at campus. The original PV production was based on a 10 kW system from Risø Campus. The PV size was artificially increased and can be seen in figure 3.1 along with the office consumption.

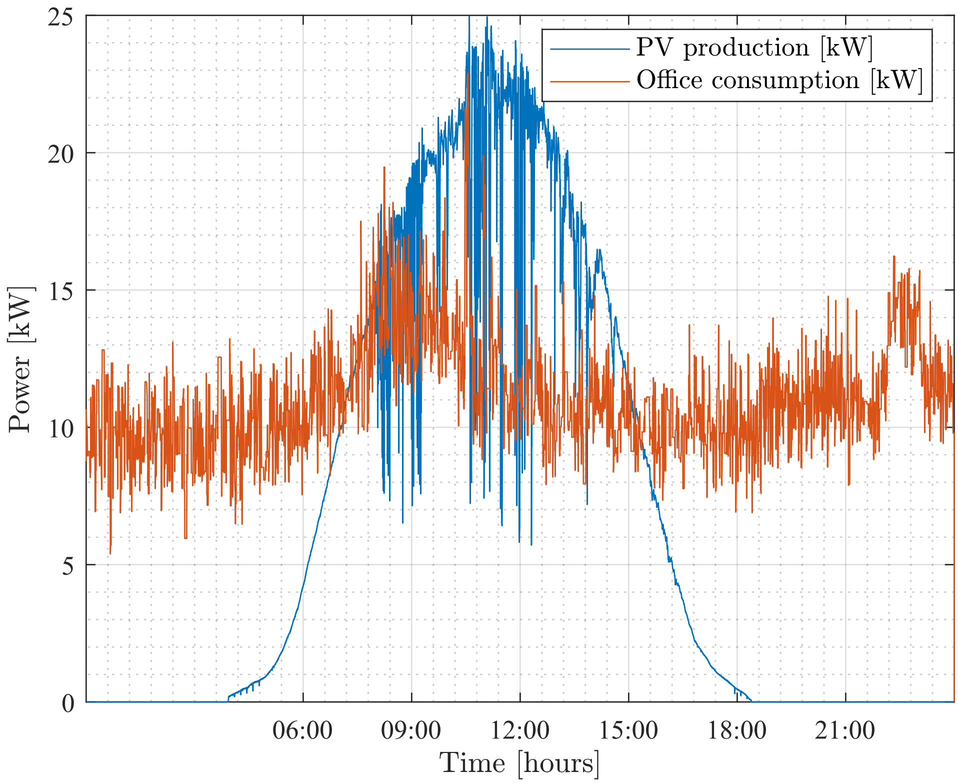


Figure 3.1: PV production and office consumption at Risø Campus

The PV production was increased by a factor of 2.5 to better replicate a future scenario where PV plants are sized to cover the office consumption during a normal day. In this way the model could also be tested to only charge when there is a production surplus.

3.1.3 Early stage schematic

An early stage schematic of the novel control architecture of the EV smart charger is shown in figure 3.2. Step by step the model was developed in Simulink to include the charger control logic, EV model representation, sequential connection logic, virtual aggregator capabilities and priority. A more detailed explanation of every expansion, and its intended function will be outlined in the following sections.

3.2 System modelling

An overview of the system is shown in figure 3.3. From the bottom left, the distribution grid and the local transformer is delivering power to the distribution board, as in a normal

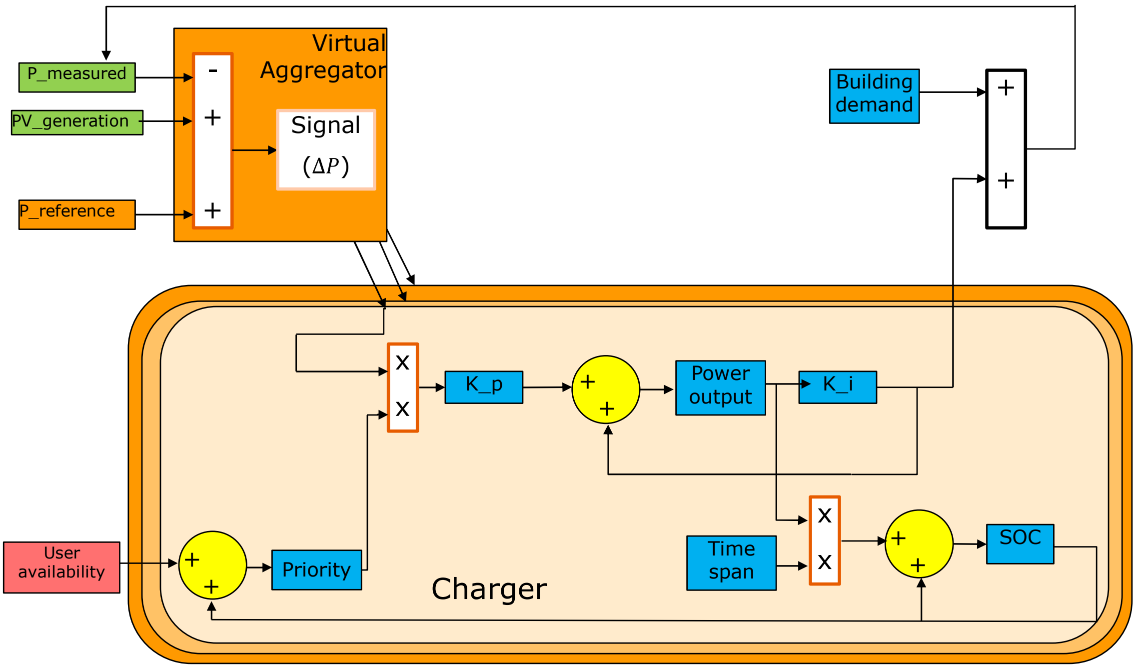


Figure 3.2: Caption

building. From the bottom-right inputs such as workplace loads, charger demand and PV production also goes through the distribution board, and is recorded by the smart-meter. The smart-meter distributes information about the load from what is now named point of common coupling (POCC). The POCC can be thought of as the connection points for electrical loads, or a bus bar. This signal goes into the Virtual Aggregator (VA). Inside the VA, the load from the POCC, $P_{measured}$, is subtracted from the $P_{reference}$ as shown in equation 3.4. $P_{reference}$ is a signal that represent a dynamic power threshold. $P_{reference}P$ is determined based on the characteristics of the electrical system, such as fuse size, and desired mode of operation. The VA distributes a signal, ΔP to the charging controller. The ΔP can be thought off as the measured error, in terms of control theory. Both the VA and the charger are physically in the same unit, inside the charger unit at the parking lot. The charger outputs a control signal to the EV, which then the onboard charger follows, and the EV receives its charge. The mode of operation, known as modes, can be determined by the user or DSO. This could be to only charge when price is low, only charge surplus PV production, or demand response such as limiting the total consumption on the POCC. In other words, flexibility.

3.2.1 Virtual aggregator

The VA can be thought of as the coordinator for the chargers. It is connected to the cloud, and receives signals hereafter. In this model, only one VA is distributing the ΔP. A more redundant system could be realised by including a VA in every charger, where every VA could take the role as coordinator, if the current coordinating VA breaks down. The most important feature of the VA, related to control of the power is, as described in section 3.3 to calculate, and distribute the ΔP.

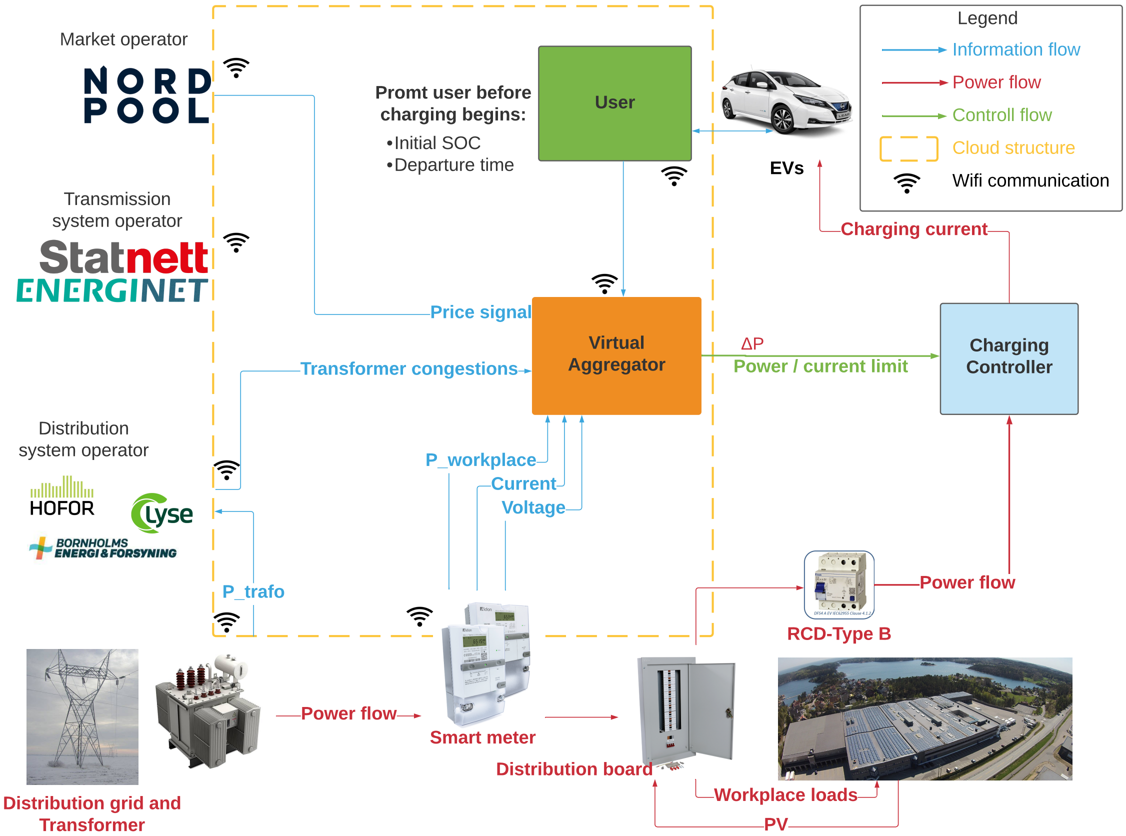


Figure 3.3: Overview of the system

The VA also incorporate capabilities of PV production matching, through measurement from the smart meter. In the future, it could be possible with predicted production matching. In this thesis, only historical data from office load, and PV is used to showcase the aggregated response from the EVs. In the model, a signal can be sent to the VA to change $P_{reference}$ to effectively limit the load of the chargers at the POCC to e.g. 75% or 50%.

In a bigger picture, if the TSO requires congestion management, a signal from the TSO can be sent to an aggregation of VAs in an area, which again controls an aggregation of chargers to limit, or increase its consumption. However, currently this requires that a larger quantity of chargers are connected, because to participate in the manual frequeny restoration reserve (mFRR) market, current market regulations requires minimum bids in MW-range [32]. The mFRR market is a manually activated frequency reserve capacity market. A TSO is required to have some reserves in case of a faults where large production units disconnects unintentionally. Large consumers or power plants can offer their services, usually reducing loads, or increasing production, which the TSO can activate in case of a larger frequency deviation.

3.2.2 Priority

Based on the current SOC of the EV, $SOC_{i,t}$, and time of departure, TOD, priority is given to the EV, as shown in equation 3.1.

$$Priority = \frac{SOC_{i,t}}{TOD} \tag{3.1}$$

Priority gives it a status of either high, medium, or low, and charging power is decided thereafter. This is not to be confused with the connection logic, which is a separate functionality. If an EV leaves and returns several times during a day, the priority is calculated based on the nearest departure time to come, hereby securing a higher SOC when departing. Priority calculations are compared with some threshold values, plus a safety margin to decide a high, medium or low charging output.

In the case of two EVs parked at the same charger, with a combined averaged low SOC, higher priority will be given to this charger as well. This to ensure that in the mentioned event, the unfortunate second EV will have an increased chance of receiving charge.

3.2.3 EV battery model

All EVs are modelled as a Nissan Leaf with a 24kWh battery. The most important function this block in figure 3.4 intends to realise is the SOC. In addition, it gives a signal if the SOC goal is achieved.

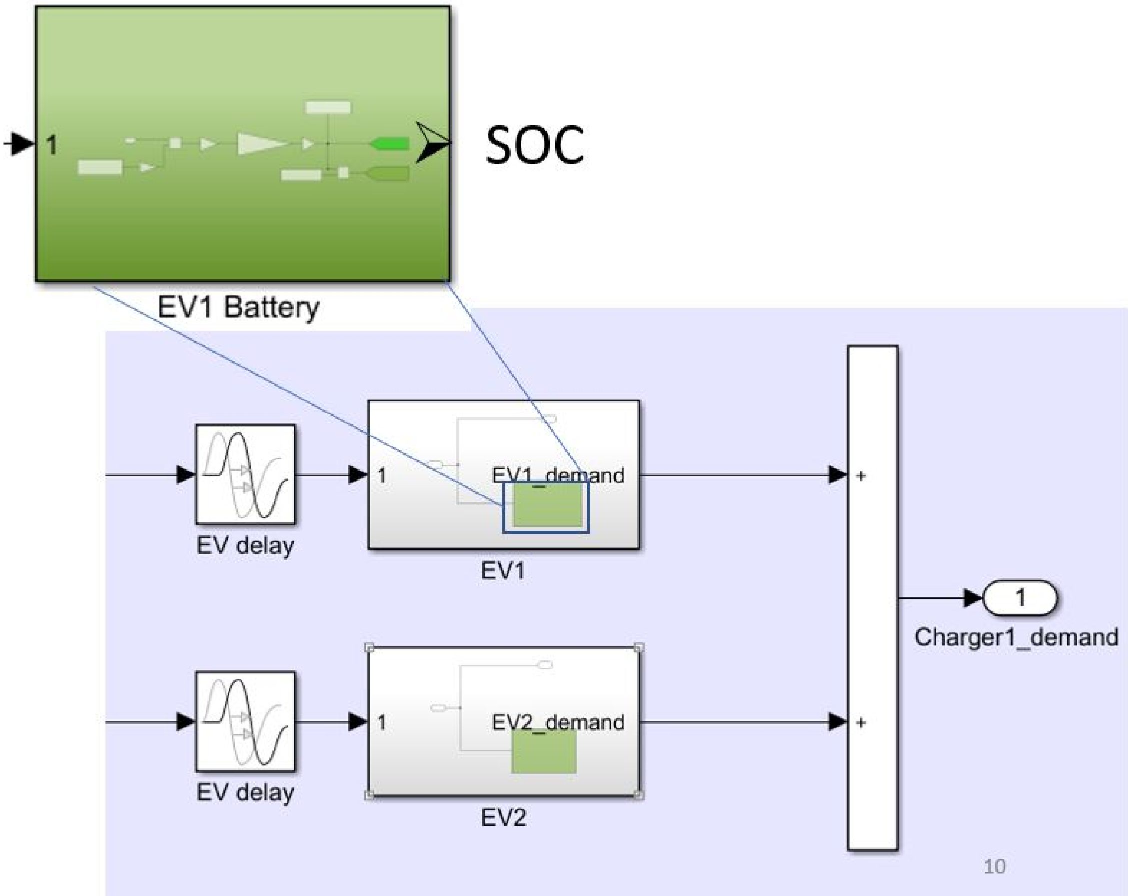


Figure 3.4: EV battery model

In general, SOC of an electric battery can be defined as the remaining battery charge, and is derived as a ratio between currently available energy and maximum available energy, when fully charged. Simplified, it can be expressed in the following way:

$$SOC = \frac{kWh_{available}}{kWh_{max}} * 100\% \tag{3.2}$$

Some manufacturers tend to limit the usable capacity of the battery, i.e. only allowing utilisation of 95% of the battery. The reason for this is related to preventing battery degradation. A battery requires DC power supply to charge, thus every EV have an on-board rectifier. Most electric motors found in EVs, requires AC. Therefore it also need an inverter. Usually these are combined in a single unit. In Simulink, the SOC is realised independently for every EV in the following way, described in equation 3.3.

$$SOC_{i,t} = SOC_{i,0} + \int_0^t P_{i,t} dt * \eta_{i,ch} \tag{3.3}$$

The current SOC is dependent on the accumulated power, $P_{i,t}$, and the initial SOC, $SOC_{i,0}$. To simplify, charging losses are neglected, thus $\eta_{i,ch} = 100\%$. It is of note that charging efficiency in a Nissan Leaf normally range between 85% - 90% [33], depending on temperature, SOC, charging power, etc.

A schematic of EV infrastructure is shown in figure 3.5. Two sockets are available in each charger. Nine chargers in total gives a possibility of 18 EVs plugged in simultaneously. This enables more EVs to be connected at the same time, and potential flexibility increases. It could also reduce the need to manually go to the parking lot switch plugs during a normal work day. However, power can only be delivered to one of the two sockets concurrently. The chargers are connected through a 63A fuse to the POCC. The building load and PV panels are on separate fuses. Measurements from the smart meter is transmitted to the virtual aggregator (VA) in a 10 seconds cycle, displayed as a "Measurement delay" [34]. The EVs are assumed to have a 2 second delay within, related to the on-board converter and its software. There is also a transport delay from the POCC to the different positions of the chargers relative to distance. The transport delay is in the range of 1 - 1.4 second with 0.5 second intervals, where charger number 1 have the shortest delay, and charger number 9 has the longest delay.

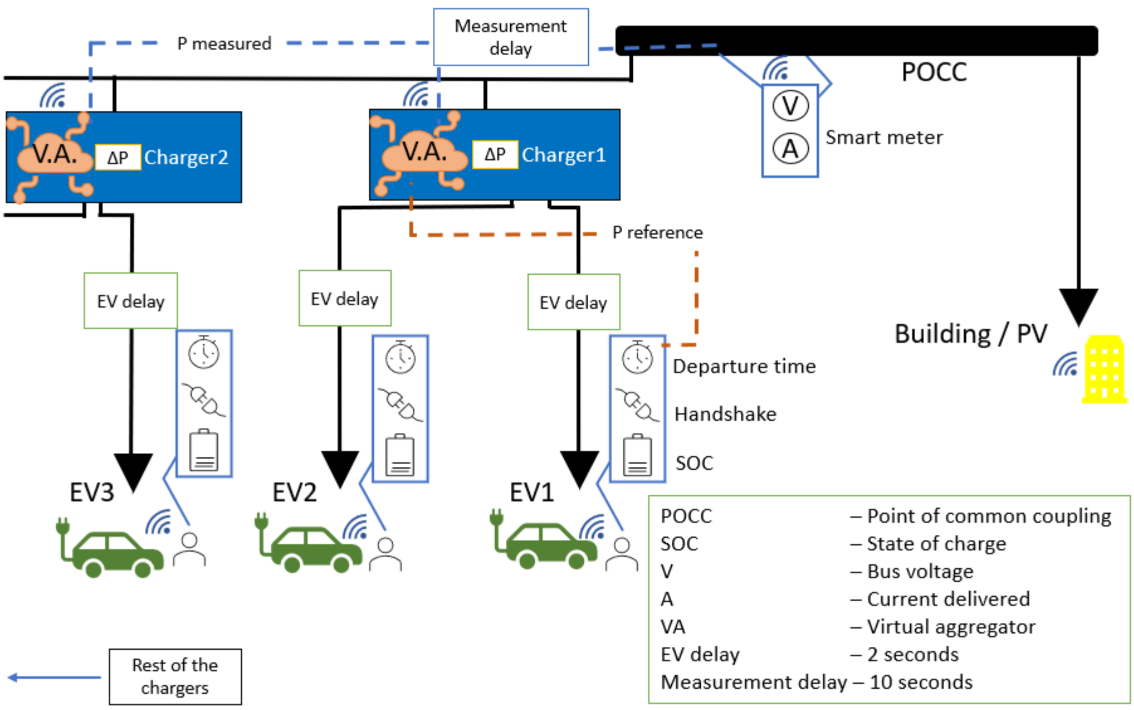


Figure 3.5: Technical schematic of EV infrastructure

3.3 Overview of the autonomous charging model

With data from 18 EVs, a charging model with 9 chargers was developed. The aim of the model was to incorporate virtual aggregator capabilities enabled by one way communication. A simplified simulation model is shown in figure 3.6.

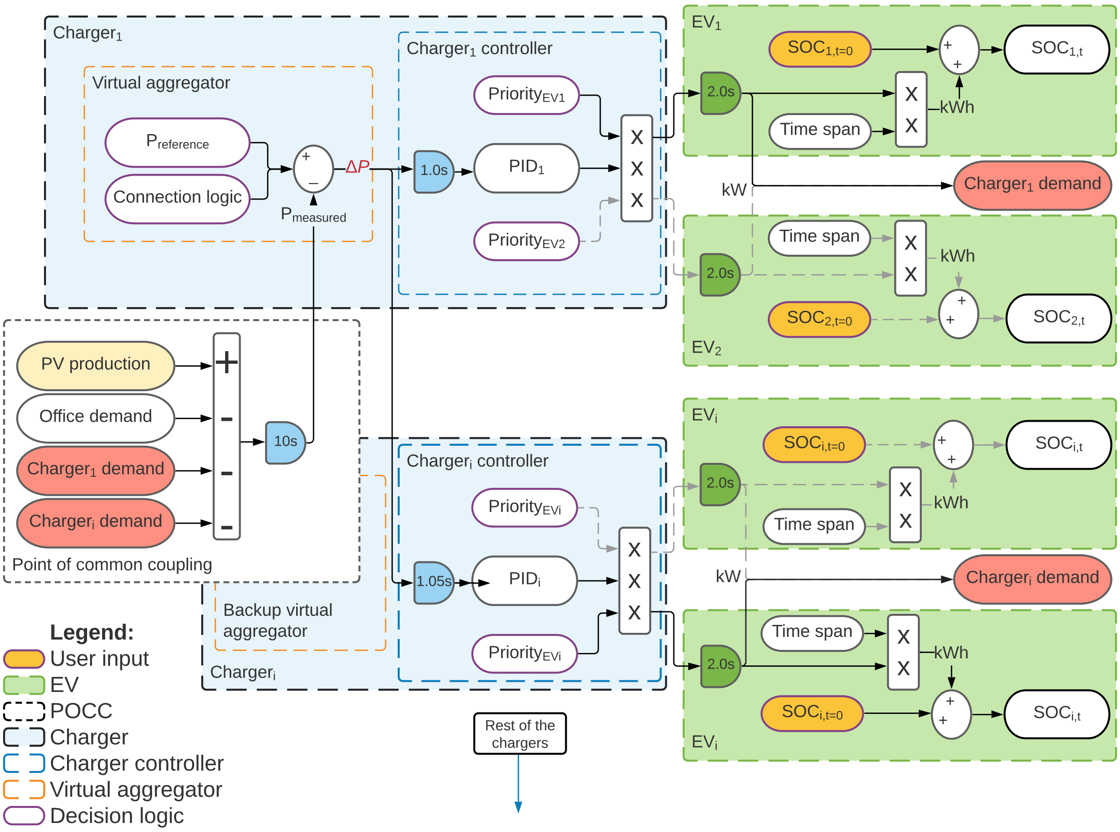


Figure 3.6: Simplified simulation model

Starting from the left, the smart-meter sample values at the POCC, and stream out values every 10 seconds. The virtual aggregator broadcasts the control signal ΔP which most of the time be the error term formed by the reference power subtracted the measured power at the POCC, as shown in equation 3.4. A broadcast delay range between 1 - 1.4 seconds, dependent on the distance from the VA to each charger. The ΔP goes into a proportional-integral-derivative (PID) controller, which effectively controls the output charging power.

$$\Delta P = P_{reference} - P_{measured} \tag{3.4}$$

The chargers output power are also effected by the individual priority level. Priority is based on current SOC of the EV, $SOC_{i,t}$, and departure time. Next, depending on which EV arrived first, the charging starts. The connection logic will be explained in detail in section 3.3.1.

3.3.1 Sequential connection logic

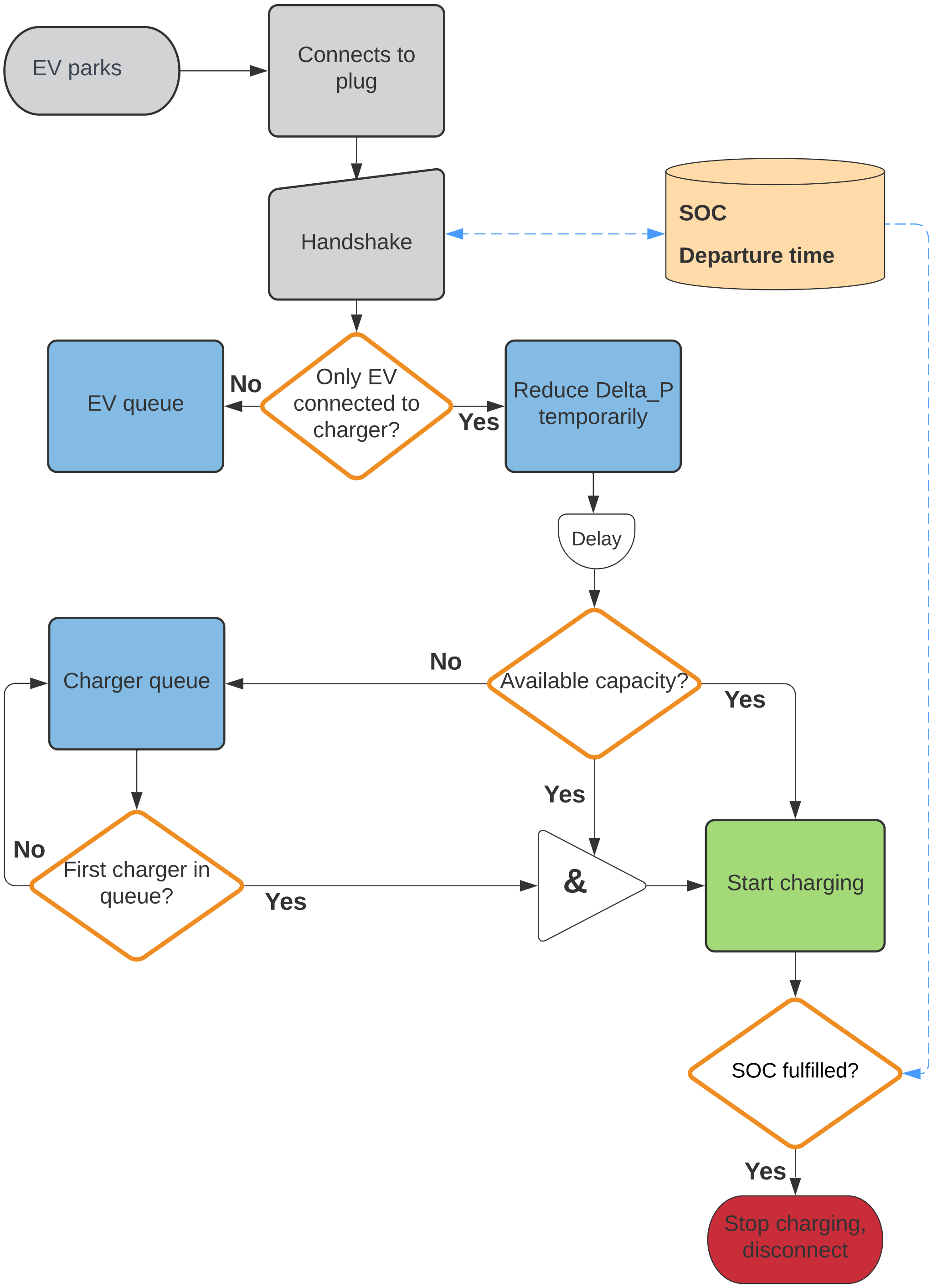


Figure 3.7: EV connection sequential logic

A sequential connection logic was designed in Simulink to demonstrate the desired functionality of the smart charger. Figure 3.7 shows the steps of the decision making logic from an EV arriving at the parking lot, until the SOC goal is reached, or the EV leaves. For simplicity it is assumed that all EVs plug in when they arrive, and handshake goes without faults, illustrated by the grey blocks. Blue boxes represent states where the process is waiting for inputs to continue. Yellow cylinder indicate information from the cloud, via the VA to the charger, prompted from the users. In a real application battery capacity would also be prompted, but here, we are only considering 24kWh batteries. Naturally, the first EV that arrives and connects to a charger is prioritised. The second EV to connect to the same charger will have to wait for the first EV to reach its SOC goal, before receiving any power.

When an EV plugs in, a signal is sent to the VA. In response, the VA temporarily reduces ΔP for 10 seconds. The reduction is subject to the number of chargers already connected, $Ch_{connected}$, as shown in equation 3.5. This ensures a reduction in the right proportion.

$$\Delta P_{temporarily} = \frac{3.6}{Ch_{connected}} \tag{3.5}$$

The reason for a 10 second reduction is due to the smart-meter duty cycle. The VA is receiving 10 seconds delayed discrete measurements, and this reduced visibility from the POCC, from the charger controllers perspective.

Next, the logic checks if there is available capacity at the POCC. If yes, it will start charging. If no, then the charger will be queued. When there is available capacity, the charger first in queue will start charging. To prohibit several chargers to start charging momentarily, the charger second in line, will wait some time, before it moves forward in the queue.

3.3.2 Charger

Since we are considering AC 1-phase charging between 6 - 16A, or 1.38 - 3.68 kW a flat charging curve is assumed. Effects caused by low battery temperature, or high SOC are neglected. These assumptions are fair considering the low charging power investigated. ΔP is the signal the charger receives from the VA. The charger control unit, a PID controller, have been tuned by trial and error. The aim was to achieve a fast charging controller, without compromising stability. In general a faster response is considered an advantage. However the plant, in this case the EV on-board converter, will have some limitations outside of the chargers control when it comes to adjusting charging power.

According to the standard IEC 61851, the signal on the communication line, named Control Pilot line, is used to limit the allowed upper charging current [35]. This is done with Pulse Width Modulation (PWM), that is adjusted by changing the duty cycle of the signal. For sake of simplicity a PWM signal is not incorporated in the model. The current can be limited between the minimum current, 6A and in granular steps of 0.6A up to rated current, which is limited to 16A in this case. This is achieved by using a quantizer block. The PWM signal is only limiting the maximum current allowed, but it is the characteristics of the on-board converter, and the software controlling it, which dictates the actual current drawn, and the rate of which it is happening. The model accounts for this by a 2 second "EV delay", as displayed in figure 3.4.

More chargers connected would synchronise, and their aggregated output power, with an aggressively tuned controller could lead to stationary oscillations. The reason they synchronise is the constant 10 second cycle the smart-meter distributes the current load on the POCC.

4 Results - EV charging simulations

Based on the provided historical driving pattern, a cumulative sum of the EVs that are connected (if the amount of chargers was equivalent to the amount of vehicles) is shown in the upper part of Figure 4.1. The lower part is showing connection of chargers, after EVs have been assigned a charger in pairs of two with the configuration considered in this thesis. As aforementioned in section 3.1, the process of deciding the EVs pairs to a charger is not optimised for best result, i.e. largest total energy charged, but rather to reflect a more realistic scenario. The Simulink model is identical for all cases, except for the differences described in section 4.1. The aim was to opt for the most autonomous solution, rather than the most optimal results, such as SOC goal fulfilment and never breaking the Ampere limit.

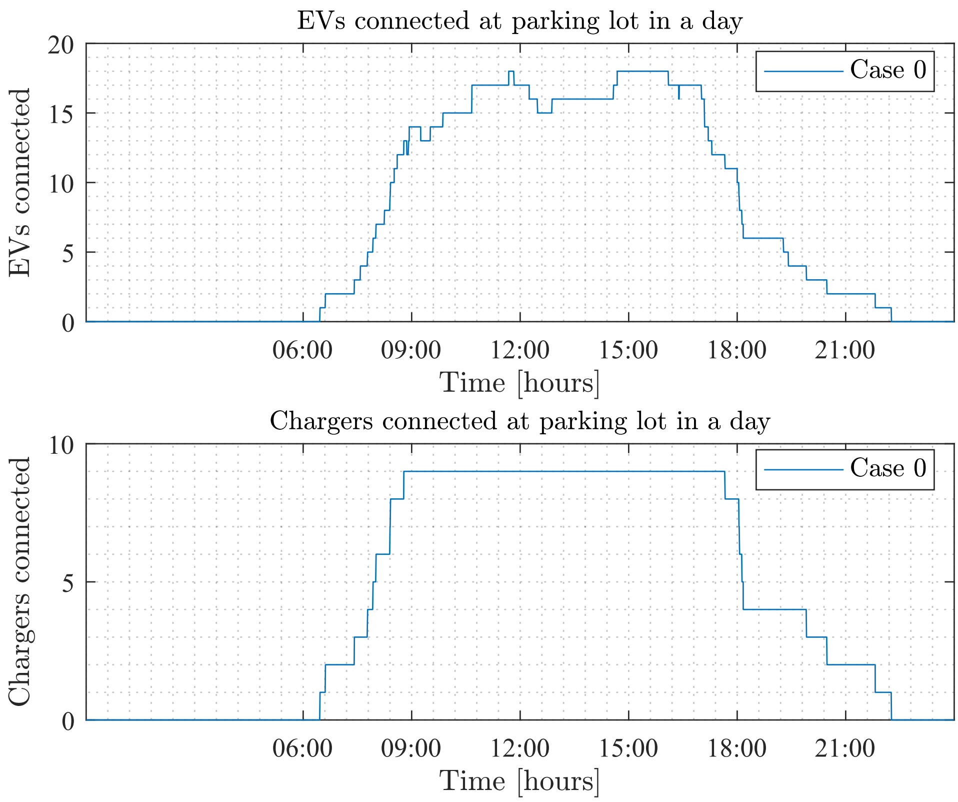


Figure 4.1: Historical EV data; individual, and in pairs of two.

There are mainly two resultant parameters the charging control have been evaluated after. The first was the ability to stay within the Ampere limit, to not blow the fuse. For this model it was 63 Amps. The second parameter was how close the increased SOC of all EVs are to reaching the 90% SOC goal. This is accumulated to a total energy charged, and the final results are presented in table 4.1. After a short description of the different cases, the results are presented in the following order: First, result related to staying within the power limit is presented. Second the resultant SOC for the EVs are shown. Third a comparison of the total energy charged for the different cases.

4.1 Introduction to cases

A total of four cases have been investigated. An overview of the different cases, and what distinguishes one from another is described below. All cases have been simulated for 24 hours, except case 0, which is not simulated, but calculated based on the EV driving data from section 3.1.

- **Case 0**: The base case, also known as case 0, is a theoretical calculation of how the load profile would look, displayed in figure 4.2, assuming uncontrolled charging.
- **Case 1**: Case 1 is utilising controlled charging, but without priority, displayed in figure 4.3.
- **Case 2**: Case 2 is utilising controlled charging, with priority.
- **Case 3**: Case 3 is similar to case 2, but now behind the meter production and consumption are added, PV and office consumption, respectively.

Case 1, 2 and 3, are also divided into three different scenarios. The scenarios differ by adjusting the $P_{reference}$, i.e. adjusting the dynamic power threshold.

- **a**: $P_{reference}$ is kept at 100%
- **b**: $P_{reference}$ is kept at 75%
- **a**: $P_{reference}$ is kept at 50%

A notice for case 3, is that although the reference is kept the same, the PV and office consumption data contain large steps in both production and loads, which resulted in overshooting the 63 Amp limit more frequently than desired.

4.2 Case 0, uncontrolled charging

As seen in figure 4.2, the unconstrained, uncontrolled charging would result in a maximum current of 208 Amps. This would demanded large investments in local grid infrastructure, given the current limit is 63 Amps. Although 18 EVs are considered, only 13 EVs are actually charging simultaneously, but would require owners to move their vehicle during the day, if only 13 chargers were considered. This thesis proposed a solution to this, reducing the amount of chargers while allowing more EVs to be connected during the same time, and in addition reducing the need to move the EVs during the day.

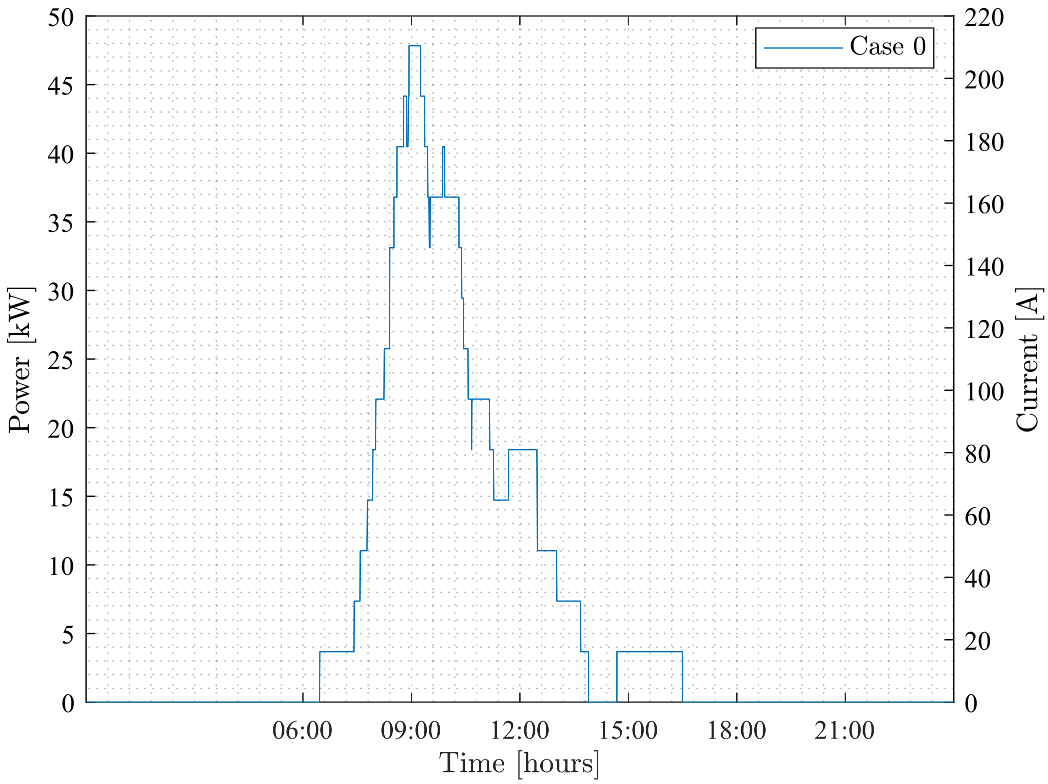


Figure 4.2: Calculated demand with 18 chargers, based on historical EV data.

4.3 Case 1, controlled charging without priority

Case 1 is utilising controlled charging. Figure 4.3 demonstrates that charging can be controlled and kept within limits except for some spikes. This case does not include priority, meaning that all chargers will charge with the same power level between 1.38 - 3.68 kW. There are some spikes violating the $P_{reference} = 63A$ limit, and the fuse limit of 63A. The spike happens after the following event: An EVs battery is full, or the owner wants to leave, and thus stops to charge. This is followed by another charger starting to charge. Common to all these spikes is that they only last for a maximum of 10 seconds. The reason for this is the reduced transparency caused by the 10 second cycle output from the smart-meter. This makes the charging controller "blind" for 10 seconds, allowing the $P_{measured}$ to exceed its limit. The amplitude of the spike is determined by the point of time within the 10 second smart-meter output cycle the described event starts. A more detailed explanation is given in appendix A.1. However the measured spike only last for 10 seconds, and usually is in the area between a 0-20% overshoot. It should be noted the actual spike is higher than the measured one, but also last for a shorter time, due to the measurement cycle. In the end there is a small chance of triggering protecting fuse. This is of course depending on the tripping characteristics of the residual current device. Another solution to reduce overshoot could be to tune the PID controller to have a slower response. Or to implement a safety margin in the $P_{reference}$.

Figure 4.3: Case 1a.

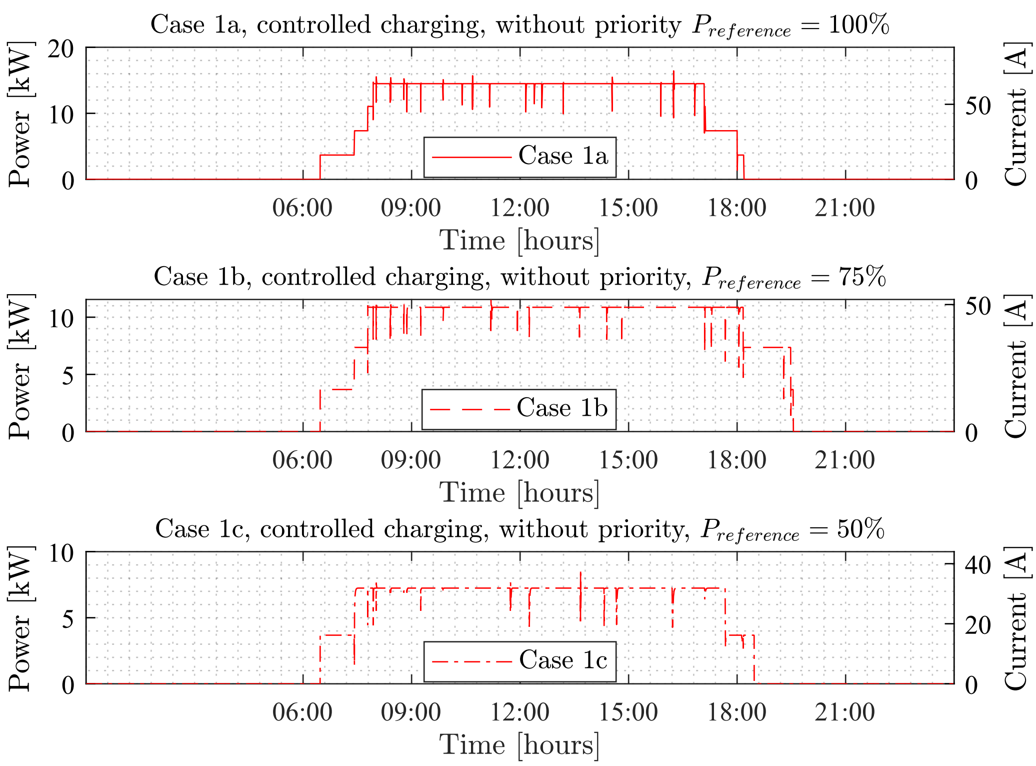


Figure 4.4: Case 1, controlled charging, without priority. Scenario 1a, 1b and 1c with $P_{reference}$ at 100%, 75% and 50%, respectively.

Figure 4.4 gives an overview of the measured charging power for scenario a, b and c for case 1. An interesting observation can be made in for case 1c. Rather unexpectedly the charging in case c ends before case b. Since the charging power is more constrained in case c, on would normally expect the duration of charging to be longer. A analysis shows that this is related to the connection queuing logic. A more detailed explanation is given in appendix A.2. It should be kept in mind that in case number c, only five out of nine chargers can charge simultaneously, so it is a very constrained scenario. Thus in the overall result it has a minor impact. There are some spikes in scenario b and c, but these are even less of a problem since there is good safety margin between the 63 Amp limit and the $P_{reference}$.

4.4 Case 2, controlled charging with priority

Case 2 is utilising controlled charging, and priority. As mentioned in section 3.3.2, a quantizer block from Simulink is normally utilised to replicate the granular steps of 0.6 Amps. A comparison of the result, without and with the quantizer block in every charger is shown in figure 4.5. As seen in the lower part of the figure, some oscillation occur between 09:00, and 17:00. Common for this time period are that there is a high number of chargers charging simultaneously. This is expected to happen because of the ΔP requesting a charging power between two of the steps of 0.6 Amps. When this happens, the PID controller will try to correct the value, which results in the power going up and down between the two closest current levels. Because of the controllers synchronising, the oscillations are aggregated when more charges charge. It was also found that a controller tuned too aggressively, would lead to a bigger problem, causing the controller to change between several steps larger than 0.6 Amps. When the chargers were operating close to their upper and lower limit, 1.38 kW and 3.68 kW, respectively. The controller would try to adjust the charging below or above the minimum or maximum value. This caused larger oscillations. Therefore a function that effectively reduced the ΔP, and thus the input to the controller was implemented. The result of this is shown in the lower part of figure 4.5. However the quantizer block was taken out of the model for all the other simulations, to better show the actual values.

Figure 4.6 gives an overview of the measured charging power for case 2 scenario a, b and c. An interesting observation is that when comparing case 1a and 2a, the priority seems to removes some of the spikes entirely, while others are have a reduced magnitude, and some are moved. It is fair to assume that the spikes with reduced magnitude, which are happening at the same time, come from the priority function. The reason for this is that most likely an EV is given low priority when starting to charge, as priority is calculated based on equation 3.1. The spikes that are removed, or moved, can not be directly linked to the priority function, without further analysis. It is more likely related to the connection queue logic as described in A.2.2. However the only difference between the simulations are the priority function, so indirectly it has an positive impact.

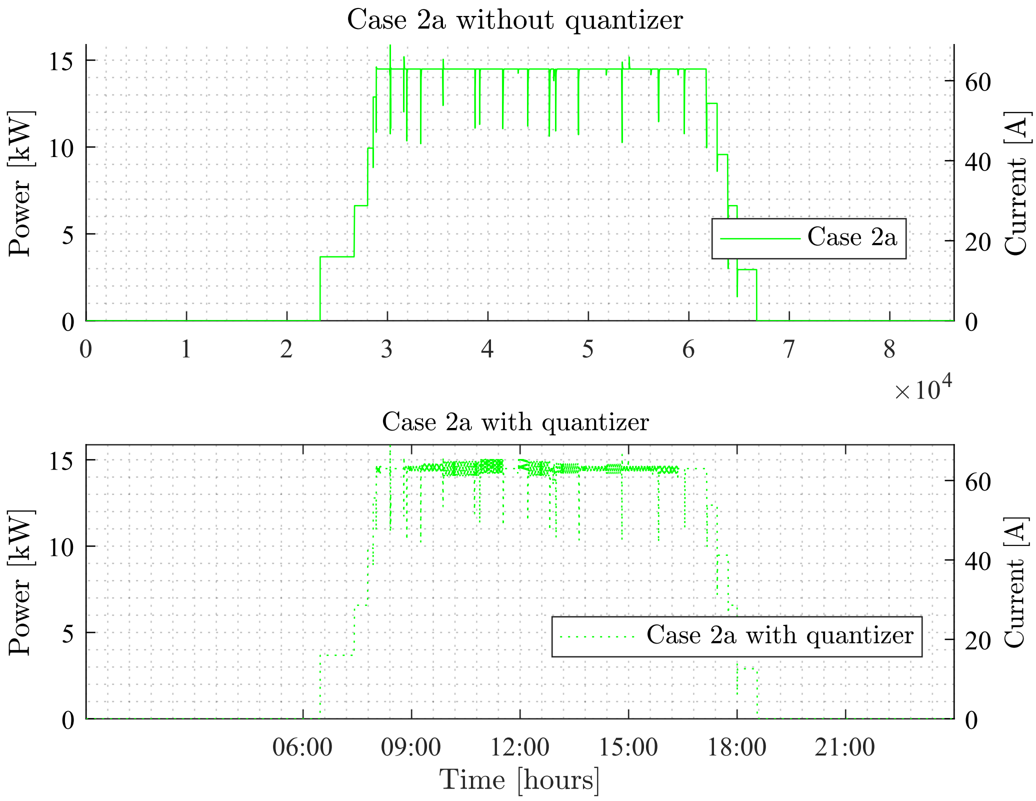


Figure 4.5: Case 2a comparison without, and with quantizer block.

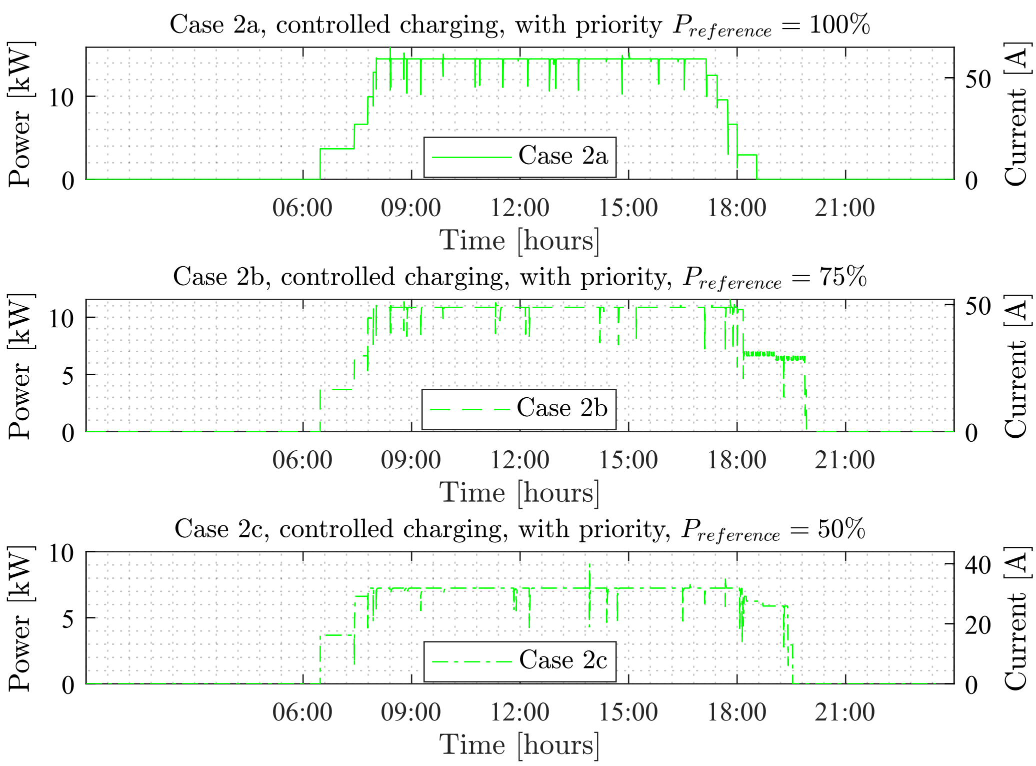


Figure 4.6: Case 2, controlled charging, with priority. Scenario 2a, 2b and 2c with $P_{reference}$ at 100%, 75% and 50%, respectively.

In figure 4.7 the SOC for all EVs are shown during the 24 hour period for case 1a. As mentioned in section 3.1, the process of assigning EVs to charging spots is not optimised for maximum delivered energy. The EVs are assigned a charger in pais of two. EV 1 and 2 on charger 1. EV 3 and 14 on charger 2, EV 5 and 6 on charger 3, and so on. All EVs reach their SOC goal of 90% except for EV 2, which is promising, considering the limited charging power compared to case 0. EV 1 and EV 2 are connected to the same charger. They have both a relative low SOC when arriving, 25% and 17%, respectively. At the same time EV 2 is only connected for 6 hours, and arrives later compared to EV 1. EV 1 starts charging first, which means that EV 2 will not charge until EV 1 is done. This is the reason that EV 2 is not reaching its SOC goal, but instead just below 50%. After analysing table 3.1, EV 2 is only connected about 3 hours and 19 minutes during the second session. Since EV 1 arrived first, the maximum SOC EV 2 can reach is 68%, given the circumstances that it can only charge during its second session.

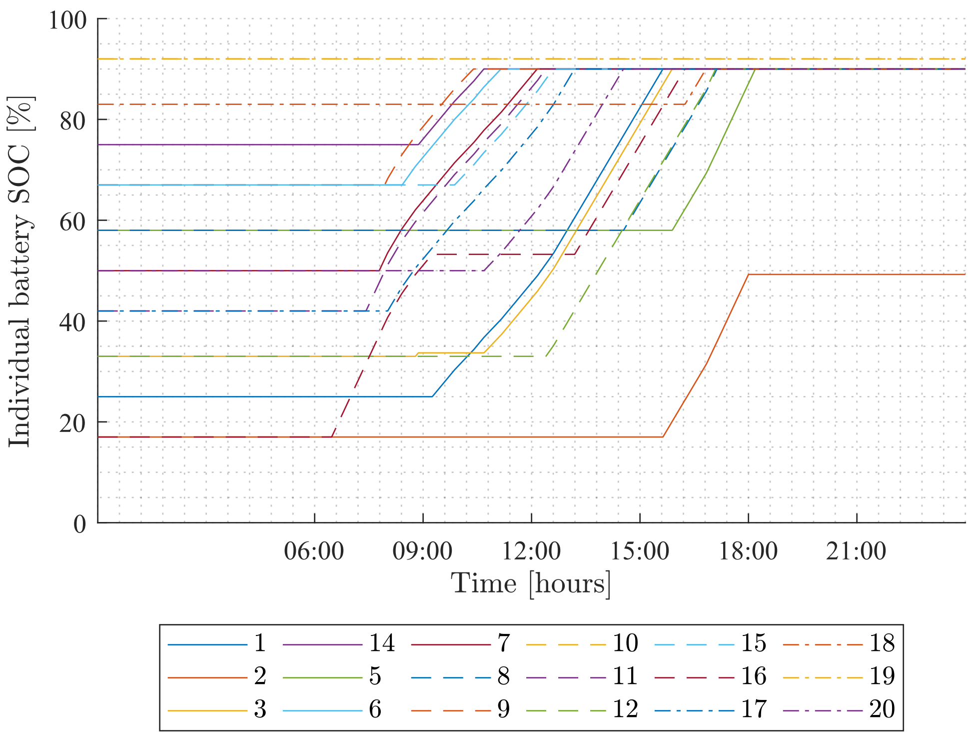


Figure 4.7: Individual EV SOC, case 1a, controlled charging, priority, $P_{reference} = 100\%$.

In figure 4.8 the SOC for all EVs in case 2a is shown. Compared to case 1a there are small differences, but the most noticeable is that EV 2 reaches a 60% SOC. When comparing the SOC curves for EV 1, one can spot that EV 1, the blue line starting with a SOC of 25%, has a steeper curve in figure 4.8, compared to figure 4.7. If looking at the SOC curve for EV 2, the orange line starting with a SOC at 17%, one can also see that it is steeper compared to case 1a. This shows that the priority function as intended.

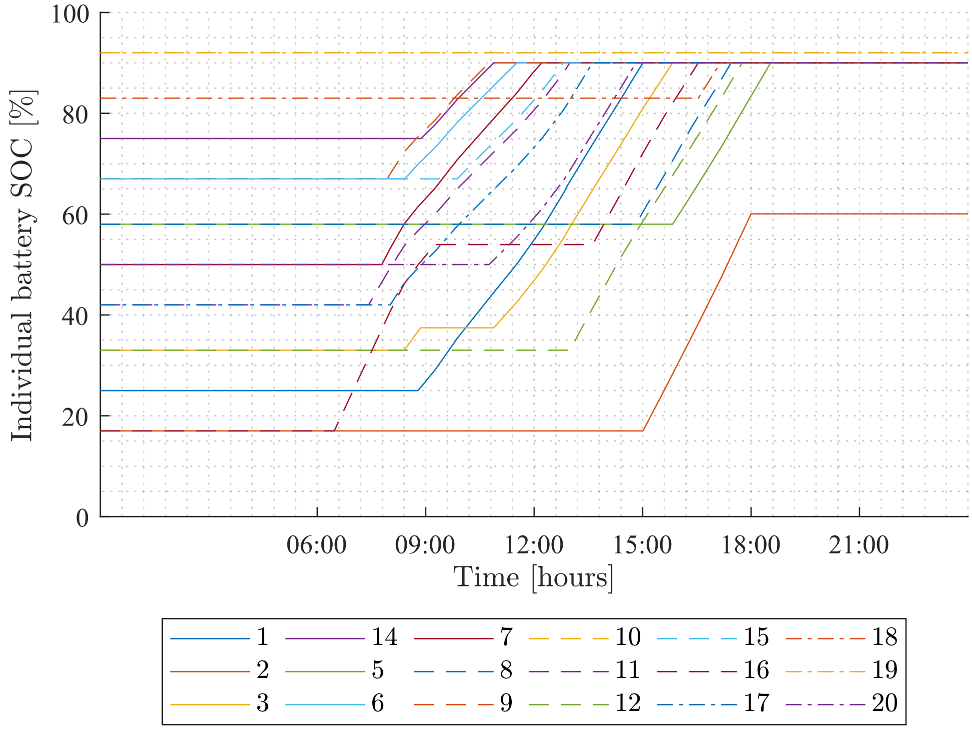


Figure 4.8: Individual EV SOC, case 2a, controlled charging, priority, $P_{reference} = 100\%$.

Figure 4.9 shows the accumulated SOC for every EV in case 2b. EV 2 and EV 16 are the outliers with a SOC at 20% and 69% which pulls the total energy charged down. SOC for EV number 3, 7, 8, 18, lies around 83-90 % which is very close to the goal.

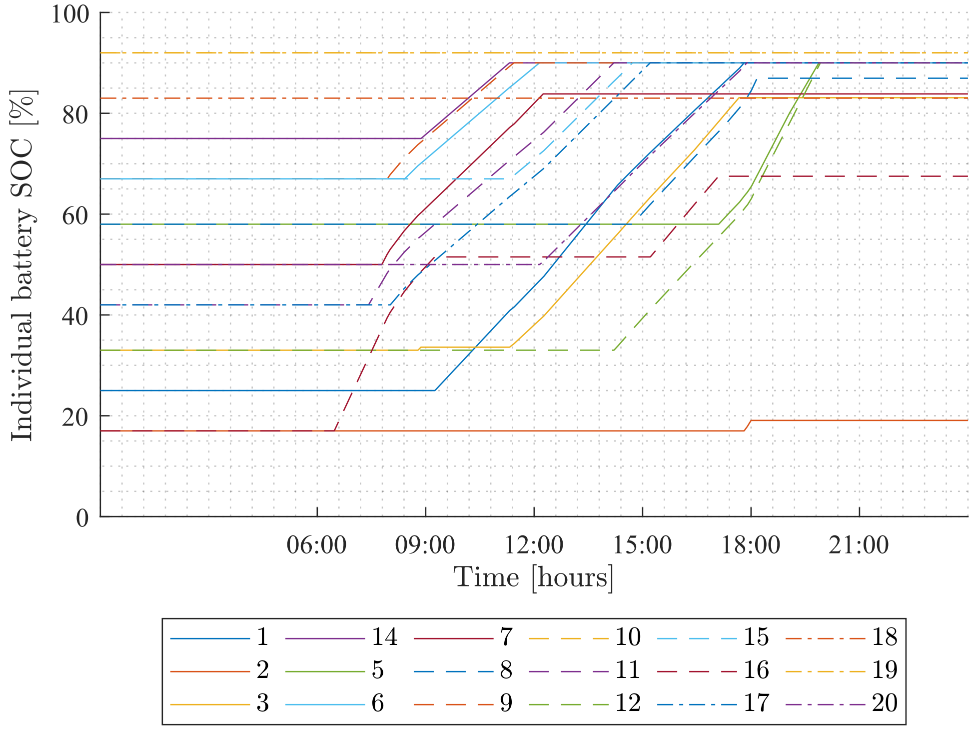


Figure 4.9: Individual EV SOC, case 2b, controlled charging, priority, $P_{reference} = 75\%$.

Case 2c are showcased in figure 4.10. This case is a worst case scenario, but shows the potential flexibility a aggregation of EVs can provide. 18 EVs sharing 9 chargers with a combined max charging power of 7.2 kW, compared to 18 EVs with dumb charging with a potential combined max power of 66 kW. Strictly speaking only 13 EVs would charge simultaneously in this case, so 47 kW would be more fair. However this showcase the large flexibility potential EV charging can provide.

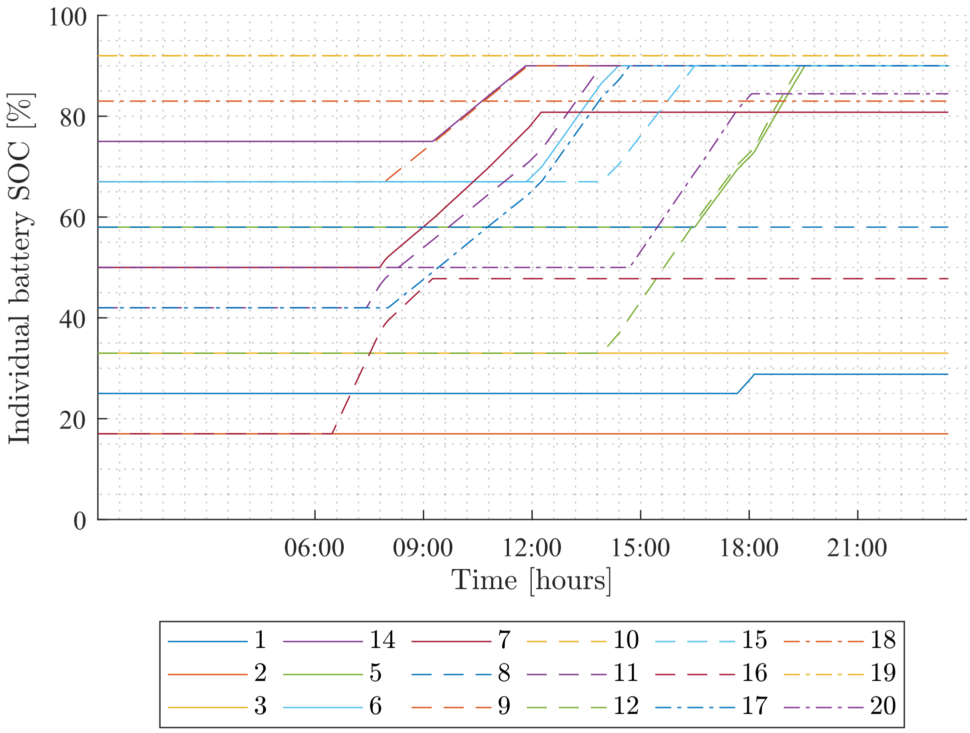


Figure 4.10: Individual EV SOC, case 2c, controlled charging, priority, $P_{reference} = 50\%$.

4.5 Case 3, controlled charging with priority, PV production and office consumption

Case 3 is utilising controlled charging and priority, so its identical in terms of charging control tocase 2. The difference is that PV production and office consumption from figure 3.1 is added at the POCC. So now $P_{measured}$ is the sum of office load and charging load, minus PV production. In the case that the PV is not producing anything, this forces the charging control to take into account that both the office consumption and EV charging does not exceed 63 Amps, or 14.49 kW. Now this case is also a bit on the extreme end, with a PV maximum production capacity of 25 kW, and an office load which averages around 10 kW. It should be noted that there is no lower limit on the $P_{measured}$ variable, meaning that if PV production exceeds the office consumption, the VA will distribute a ΔP with a higher value than the set $P_{reference} = 14.5$. This causes the chargers to exceed 63A limit at the fuse, trying to consume all the available PV effect, as seen in figure 4.11. This makes a direct comparison between the other cases less suitable, but it is an interesting case nonetheless. A proposed solution could be to adjust $P_{reference} = 0$, and only charge the surplus PV effect. However case 3c with a $P_{reference} = 7.2$ is exceeding the limit to a less extent, making it more comparable against the other cases.

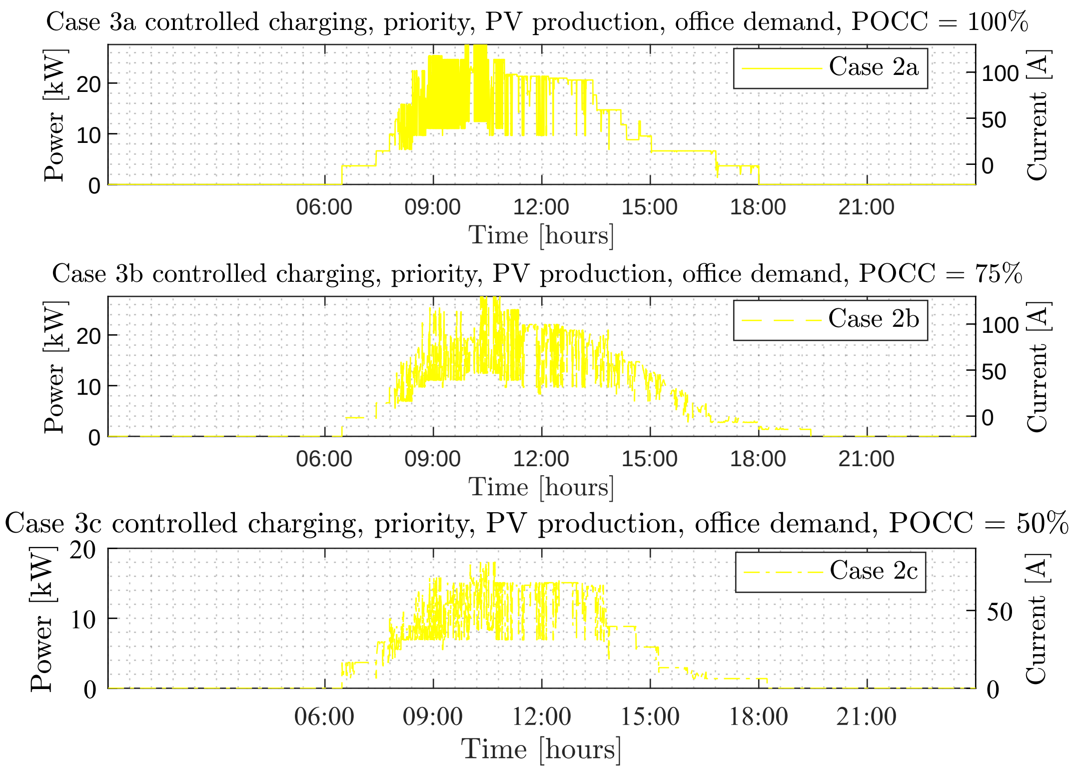


Figure 4.11: Case 3a, 3b and 3c with $P_{reference}$ at 100%, 75% and 50%, respectively.

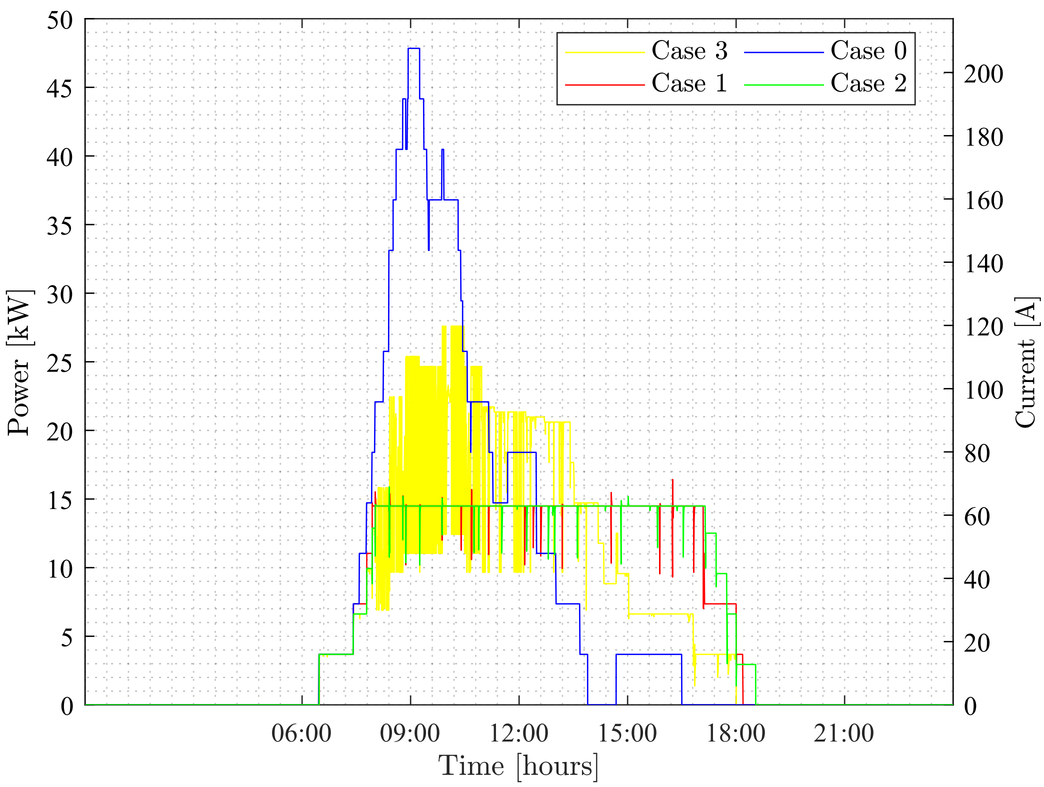


Figure 4.12: Comparison between all cases with power limited at 14.45 kW.

A comparison of the case 0, 1a, 2a and 3a is shown in figure 4.12. It shows a nice overview of the different cases. One can appreciate that only 4 EVs connected to a dumb charger would require the same amount of effect as charging 18 EVs. Even though the combined charging effect is 3 times lower, almost the same SOC goal is achieved as seen in the comparison of total energy charged in figure 4.13. As expected the cases with the highest $P_{reference}$ are the closest to case 0, and the cases with lowest $P_{reference}$ are the furthest away. An interesting thing about the plot is that the slope of the lines indicates the combined charging power. Case 0 has by far the steepest curve, and as shown in figure 4.12, the highest charging power. Another interesting thing to compare is at what time the curve flatten out, indicating charging has stopped. For case 0 it is around 16:00, while for case 2b around 20:00. Case 2b seems to be charging for a longer period compared to case 1c, even if case 1c still have long way before reaching its SOC goal. The reason for this have been explained in appendix A.2. All in all the SOC goal reaches a satisfying level. Especially considering the use of a novel charging control architecture, tested in what is a considered by the author a very constrained case. A summary of the total energy charged is found in table 4.1.

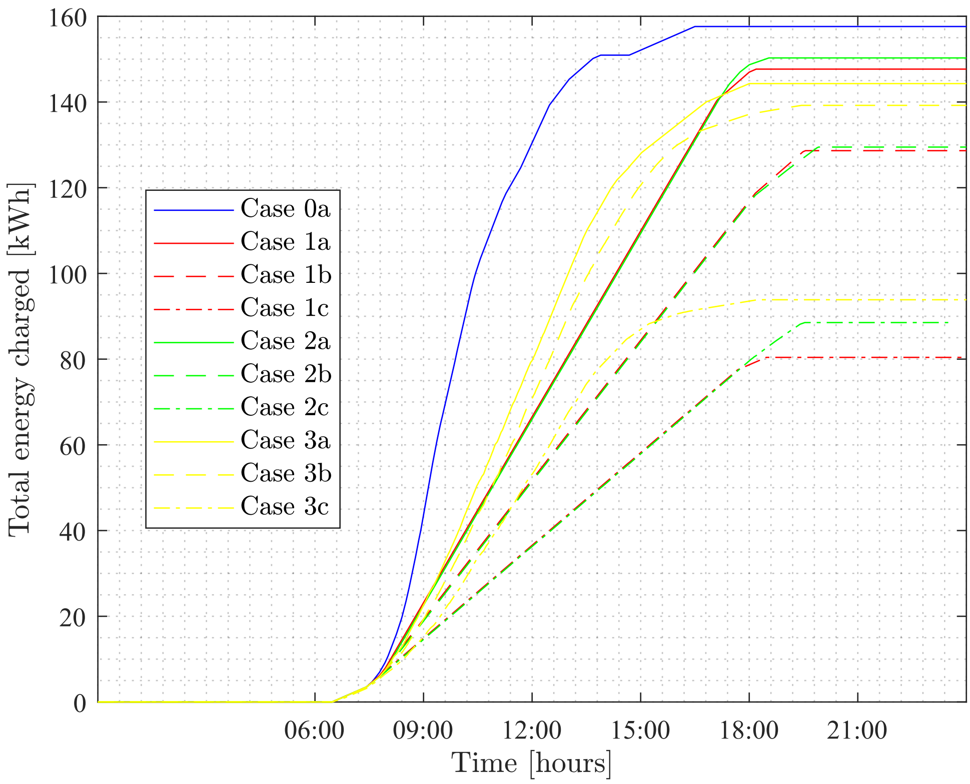


Figure 4.13: Total energy charged comparison.

Simulation result, total energy charged [kWh]				
Scenario	Case 0 uncontrolled charging	Case 1 controlled charging, no priority	Case 2 controlled charging, with priority	Case 3 controlled charging, with priority + PV and office consumption
a $P_{reference} = 100\%$	158	148	150	144[1]
b $P_{reference} = 75\%$		129	130	139[1]
c $P_{reference} = 50\%$		80	89	94[1]

Charging current in these cases exceed the limit for a considerably amount of time[1]

Table 4.1: Summary of simulation results for most important cases, total energy charged

4.6 Economical assessment of the distributed approach

In this section a brief description of the economical considerations related to this type of investment is described. Prices for chargers are retrieved from [36]. Prices range from 3000,- DKK to 23 000,- DKK for a dumb charger. Price of a smart charger range from 14200,- DKK to 29200,- DKK. A price of 5000,- DKK is assumed for a dumb charger, and 15000,- DKK for a smart charger. The price for upgrading a tariff fuse is assumed a one time 1000,- DKK per Amp. It could very well be that if you were to upgrade from a 63 Amps fuse, to 288 Amps, there would be other cost, such as cable upgrade, potential increased effect tariffs, etc. But for sake of simplicity these are not considered. These are prices for household fuse upgrades, and not for a workplace where prices probably would be different. However this is just to give an indication of the price range we are discussing. Figure 4.14 gives an overview of prices for different investments.

No. EVs	Power [kW]	Amps per phase	No. of chargers	Price [DKK]	Fuse total cost above 63A [DKK}	Approx investment [DKK]
18	3.68(1-p)	288	18	90000	225000	315000
18	3.68(1-p)	208	13	65000	145000	210000
18	3.68(1-p)	63	9	135000	0	135000

Figure 4.14: Investment cost of to charging equipment, depending on type and required current

The first investment with 18 dumb chargers, would cost approximately 315 000,- DKK. If we only consider 13 chargers, the price goes down for both number of chargers, and required fuse size to 210 000,- DKK. With the smart charging investment one could stay on the fuse level of 63 Amps and get away with only investing in smart chargers. This would cost approximately 135 000,- DKK. As shown above, there are significant saving to be made if smart chargers are selected. A smart charger is more likely to be capable of receiving future software updates, and new smart functions related to the internet of things, and so on. Not to mention the potential for participating in future flexibility markets, as a part of an aggregation of EVs controlled in a distributed manner. User remuneration is not considered in this thesis, but with the distributed control architecture, it is not long before this is attainable.

5 Conclusion

The thesis work focused on designing and implementing coordinated and autonomous charging control in a workplace parking lot, by use of a distributed control architecture. The results presented are based on a model created in Simulink. The first step was to design a charger controller which could coordinate and provide charging to a total number of 18 EVs autonomously. The overall goal was to develop a charger control that could provide behind the meter services such as power limitation, load balancing, by use of a virtual aggregator responding to demand-response signals. The model utilised historical driving patterns from 18 Nissan Leaf. The work focused on two main research questions, as listed in section 1.2. This chapter aims to conclude them, relying on results an knowledge gained.

- **How is it possible to design a coordinated and autonomous charging controller?** Before starting the design process, information about the distributed control architecture had to be acquired from different sources. This lead to a better understanding of the project, and the design process could start. The design of the coordinated and autonomous charging controller was build step by step in Simulink. The model should reflect a realistic charging model, and therefore input values, delays, and information flow needed to me properly designed. The main inputs are the historical EV data, containing arrival time, departure time, and initial SOC when arriving. Other inputs such as the POCC limit or fuse size, historical PV data, and Office loads was also considered. Measurement cycle from the smart meter, delay related to the on-board EV charging system, and transportation delay from the VA to the other chargers was included. Outputs of the model is the SOC for every EV and the charging power from every charger. The connection logic process is also of great importance, which is the logic that makes sure power limitation is kept, and that the power is distributed fairly between the EVs. A priority logic is also designed to improve charging fairness, and emulate a last call function.
- **How is it possible to assess the grid service flexibility of an aggregation of EVs?** To assess the grid services flexibility, flexibility have to be defined. In this case, flexibility is defined as the ability to respond to a demand response signal, which is a dynamic power reference distributed to all chargers from the VA. The VA could receive a signal from the DSO or TSO, if the VA has placed a bid in the mFRR market, which the DSO or TSO can then activate if needed. The aggregation of EVs requires a certain size, to be allowed to participate in this market. Usually in the MW size, but depends on legislation in the area. If activated the aggregation of EVs will reduce its demand, and thus provide flexibility to the grid operator. Another type of grid service flexibility could be behind the meter services, such as power balancing with local PV production and consumption. Another mode EVs could provide flexibility is by adjusting the dynamic power reference signal after a price signal from Nordpool. Other operational modes could be to operate below the power limit, for example 75% or 50% of the power limit at the POCC, defined by the fuse and cable connected.

5.1 Future work

Under this section it will be described some future topics and proposals that are not covered in this thesis:

- Improve the connection logic functionality.
- Implement VA redundancy.
- Design and implement a disconnect logic that will allow the VA to disconnect EVs as seen fit, if a sudden flexibility is required.
- Investigate user remuneration from provided flexibility.

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A A

A.1 Spike explanation

The spike investigated is the one highlighted with blue in figure A.1 from case 1a.

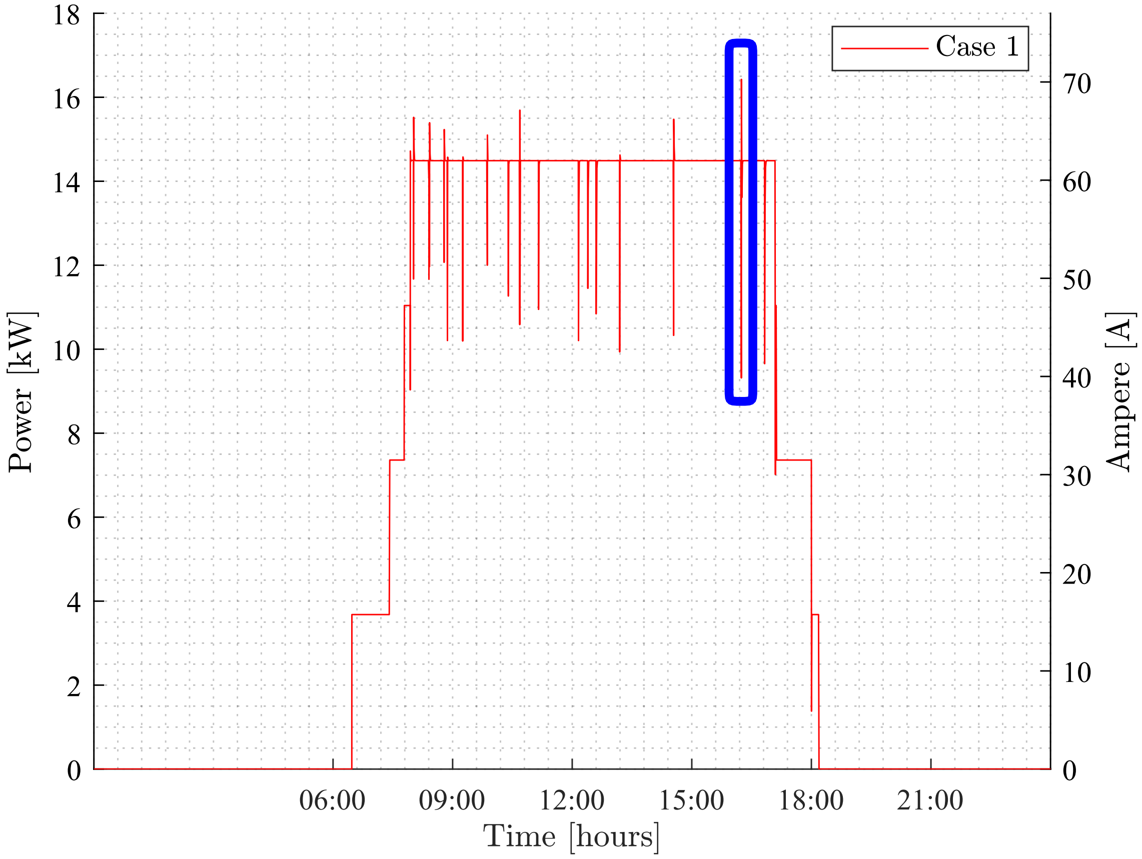

Figure A.1: Overview of $P_{measured}$,largest spike from case 1a marked in blue

The enlarged blue area is shown in figure A.2. Four points are marked illustrating the measurements of the 10 second measurement cycle. These points show the actual values, $P_{measured}$ that are being sent from the smart-meter to the VA.

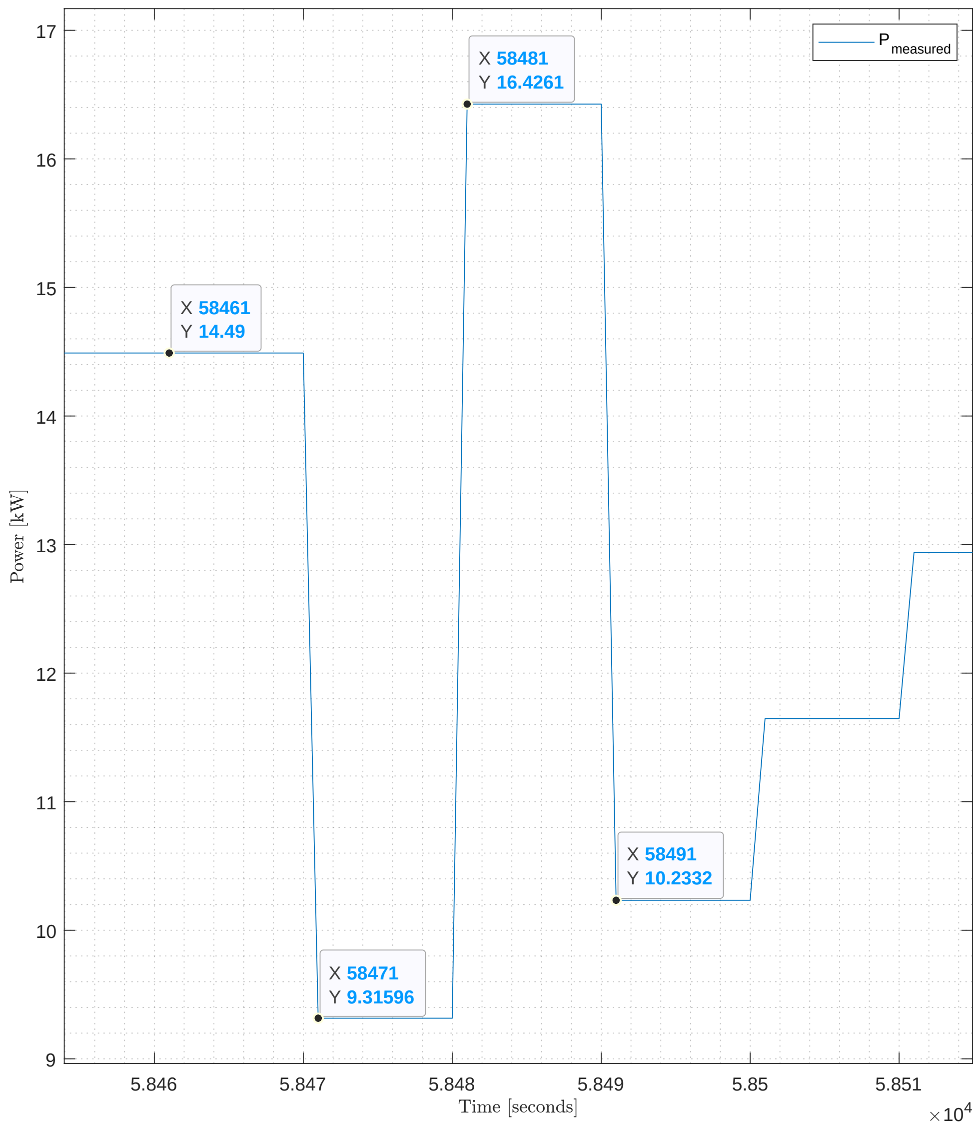

Figure A.2: Detailed overview of $P_{measured}$, largest spike from Case 1a

The same points from figure A.2 in terms of time, are marked in figure A.3. The y-axis shows individual charging power, the points describe the total $P_{measured}$ at the same time. The first point at $t = 58461$, also represent the $P_{reference}$ at 14.49 kW. The system is in perfect balance before the event starts, in other words the measured error, $\Delta P = 0$. Shortly after this, between 1-2 seconds, charger 8 disconnects. The smart-meter is not distributing a new signal until 8 more seconds has passed, as seen in figure A.2. On the contrary, the VA is immediately notified that a charger has disconnected, and allows the next charger, which is first in the queue, to connect, but not to start charging. The VA starts to distribute the $\Delta P_{temporarily}$, for 10 seconds, as described in equation 3.5. Normally this is a function that is activated when a charger connects, to reduce overshoot that occur the moment the charging begins. At the point of the second measurement cycle, the output power has been reduced for a period of 8 out of the 10 seconds, as is should do. At this time, the smart-meter also distributes a new value, $P_{measured}$. To summarise, the $\Delta P_{temporarily}$ function is still active, output power have been reduced, and charger 8 recently disconnected. These three factors add up, and changes the error term to a bigger then desired. ΔP is now a large negative value, that goes into the charging controller.

The PID will try to eliminate the error by increasing the output signal, and thus increase charging power. The short delay before charging power increases is due to the transport delay from the VA, to the different chargers. Since the error term is very negative, the increased charging power response is equivalent positive. Around the same time charger 6 starts charging, the $\Delta P_{temporarily}$ function deactivates, which causes the slope of the charging to slightly reduce it self. However the response form the controller is so strong that within the third measurement cycle, the $P_{measured}$ have exceeded the 63 Amp limit, and the result is a spike in total power consumption. This spike is regarded as a worst case, where the smart-meter have just measured before a charger disconnects. Also, case 1 is without priority, which has a side effect that tend to reduce spikes, although that is not the primary function of the priority.

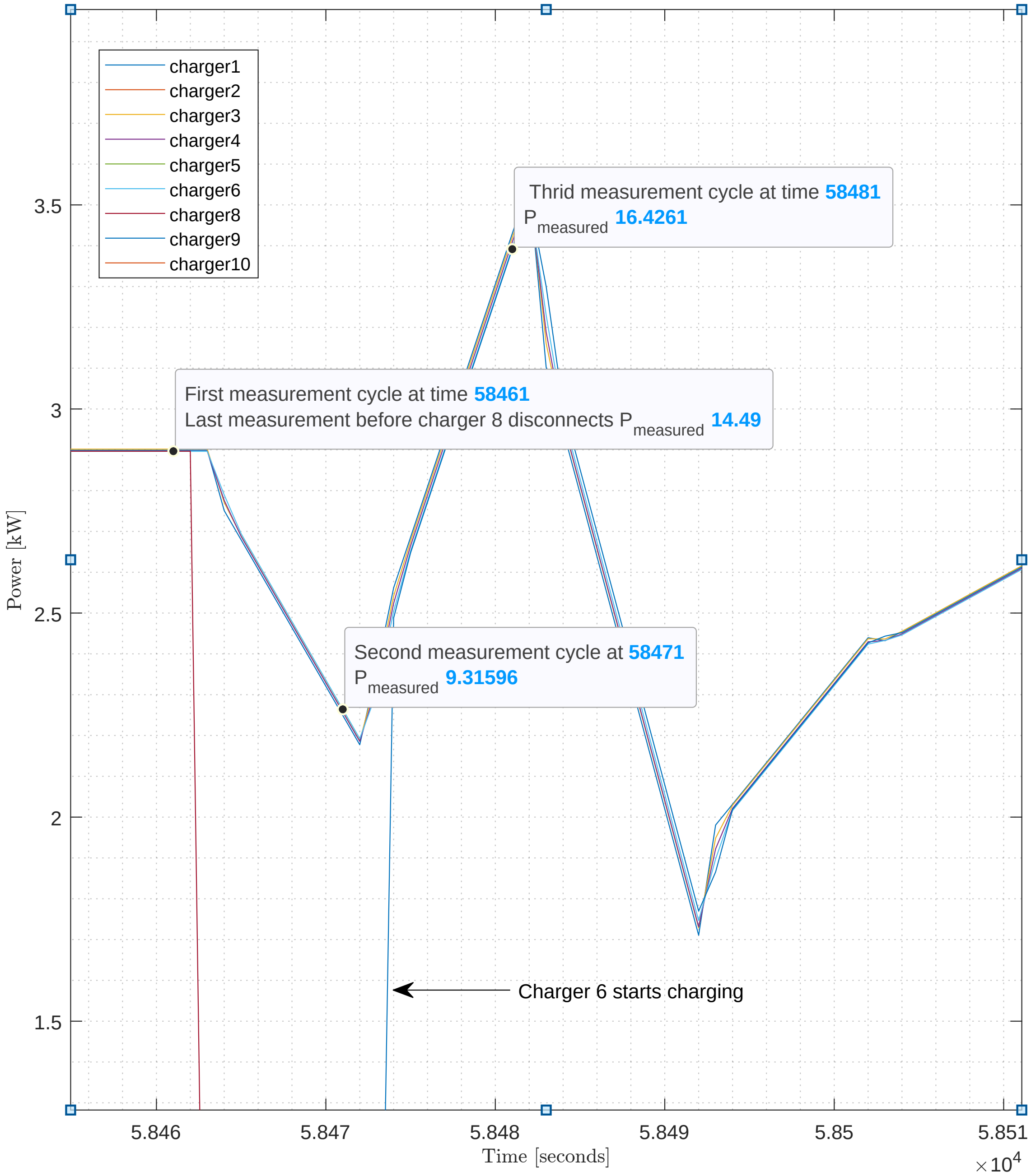

Figure A.3: Detailed overview of chargers, largest spike from Case 1a

A.2 Connection queue logic explanation

A.2.1 Queuing logic

The reason for case 1c is not charging to its fully extent is related to mainly two reasons. The first reason requires an explanation of the queuing logic. The charging queue logic consist of a integrator that can be thought of as a counting device. When a charger is denied charging, the integrator starts counting, and its value increases. If a second charger is denied charging, another integrator start counting. Every charger has an counter. To be allowed to charge, it has to be the the counter with the highest counted value, as well as other criteria such a as available capacity at POCC. Ideally the integrator would been reset, when the charger was allowed to charge. But due to time constrain of the thesis, this was not possible to achieve without violating other aspects, more important to the model, such as power limitation. The downside to this is that the counter for the charger second in queue has to surpass the counted value of the charger first in queue. This cause a delay for charging to start, and can effect the individual SOC of the charger that has to wait. However, in the meantime the other chargers will increase their power output. Therefore the total energy charged will only have a slightly reduced value. But when it is getting close to the end of the day, and this queue delay could cause an EV to not fulfil its goal, because of the reduced available charging time due to the counting delay.

A.2.2 Connection logic

The second reason is related to the connection logic. To be able to connect, there has to be available capacity at the POCC. This is checked by reducing the ΔP temporarily, with an value given by equation 3.5. The function that checks available capacity is triggered by an EV connecting, or disconnecting. This works fine most of the time. But some times not, and that is related to the described queue logic above. In the event, that two chargers disconnects relatively close in time, charger 1 and charger 2. And there are two chargers in queue, charger 3, and charger 4. The first charger in queue, charger 3, will connect just after the charger 1 disconnected, since this charger have waited for the longest time. Now, because the integrator counter is not reset, charger 4, which is in queue will now have to count until it surpass the waiting time of the charger 3. In the mean time charger 2 disconnect, triggers the capacity check function, but there is no charger which is first in the queue, because charger 4 is waiting for the counter to surpass charger 3. After the ΔP temporarily reduction, other chargers will increase their charging power again to use all of the available capacity at the POCC. Charger 4 will have to wait until next time the POCC is reduced.

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