Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Anna Liv Leikanger Aasen

# Integration of Fast-Charging Stations in the Distribution System

## Exploring the Potential of Alternative Grid Connection Agreements

Master's thesis in Energy and Environmental Engineering
Supervisor: Olav Bjarte Fosso
Co-supervisor: Iver Bakken Sperstad and Aurora Fosli Flataker
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# Preface

This master's thesis is the final work of my Master in Science in Energy and Environmental Engineering at the Department of Electric Energy at the Norwegian University of Science and Technology (NTNU) in Trondheim. It has been five exciting years where I have learned a lot and developed as a person.

I would like to thank my supervisor Olav Bjarte Fosso for his guidance, expertise and academic discussions throughout the semester. Special gratitude is extended to my co-supervisors, Iver Bakken Sperstad and Aurora Fosli Flataker, for their valuable input, insightful discussions, and support throughout the semester. Additionally, I want to thank Bendik Nybakk Torsæter at SINTEF Energy Research for his enthusiasm and useful perspectives regarding my thesis.

June 9th, 2023
Trondheim, Norway

Anna Liv Leikanger Aasen

# Abstract

In order to reduce the Norwegian greenhouse gas emissions from the transport sector, which accounts for nearly 30 % of the emissions, adopting electric vehicles and phasing out fossil-fueled cars will be essential. A significant increase in electric vehicles will require the charging infrastructure to develop at the same speed. Connecting fast-charging stations (FCSs) to a large extent in the distribution grid will lead to a need for upgrades in the existing distribution grid. As reinforcing and expanding the power grid both take time and are costly, it is interesting to investigate alternatives to the common practice.

Two main issues with connecting FCSs to the distribution grid are overloading of components and voltage deviations. By utilizing measures such as active power curtailment and reactive power provision, or a combination, the need for grid upgrades may be postponed or reduced as the measures counteract voltage drops and reduce the loading of components. Grid connection agreements which utilize such measures were defined as *alternative grid connection agreements* in the thesis. The potential of alternative grid connection agreements was explored by developing a methodology for technical analysis that Distribution System Operators (DSOs) can perform to evaluate the feasibility of such agreements.

The methodology was applied to a case study to provide insights and recommendations to both charging operators and DSOs. In the case study, a fast-charging operator requested an FCS connected to a 124-bus MV reference system. The case study showed that the FCS could draw its maximum capacity in 95.5 % of the year; the maximum consumption of the FCS only triggered undervoltage problems in 392 hours. The voltage problems were solved with the use of measures, showing that there was a great potential for alternative grid connection agreements.

The most suitable agreement will be case-dependent as every connection request varies. The charging operator's needs will influence the most appropriate alternative. Active power curtailment will be the best measure to use if it is not essential to always have access to maximum capacity as it does not require extra investments. Reactive power provision is favourable if the charging operator wants to be guaranteed maximum capacity always. However, this will require an extra investment as a more complex converter is required to supply reactive power back to the grid.

# Samandrag

For å redusere norske klimautslepp frå transportsektoren, som i dag står for nesten 30 % av utsleppa, vil det å fase ut fossil-drivne køyretøy og implementere elektriske køyretøy vere essensielt. Ei betydeleg auke av elektriske køyretøy vil krevje at ladeinfrastrukturen utviklast i same tempo. Å kople hurtigladestasjonar til distribusjonsnettet i stor skala vil føre til eit oppgraderingsbehov i det eksisterande distribusjonsnettet. Sidan forsterkning og utviding av straumnettet både er tidskrevjande og kostbart, er det interessant å undersøkje alternativ til dagens praksis.

Overbelastning av komponentar og spenningsavvik er to av hovudproblema med å kople hurtigladestasjonar til distribusjonsnettet. Ved å bruke tiltak som struping av aktiv effekt, levering av reaktiv effekt, eller ein kombinasjon, vil behovet for nettoppgradering kunne bli utsett eller redusert, då tiltaka motverkar spenningsfall og redusera belastning av komponentar. Tilknytingsavtalar som tek i bruk slike tiltak er definert som *alternative tilknytingsavtalar* i masteroppgåva. Potensialet til alternative tilknytingsavtalar vart utforska ved å utvikle ein metodikk for ei teknisk analyse nettselskap kan ta i bruk når dei skal evaluere om slike avtalar kan nyttast.

Metodikken vart brukt i ein casestudie for å gi innsikt og anbefalingar til både ladeoperatørar og nettselskap. I casestudien ønska ein ladeoperatør å knytte ein hurtigladestasjon til eit referansesystem med 124 samleskinner. Det vart vist i casestudien at hurtigladestasjonen kunne forbruke maksimal kapasitet i 95.5 % av året; maksimalt forbruk frå hurtigladestasjonen provoserte kun spenningsproblem i 392 timar. Spenningsproblematikken vart løyst ved bruk av tiltak, dette viser at det var eit stort potensial for alternative tilknytingsavtalar i casestudien.

Den mest passande avtalen vil variere frå tilknytingsførespurnad til tilknytingsførespurnad. Behova til ladeoperatøren vil påverke kva som er det beste alternativet. Dersom det ikkje er essensielt å alltid ha tilgang på maksimal kapasitet, vil struping av aktiv effekt vere det beste tiltaket då dette ikkje krev ekstra investeringar. Levering av reaktiv effekt vil vere det føretrekte tiltaket viss ladeoperatøren alltid vil vere garantert maksimal kapasitet. Dette vil krevje ekstra investering då ein meir kompleks omformar er nødvendig for å kunne levere reaktiv effekt tilbake til nettet.

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# Acronyms

**EV** Electric Vehicle

**DSO** Distribution System Operator

**FCS** Fast-Charging Station

**OPF** Optimal Power Flow

**VCC** Variable Capacity Contract

# Chapter 1

# Introduction

## 1.1 Motivation

The transport sector accounts for nearly 30% of greenhouse gas emissions in Norway [1]. All new cars must have zero emissions by 2025, according to an agreement by the Norwegian government [2]. Phasing out fossil-fueled vehicles and adopting electric vehicles will be crucial in both achieving this goal and reducing greenhouse gas emissions from the transport sector. In August 2022, electric vehicles accounted for 18% of the total vehicle fleet in Norway [3], a percentage expected to rise significantly in the coming years. The rapid growth of electric vehicles will necessitate an expanded charging infrastructure, including an increased number of fast-charging stations.

Connecting fast-charging stations to the distribution system may lead to high aggregated peak loads and voltage issues [4]. Capacity shortages due to a high peak load may trigger overloading of electrical components and unacceptable voltage levels in the grid. To solve these issues, the common practice is to reinforce or expand the existing distribution grid [5]. As reinforcing and expanding the existing distribution grid is a time-consuming and costly process [6], it is interesting to investigate alternatives to grid upgrades.

A smarter use of the existing distribution system may defer or mitigate the need for grid upgrades. In cases where the connection of fast-charging stations leads to unacceptable voltage levels or thermal overload of components, one could consider one, or both, of the following in order to reduce the need for reinforcements of grid components:

- Reactive power provision from the FCS in periods with high load
- Limit the available active power of the FCS in periods with high load

When the grid is suffering congestion or the voltage levels are unacceptable, a reduction of the power consumption of the fast-charging station and provision of reactive power from the fast-charging station back to the grid will reduce the loading of the power lines and increase the voltage level [7].

On April the 15th, 2021, a new regulation came into force in Norway, enabling Distribution System Operators (DSOs) and charging operators to enter into a grid connection agreement where the DSO can either disconnect the FCS or limit the available active power of the FCS during periods with high load in the grid [8]. The last option can be characterised as a variable capacity contract (VCC) where the available capacity of the FCS is time-dependent and scheduled in the agreement [9]. Reactive power provision is not a part of variable capacity contracts today, but there is a potential to also incorporate this [9]. Such agreements are alternatives to the common practice today and are thus defined as *alternative grid connection agreements* in this thesis.

Alternative grid connection agreements may delay or reduce the need to expand and reinforce the grid, thus expediting the connection process and avoiding the cost of grid upgrades. Such agreements are currently uncommon, and their potential has not been extensively studied. This master's thesis will thus investigate the potential of alternative grid connection agreements between DSOs and fast-charging operators.

## 1.2 Objectives

The main objective of the master's thesis is to:

- Investigate the potential of alternative grid connection agreements between Distribution System Operators (DSOs) and fast-charging operators

which will be achieved through the sub-objectives:

- Develop a methodology for a technical analysis DSOs can perform when assessing the potential for alternative grid connection agreements with fast-charging operators
- Apply the developed methodology to a case study on an MV reference system in order to provide insights and recommendations for DSOs and fast-charging operators seeking to implement alternative grid connection agreements

The master's thesis is associated with the ongoing research project FuChar (Grid and Charging Infrastructure of the Future) and the research centre FME CINELDI (Centre of Intelligent Electricity Distribution) led by SINTEF Energy Research. FuChar's main goal is to minimize investment and operating costs related to the grid integration of electric transport, with a focus on high-power charging [10]. FME CINELDI's main goal is to enable and facilitate a cost-efficient realisation of the future flexible and robust electricity distribution grid [11].

## 1.3 Limitations

The master's thesis investigates the technical aspect of alternative grid connection agreements; the regulatory aspect is not taken into consideration. The methodology which is developed and proposed is seen from the perspective of the Distribution System Operator. By this, it is meant that the load of the fast-charging station is accounted as the aggregated load of all chargers in the station. The number of chargers and the distribution of them within the station is not taken into account.

## 1.4 Structure

The rest of the master's thesis is structured as follows: Chapter 2 provides relevant background information and theory necessary to understand the master's thesis. Chapter 3 presents and describes the developed methodology for the technical analysis. In Chapter 4, a system description and case study description will be given. Chapter 5 presents the results from the case study. In Chapter 6, the results of the case study and the potential of alternative grid connection agreements will be discussed. Chapter 7 summarises the thesis in conclusion and suggests further work.

## 1.5 Own contribution

The master's thesis provides a methodology for investigating the potential of alternative grid connection agreements between Distribution System Operators and fast-charging operators when the charging operator requests a fast-charging station connected to the grid. The methodology is applied to and validated in a case study on a 124-bus medium voltage reference system. The case study serves valuable insight and recommendations to both Distribution System Operators and fast-charging operators seeking to implement alternative grid connection agreements.

# Chapter 2

# Background and theory

In this chapter, background information and relevant theory for the master's thesis will be provided. Information about the development of electric vehicles (EVs) and fast chargers in Norway in recent years and potential future scenarios, the Norwegian power grid, challenges associated with connecting fast-charging stations to the distribution grid, alternative grid connection agreements, and flexibility in terms of curtailment of active power and reactive power provision will be given. The chapter also covers theory about power, thermal overloading of power system components, and voltage drop along radials.

## 2.1 Electrification of the Norwegian car park

This and the next paragraph, Figure 2.1, and Figure 2.2 are retrieved from [12], which is the specialisation project report of the author. Europe's electric vehicle fleet has increased significantly over the last few years. In 2021, 18 % of the new car registrations in Europe were electric cars [13]. Of the European countries had Norway the highest penetration of electric cars in 2021 [13]. From the end of 2017 to the end of 2018, the electric vehicles share in Norway increased by 40.6 % [14]. Over the past few years, Norway's market for electric vehicles has steadily grown. The development of electric vehicles in Norway from 2010 to September 30, 2022, is shown in Figure 2.1 [15].

As the number of electric vehicles on Norwegian roads increases, the demand for charging stations also increases. Fast-charging stations are typically located along highways and close to shopping malls. A fast charger is characterized as a charger with a capacity from 50 kW to 149 kW [16]. Since 2018, Norway has also had ultra-fast chargers on the market, which offer even higher charging speeds if your car's battery can handle it [16]. An ultra-fast charger has a capacity of 150 kW and above [16]. There has been a significant growth of fast and ultra-fast chargers since 2012. Figure 2.2 shows the number of fast and ultra-fast chargers in Norway from 2012 to 30.09.2022 [16]. By 30.09.2022, it was registered 5041 chargers with a charging capacity above 50 kW [16].

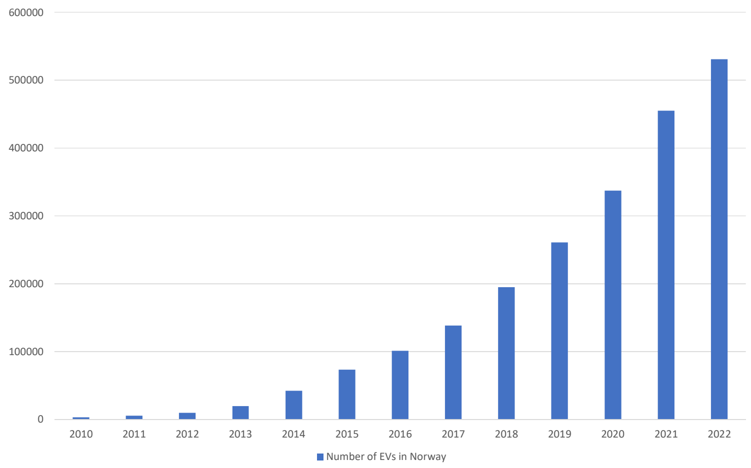



**Figure 2.1:** Number of electric vehicles in Norway from 2010 to 30.09.2022 [15]

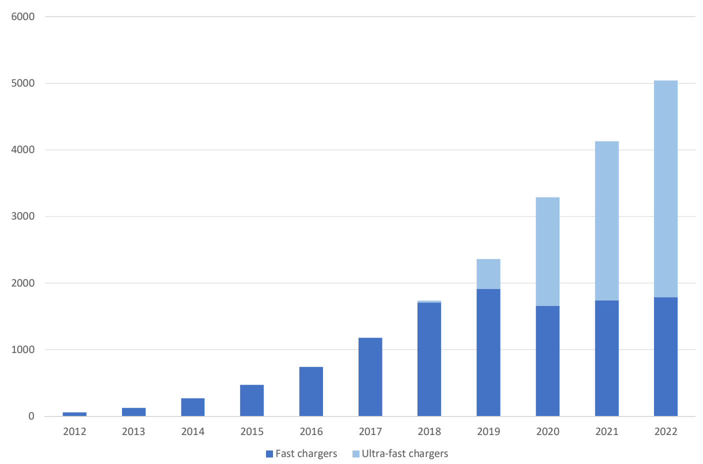



**Figure 2.2:** Number of fast chargers and ultra-fast chargers in Norway from 2012 to 30.09.2022 [16]

According to [17], there will be around 1.7 million EVs in Norway in 2030 if the sale targets set in the Norwegian Transport Plan (NTP) are reached. If this is to be feasible, the charging infrastructure needs to develop at the same rate. Ref. [17] predicts that in 2025 there will be around 9.000 fast chargers for light vehicles, and by 2030, there will be between 10.000 and 14.000. The power rating of chargers is increasing in order to compete with the filling time of fossil cars [18]. A

350 kW DC ultra-fast charger would only use 10 minutes to append 322 km (200 miles), in contrast to a 50 kW fast charger that would use more than an hour [18]. With the expected high percentage of fast chargers in 2030 and the ability of chargers to charge at higher power levels, a strong, developed and robust power grid will be required.

## 2.2 Fast-charging stations

Today, most EV owners have their own chargers at home or charge at work, but with the increasing adoption of EVs, more public charging infrastructure, like fast-charging stations, will be needed [19]. Ref. [17] defines a *charging station* as "a location with one or multiple charging points". Based on this definition, a fast-charging station can be defined as a location with one or multiple fast-charging points. As written in the previous section, fast and ultra-fast chargers have a capacity respectively from 50 kW and from 150 kW. Multiple fast or ultra-fast chargers at a location will thus result in a significant aggregated load for the distribution grid to handle if all chargers are used simultaneously.

The installed apparent power of the converter of a charger determines the maximum possible power transfer between the grid and the charger [20]. The apparent power is defined in the following equation.

$$S^2 \geq P^2 + Q^2 \tag{2.1}$$

In Equation 2.1, $S$ denotes maximum apparent power, $P$ active power and $Q$ reactive power. $P$ and $Q$ can be both positive and negative; the different operation regions of the converter are illustrated in Figure 2.3 [20]. In quadrant I, both $P$ and $Q$ are positive, which implies that the charger is drawing both active and reactive power. On the other hand, when the converter operates in quadrant III, the EV supplies both active and reactive power to the grid. There exist converters suitable for fast chargers which are capable of operating in all four quadrants, and thus both draw and supply active and reactive power [21]. When the converter operates in quadrant IV, the EV can draw active power while simultaneously supplying reactive power to the grid [22]. As the bidirectional chargers are more complex than the unidirectional ones, they are more expensive [23]. Although there exist converters for chargers which can operate in all four P-Q quadrants, the converters used today typically consist of a diode-bridge rectifier and a boost converter where power exchange only is possible in one direction - from the grid to the charger [24].

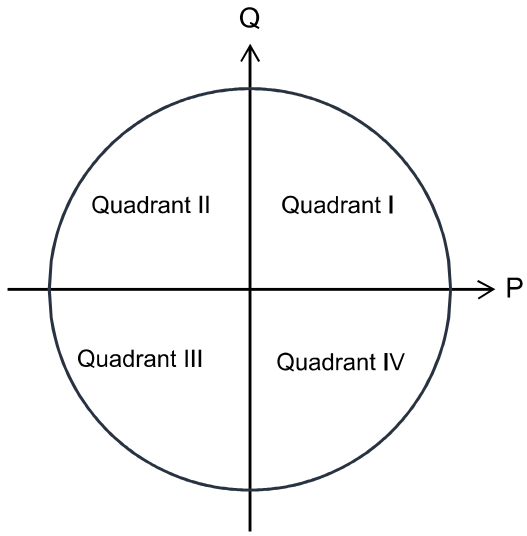



**Figure 2.3:** Operating regions of the converter in a bidirectional charger [20]

## 2.3 The Norwegian power grid

The Norwegian power grid is grouped into three hierarchical levels - the transmission grid, the regional grid, and the distribution grid. The voltage level of the transmission grid ranges from 132 kV to 420 kV, while the regional grid ranges from 33 kV to 132 kV [25]. The distribution grid operates at voltage levels ranging from 230 V to 22 kV and is responsible for delivering electricity to end users [25]. The distribution grid in Norway has typically been operated as radial networks [26]. The fast charging stations are usually connected to the medium voltage distribution grid [7].

A significant increase in fast-charging stations will require much from the distribution grid. The power demand will potentially be high, leading to local capacity shortages. Historically, capacity shortages have been solved by reinforcing or expanding of the existing grid [5]. Reinforcing and expanding the distribution grid is a time-consuming and costly process [6]. To prevent the distribution grid from becoming a limiting factor in the electrification of the transport sector, alternative solutions to reinforcement and expansion of the grid must be addressed and investigated.

## 2.4 Issues with connecting fast-charging stations to the distribution system

The problems that arise and cause the need for grid upgrades must be studied before looking at alternatives to reinforcement and expansion of the existing distribution grid. As the connection of an FCS to the grid will give a high aggregated load if multiple fast chargers are used simultaneously, integration of FCSs to the grid may lead to high peak loads and voltage deviations [4]. As the distribution grid is mainly operated as a radial network are two main issues with connecting a fast-charging station to the distribution grid [23]:

- Thermal overload of power system components
- Voltage drop along radials

### 2.4.1 Thermal overload

Each electrical component has an upper thermal transfer limit; if this limit is exceeded over time, it will lead to wear and failure of the component [26]. As the implementation of fast-charging stations in the grid introduces a significant load-add to the system, it can lead to overloaded electrical components such as power lines and transformers.

### 2.4.2 Voltage drop

Voltage drop along the radial is an issue that can occur when connecting new loads to the distribution grid. The theory that will be given in this subsection is obtained from [26]; see [26] for more detailed information. A distribution grid can be represented simply as in Figure 2.4. $U_1$ is the voltage at the transformer, while $U_2$ is the voltage at the end of the radial where a load is connected. The network is represented by the impedance Z which contains of the resistance R and the reactance X. In the figure, the positive direction of active power, P, and reactive power, Q, is to the right. The voltage drop along the radial can be represented as in Equation 2.2.

$$U_1 - U_2 = \frac{1}{U_2} \cdot (RP + XQ) + j(XP - RQ) \tag{2.2}$$

Equation 2.2 can be approximated to Equation 2.3 in order to illustrate some principles.

$$U_1 - U_2 = \frac{R}{U_2} \cdot P + \frac{X}{U_2} \cdot Q \tag{2.3}$$

As seen from Equation 2.3, if the load is greater than the production, P will be positive and there will be a voltage drop between $U_1$ and $U_2$. On the other side, if the production is bigger than the load, P will be negative, and the voltage will rise along the radial. Drawing reactive power will likewise give a voltage drop, while supplying reactive power will increase the voltage.

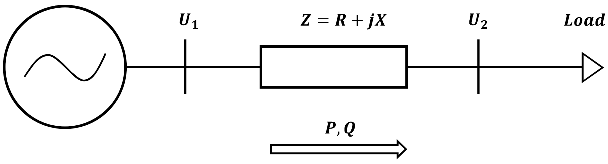



**Figure 2.4:** Simple representation of a distribution grid (based on [26])

The $\frac{R}{X}$ ratio plays an important role when it comes to which of active and reactive power who has the most influence on the voltage. The ratio typically ranges from 0.5 to 2 in distribution grids depending on whether the network consists mainly of overhead lines or underground cables and the cross-section of the cables and the lines. Overhead lines yield a smaller ratio than cables, and the ratio decreases as the cross-section increases. When the $\frac{R}{X}$ ratio equals 1, the active and reactive power will influence equally. When the ratio equals 0.5, the reactive power influences significantly more than the active power, and the opposite when it equals 2.

## 2.5 Grid connection

Norwegian Distribution System Operators are legally obligated to connect everyone who requests a connection to the distribution grid [27]. This assessment can be made by checking whether the existing grid has sufficient capacity to handle the new connection. By this, it is meant that the grid must have adequate capacity and must continue to operate within its limits after the connection [6]. If this is not fulfilled, the grid needs to be reinforced or expanded, and the customer must pay a connection charge (Norwegian: anleggsbidrag) to the DSO [28]. The connection charge partially or fully covers the costs for the system operator to reinforce or expand the grid in order to connect the new customer [29]. The DSO are no longer obligated to connect the customer if the customer refuses to pay the connection charge [28].

Upgrading the existing grid due to capacity shortages can typically be more time-consuming than establishing the fast-charging station [6]. In some cases, an upgrading of the existing infrastructure may be required to connect the fast-charging station to the grid, while in other cases may the use of alternative measures such as flexibility resources mitigate or defer the need for grid upgrades [6]. Ref. [30] defines *flexibility* as "The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions". With the definition of flexibility in mind, they define a *flexibility resource* as "the resource that has this ability" [30]. When an EV owner uses a fast charger at a fast-charging station, the purpose of the session is to charge the EV at high power in order to charge the EV in a short amount of time [21]. Two relevant flexibility resources for fast-charging stations are thus the curtailment of active power and the provision of reactive power. Reducing the available capacity for the FCS and providing reactive power from the FCS during peak hours may reduce the loading of the lines and enhance the voltage level at the nodes [7].

## 2.6 Alternative grid connection agreements

As mentioned in the previous section, the DSOs are obliged to connect everyone who requests a connection to the grid as long as it is feasible. From 15.04.2021, a new regulation came into force in Norway - connection with terms of disconnection [8]. This is an alternative to investing in the grid when there is insufficient capacity to connect the load normally. An agreement between the system operator and the customer is being made where the customer will be connected to the grid under the condition that the system operator can either [31]:

- Disconnect the customer in periods when the system is suffering congestion
- Limit the available capacity of the customer in periods when the system is overloaded

The system operator will not have to pay the customer for the non-delivered power in the periods when the load is disconnected or has a limited capacity available [31]. This new regulation may enable faster electrification of the transport sector, as fast-charging stations can potentially be connected to the distribution grid faster.

Ref. [9] defines two types of grid connection agreements - *Interruptible Contract* and *Variable Capacity Contract*. They can be seen as alternatives to reinforcing and expanding the grid when it exists capacity shortages. The first bullet point can go under the definition of an interruptible contract, whereas the second bullet point can be defined as a variable capacity contract. The two types of contracts will now be described.

**Interruptible Contract**

In an interruptible contract, the FCS will be curtailed in periods when the grid is suffering congestions or have other conditional issues [9]. In this contract, the total risk lies with the customer, as the DSO determines when the FCS is curtailed [9].

**Variable Capacity Contract**

In contrast to a regular connection agreement where the customer can consume a fixed amount of active power throughout the year, the available capacity in a variable capacity contract (VCC) is time-dependent [32], and given by a schedule, which can be either fixed or dynamic [9]. The available capacity can vary throughout the day, the week, or the season. Figure 2.5 illustrates how the capacity in a VCC can vary [32]. During peak periods, the available capacity is lower than during off-peak periods. The period when the available capacity is restricted is referred to as the reduction period. VCC focuses on active power and specifies how much active power the FCS have available in different periods. It is also possible that a VCC specifies reactive power provision from the FCS, but that is uncommon today [9].

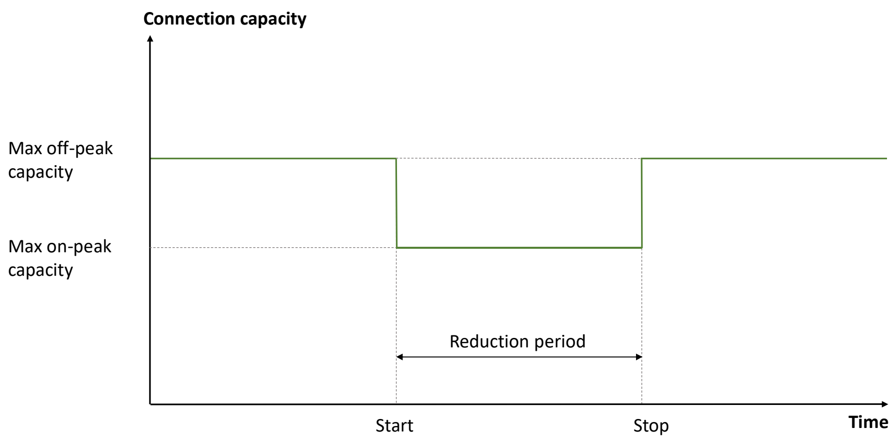



**Figure 2.5:** Illustration of a variable capacity contract (adapted from [32])

A variable capacity contract is an alternative to reinforcing and expanding the distribution grid, which utilizes the already existing grid in a smarter manner in order to connect the FCS. In this master's thesis, an *alternative grid connection agreement* is defined as a grid connection agreement which is an alternative to upgrading the existing distribution grid by using alternative measures. These measures can be one, or both, of the following;

- Reactive power provision
- Curtailment of active power

# Chapter 3

# Method

According to ref. [17], as written in Chapter 2, it has been predicted that there will be around 1.7 million electric vehicles on Norwegian roads in 2030. Generally, there is an expected significant increase in the number of electric vehicles in Norway in the next few years. However, to enable this growth, it is important to have an adequate charging infrastructure, including fast-charging stations. Connecting fast-charging stations to the distribution system will require a lot from the system, as it is a new and significant load to handle. With the expected growth in EVs and FCS, DSOs will likely receive many grid connection requests. As connecting FCSs to the distribution system may lead to capacity shortages and thus unacceptable voltage drops and thermal overload of components, grid reinforcement or expansion may be required. Reinforcing and expanding the existing grid is a time-consuming and costly process, which may constrain the integration of fast-charging stations in the distribution system. A smarter utilization of the existing grid in terms of active power curtailment and reactive power provision as alternatives to reinforcement and expansion will thus be investigated in this chapter.

When a charging operator requests a grid connection today, the following scenarios can occur:

- **Alternative 1:** The existing grid has sufficient capacity to handle the new load. The charging operator can obtain the requested capacity without any connection charge (Norwegian: "anleggsbidrag") for upgrading the network.

- **Alternative 2:** The new connection will cause thermal overload and/or unacceptable voltage drop in the grid. This will be resolved by reinforcing or expanding the existing grid, which will require a connection charge payment from the charging operator. However, the charging operator will be granted the requested capacity to use.

- **Alternative 3:** The new connection will result in thermal overload and/or unacceptable voltage drop in the grid. To resolve this issue, the available active power for the FCS will be limited during periods of high load in the grid. The charging operator is not required to pay a connection charge but will have a restricted capacity available in certain periods.

In addition to the scenarios described above, the author envisions two possible additional scenarios that take advantage of the provision of reactive power in order to prevent unacceptable voltage drops.

- **Alternative 4:** After conducting an analysis, the DSO has determined that if the FCS is capable of providing a certain amount of reactive power in certain periods, there will be no need for additional actions to be taken in the grid to connect the FCS. The charging operator will not be required to pay a connection charge. The agreement between the DSO and the charging operator will specify how much and when the FCS is required to provide reactive power in the same way as available active power is specified in variable capacity contracts.

- **Alternative 5:** The new connection will result in thermal overload and/or unacceptable voltage drop in the grid. To resolve this issue, a combination of Alternative 3 and Alternative 4 will be used where both active power curtailment and provision of reactive power are used simultaneously.

Alternative 3, 4 and 5 represent alternative grid connection agreements after the definition of the author in Chapter 2. In order to explore the potential of alternative connection agreements for fast-charging stations, a method for analyzing each of the five alternatives technically was developed. Since Alternative 1 and Alternative 2 represent current practices, the main focus is on Alternative 3, Alternative 4, and Alternative 5. Although Alternative 3 can be considered the current practice as the new regulation, connection with terms of disconnection, came into force on the 15 of April 2021, it is still relatively new in Norway and not yet widely adopted. In addition, the Norwegian distribution system operators do not have a standard practice for executing connection agreements today [6]. Thus, the technical analysis that will be presented here can contribute to standardizing connection agreements. Moreover, it will challenge current practices and explore the potential for alternative solutions beyond grid reinforcement and expansion. The ultimate goal is to accelerate the electrification of the vehicle fleet and achieve Norway's ambitious goal of making all new cars zero-emission vehicles by 2025.

The different methods were developed and implemented in the programming language Python, with the assistance of the Python add-on package *pandapower*. Pandapower was utilized to conduct power flow analysis. The methodology of the alternatives will now be illustrated in flow charts and a comprehensive description will be given for each alternative.

## 3.1 Alternative 1

Alternative 1 is intended as a check to determine if there is a need for measures in order to connect a fast-charging station to an existing distribution grid. It is assumed that the grid planning approach of the Distribution System Operator is to dimension the grid based on the worst-case scenario. By this, it is meant that the grid is designed to handle the new load and remain to operate within its limits in the worst-case scenario. The worst-case scenario would be that the FCS consume its maximum capacity simultaneously as the aggregated load of the other loads in the distribution system have its peak load. The method for Alternative 1 is schematically illustrated in Figure 3.1 and will now be further described.

The need for this analysis arises when a charging operator requests a connection to the distribution grid. The distribution system operator retrieves a load data set of the existing grid for which the connection is requested and includes an expected load increase for the coming years. The load data set consists of hourly-resolution load data for an entire year. The load of all nodes in the grid are summarized for each hour of the year in order to get the aggregated load values. From this, the hour of the year with the highest aggregated load is obtained. A power flow analysis is then performed at this hour with the fast-charging station connected and consuming maximum active power. Based on the voltage level of the nodes and the loading of the power lines, it can be determined whether the fast-charging station can be connected without any required measures. If the voltage at all nodes is within the limits and the loading of the lines is within an acceptable limit, the fast-charging station can be connected. If this is not the case, measures are necessary in order to connect the fast-charging station to the grid.

## 3.2 Alternative 2

When the capacity of the grid is insufficient to connect a new load or generation, the traditional solution has been grid reinforcement and expansion. If the answer to the question "Can the FCS draw maximum active power at this hour?" in Figure 3.1 is no, reinforcing or expanding the grid would be the traditional choice. In this thesis, it will not be conducted any analysis for this alternative. The alternative is only included to illustrate that it is the usual choice, but it will not be further studied.

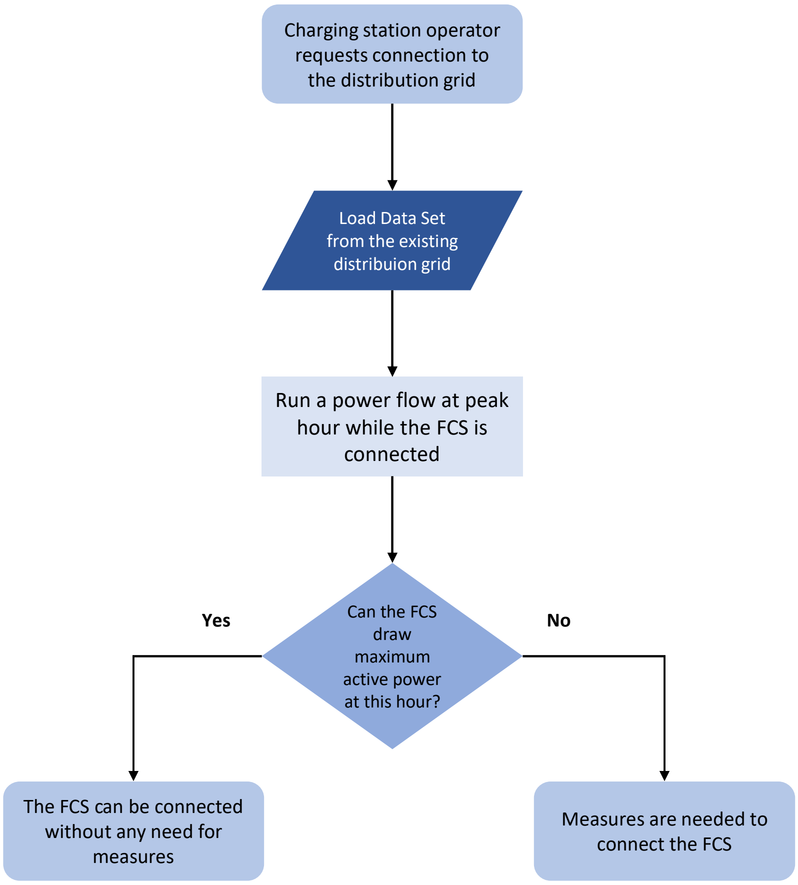



**Figure 3.1:** Methodology for Alternative 1 and Alternative 2

## 3.3 Alternative 3

The methodology of Alternative 3 is illustrated in a flow chart in Figure 3.2. It starts with a request from a charging operator which wants to connect an FCS to the distribution grid. The input to the methodology is an hourly-resolution load data set from the distribution grid where the FCS connection is being requested. The output of the methodology is the hours of the year sorted into three categories. In the categories, the hours are classified after how much active power the FCS can consume in the specific hour and are grouped as follows;

- **Category 1**: The hours when the FCS can consume maximum power
- **Category 2**: The hours when the FCS can consume a limited amount of active power
- **Category 3**: The hours when the FCS cannot consume any active power

A detailed description of the methodology will now be given based on the steps in the flow chart.

*Charging operator requests connection to the distribution grid*
The methodology starts with a customer's request to connect to the distribution grid. The customer, which is a fast-charging operator, specifies how much active power is needed and the station's location.

*Load Data Set from the existing distribution grid*
The DSO obtains a load data set for the current grid to which access is requested for an entire year. The load data set is modified to include an expected load increase, and this modified load data set is the input to the flow chart. Although the time resolution in the flow chart in Figure 3.2 is based on hours, any other preferred resolution can be used.

*Sort the hours in the load data set from largest to smallest based on aggregated load*
The load data set is sorted from largest to smallest based on the aggregated load in the system for each hour of the year. By aggregated load, it is meant that all load points in the distribution system are summarized for each hour.

*Extract the first element of the sorted load data set*
The first element of the sorted load data set is extracted, representing the hour of the year with the most significant aggregated load of the existing distribution system.

*Run an optimal power flow at this hour while the FCS is connected*
An optimal power flow analysis is conducted at the hour extracted in the last step with the FCS connected. The optimal power flow (OPF) is conducted with the aim of maximising the load on the bus where the FCS is connected. The optimisation problem is implemented as follows:

$$\text{Maximize} \quad \sum_{i \in FCS} P_i \tag{3.1}$$

$$\text{subject to} \quad P_{\text{i, min}} \leq P_{\text{i}} \leq P_{\text{i, max}}, \quad \text{for } i \in \text{FCS} \tag{3.2}$$

$$V_{\text{min}} \leq V_i \leq V_{\text{max}}, \quad \text{for } i \in \text{nodes} \tag{3.3}$$

$$L_{\text{l}} \leq L_{\text{max,l}}, \quad \text{for l} \in \text{lines} \tag{3.4}$$

$$P_{\text{ext, min}} \leq P_{\text{ext}} \leq P_{\text{ext, max}} \tag{3.5}$$

- $P_i$: Active power of load node $i$ in MW
- $V_i$: Voltage of node $i$ in p.u.
- $L_l$: Line loading of line $l$ in %
- $P_{ext}$: Total load of the distribution system in MW

*Can the FCS draw maximum active power at this hour?*

If the optimal power flow result in $P_{fcs} = P_{fcs,\,\max}$, the answer to the question is yes, and the FCS can draw its maximum capacity at this hour. The hour is then placed in Category 1. As the load data set is sorted from highest to lowest based on the aggregated load will most likely all hours after this hour also be placed in Category 1. Due to this, the process can stop here. However, it is important to remember that the aggregated load does not reflect the local conditions. There may be local variations in voltage due to the fact that the voltage depends on the load of the individual load points and not just the total load. Therefore, it may be useful to run a few more iterations until $P_{fcs}$ has stabilized and remained equal to $P_{fcs,\,\max}$ for several consecutive times. On the other hand, if $P_{fcs} < P_{fcs,\,\max}$, the answer to the question is no, which triggers the next question.

*Can the FCS draw a limited amount of active power at this hour?*
If the optimal power flow result in $0 < P_{fcs} < P_{fcs,\,\max}$, the answer to the question is yes. This means that the FCS can consume a limited amount of active power, and the hour is placed in Category 2. If $P_{fcs} = 0$, the answer to the question is no. The FCS can in that case not consume any active power, and the hour is stored in Category 3.

When an hour is allocated in either Category 2 or Category 3, it is removed from the sorted load data set. The initial second element of the sorted load data set is now the first element and is the hour to be analysed. The iteration process continues until $P_{fcs} = P_{fcs,\,\max}$ is reached, as this indicates that the fast-charging station can draw its maximum power for all the hours following that hour, due to the aggregated load being sorted from highest to lowest. However, since the aggregated load is being considered, it is possible that there may be some hours after the first time $P_{fcs} = P_{fcs,\,\max}$ where $P_{fcs}$ is slightly lower than $P_{fcs,\,\max}$ due to local variations in the load. It may therefore be useful to run a few extra iterations until $P_{fcs}$ has stabilized and is equal to $P_{fcs,\,\max}$ several times in a row.

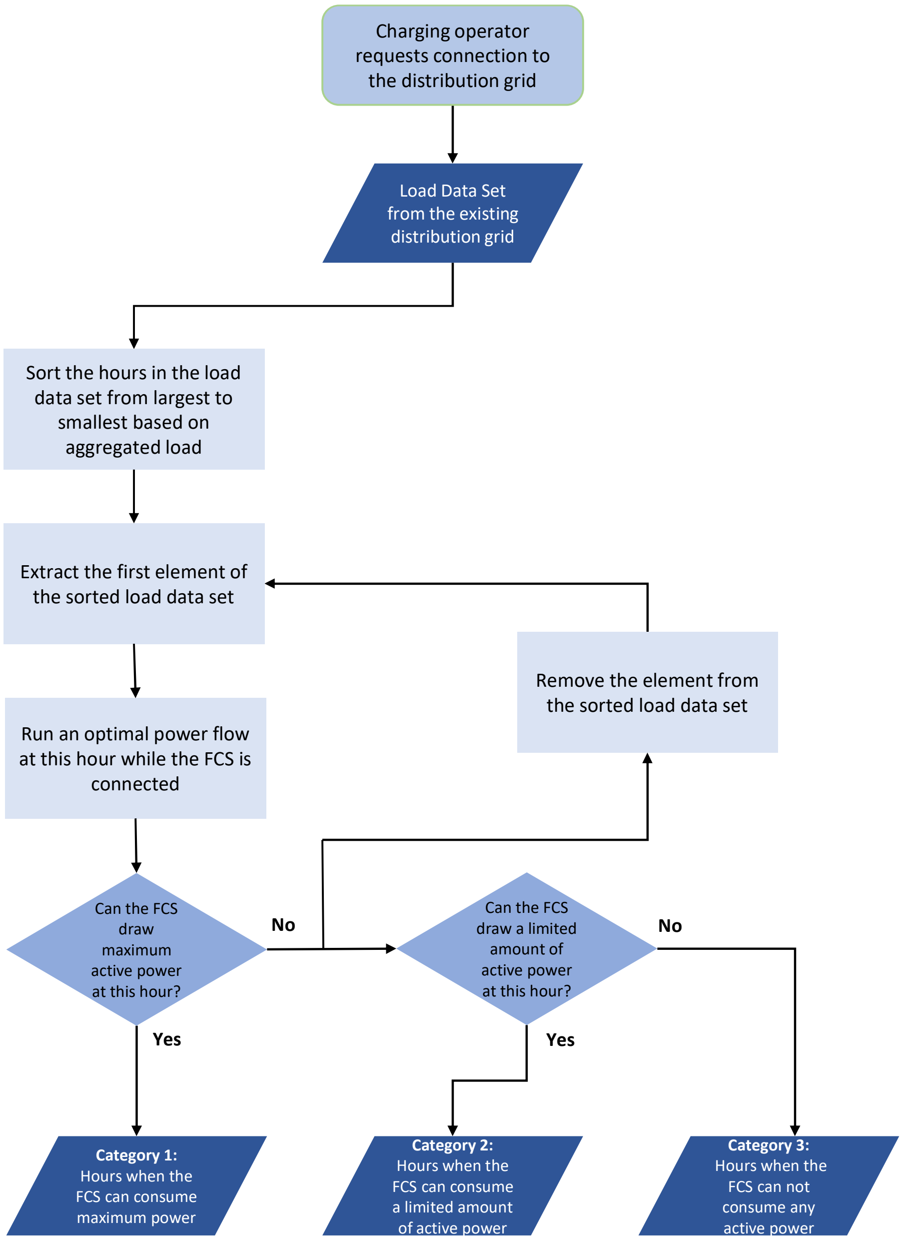



**Figure 3.2:** Methodology for Alternative 3

## 3.4 Alternative 4 and Alternative 5

The methodology for Alternatives 4 and Alternative 5 is illustrated in a flow chart in Figure 3.5. The input to the methodology is the same as for Alternative 3; an hour-based load data set for a distribution grid for one year. The output of the methodology is the hours of the year sorted into four categories. The hours are classified after how much active power the fast-charging station can draw during that hour and how much reactive power it may have to provide. The categories are grouped as follows;

- **Category 1**: The hours when the fast-charging station can consume maximum active power and does not need to deliver reactive power
- **Category 2**: The hours when the fast-charging station can consume maximum active power but must deliver reactive power simultaneously
- **Category 3**: The hours when the fast-charging station can only consume a limited amount of active power while simultaneously having to deliver reactive power
- **Category 4**: The hours when the fast-charging station cannot consume any active power

If no hours have been placed into the third category, there are no hours during the year when it is necessary to limit the active power while simultaneously supplying reactive power, and Alternative 4 is an option. In that case, Alternative 5 is no longer an option, as curtailing the active power is unnecessary. However, if hours are placed in Category 3, supplying reactive power alone is insufficient to connect the fast-charging station at maximum capacity in some hours, and Alternative 4 is not an option.

The methodology for Alternative 4 and Alternative 5 is identical to Alternative 3 until the answer to the question "Can the FCS draw maximum active power at this hour?" is no. The remaining steps in the flow chart in Figure 3.5 will now be explained step by step.

*Run an optimal power flow at this hour while the FCS is connected and providing reactive power*
A new optimal power flow is conducted for the same hour with the same conditions, but additionally, the FCS provides reactive power to the grid. The optimization problem is implemented as follows:

$$\text{Maximize} \quad \sum_{i \in FCS} P_i \tag{3.6}$$

$$\text{subject to} \quad P_{\text{i, min}} \leq P_{\text{i}} \leq P_{\text{i, max}}, \quad \text{for } i \in \text{FCS} \tag{3.7}$$

$$-\sqrt{S_n^2 - P_{\text{i, max}}^2} \leq Q_{\text{i}} \leq 0, \quad \text{for } i \in \text{FCS} \tag{3.8}$$

$$V_{\text{min}} \leq V_i \leq V_{\text{max}}, \quad \text{for } i \in \text{nodes} \tag{3.9}$$

$$L_{\text{l}} \leq L_{\text{max,l}}, \quad \text{for l} \in \text{line} \tag{3.10}$$

$$P_{\text{ext, min}} \leq P_{\text{ext}} \leq P_{\text{ext, max}} \tag{3.11}$$

where:

- $P_i$: Active power of the load node $i$ in MW

- $S_n$: Nominal apparent power of the converter in MW
- $Q_i$: Reactive power of the load node $i$ in Mvar
- $V_i$: The voltage of node $i$ in p.u.
- $L_l$: The line loading of line $l$ in %
- $P_{ext}$: The total load of the distribution system in MW

Figure 3.3 illustrates the capability curve of a fast-charging station. The light blue area illustrates the available power and the relationship between active and reactive power when active power is positive, reactive power is negative and $S_n > P_{fcs,\,\mathrm{max}}$. Here we want the converter to work in the quadrant where active power is positive and reactive power is negative, but the converter is not technically limited to operate in only one of the four quadrants. In pandapower, it is only possible to define power with square limits. To prevent the OPF from using more reactive power than what is actually available, the lower limit of reactive power, $Q_{min}$, is set to $-\sqrt{S_n^2 - P_{fcs,\,\mathrm{max}}^2}$. However, as a result, the available reactive power that the OPF sees is lower than what is actually available when $P_{fcs} < P_{fcs,\,\mathrm{max}}$. In Figure 3.4, the light blue area illustrates the available reactive power that the OPF sees, while the dark blue area illustrates the available reactive power that the OPF does not see. Here, it can be seen that when $P_{fcs} < P_{fcs,\,\mathrm{max}}$, there is more reactive power available than $Q_{min}$. When $S_n = P_{fcs,\,\mathrm{max}}$ are $Q_{min} = 0$ and the OPF does not see any reactive power. Consequently, the available reactive power is not utilized, and the full potential is not studied. This issue was solved with a brute-force solution. The solution will now be presented in a pseudo-code and further explained.

```
if p_i < p_max:
    while q_min > -sqrt(S^2 - p_min^2)
        q_min = q_min - 0.1
        run optimal power flow

        if q_i < -sqrt(S^2-p_i^2)
            q_min = q_min_old
```

The code checks if the active power the FCS can draw at this hour is lower than $P_{fcs,\,\mathrm{max}}$. If this condition is satisfied, $Q_{min}$ is reduced with 0.1 MW, and an optimal power flow analysis is performed. This process is repeated until $Q_{min}$ exceeds the physically feasible limit. The solution for this hour is the result of the optimal power flow in the iteration before $Q_{min} > -\sqrt{S_n^2 - P_{fcs,\,\mathrm{min}}^2}$. Here, the automatic optimization in the OPF is supplemented with a manual optimization as an outer loop that iterates along degrees of freedom that are locked inside the OPF.

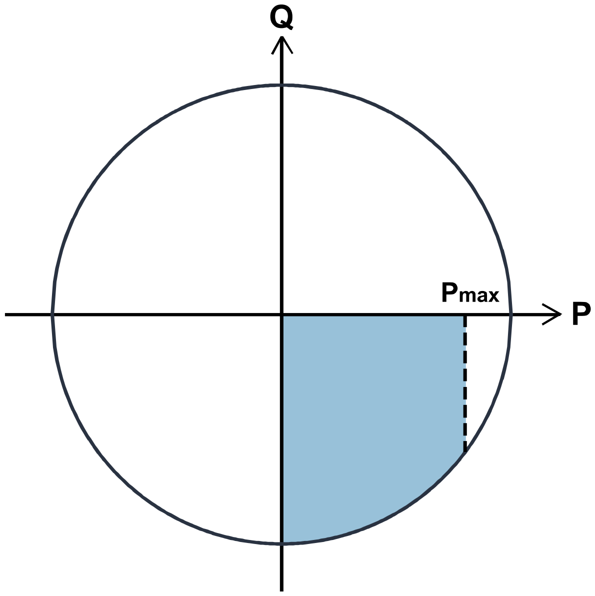



**Figure 3.3:** Capability curve of a fast-charging station when $S > P_{max}$

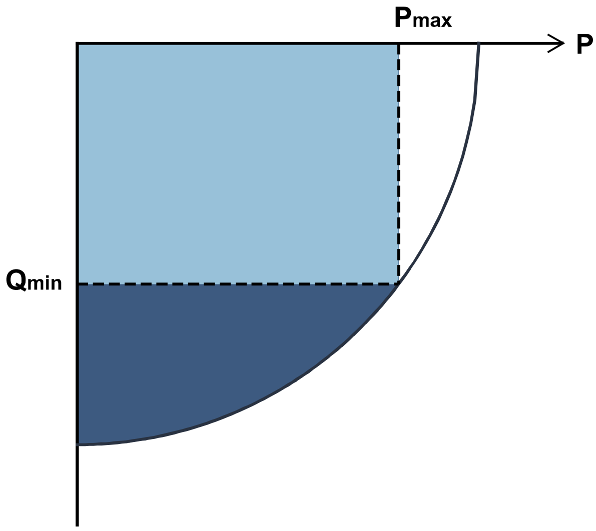



**Figure 3.4:** Illustration of utilized and available reactive power for a fast-charging station when $S > P_{max}$

*Can the FCS draw maximum active power if it provides reactive power at this hour?*
If $P_{fcs} = P_{fcs,\,\max}$ and $Q_{fcs} < 0$, the answer to the question is yes. The FCS can draw maximum active power if it provides reactive power, and the hour is stored in Category 2. If the result from the optimal power flow gives $0 < P_{fcs} < P_{fcs,\,\max}$ and $Q_{fcs} < 0$, the answer to the question is no, and the next question is triggered.

*Can the FCS draw a limited amount of active power if it provides reactive power at this hour?*
If the optimal power flow analysis gives $0 < P_{fcs} < P_{fcs,\,\max}$ and $Q_{fcs} < 0$, the answer to the question is yes. The FCS can only consume a limited amount of active power at this hour, and the hour is stored in Category 3. If the optimal power flow yields $P_{fcs} = 0$, the FCS cannot consume any active power in this hour and the hour is placed in Category 4.

When the hour is allocated in either Category 2, Category 3 or Category 4, it is removed from the sorted load data set. The initial second element of the sorted load data set is now the first element and the hour to be analysed. The iteration process continues until $P_{fcs} = P_{fcs,\,\max}$ and $Q_{fcs} = 0$ is reached, as this indicates that the fast-charging station can draw its maximum capacity for all the hours following that hour without needing to provide reactive power, due to the fact that the aggregated load is sorted from highest to lowest. However, since the aggregated load is being considered, it is possible that there may be some hours after the first time $P_{fcs} = P_{fcs,\,\max}$ and $Q_{fcs} = 0$ where $Q_{fcs}$ is slightly lower than 0 due to local variations in the grid. It may therefore be necessary to run a few extra iterations until $Q_{fcs}$ has stabilized and is equal to zero several times in a row.

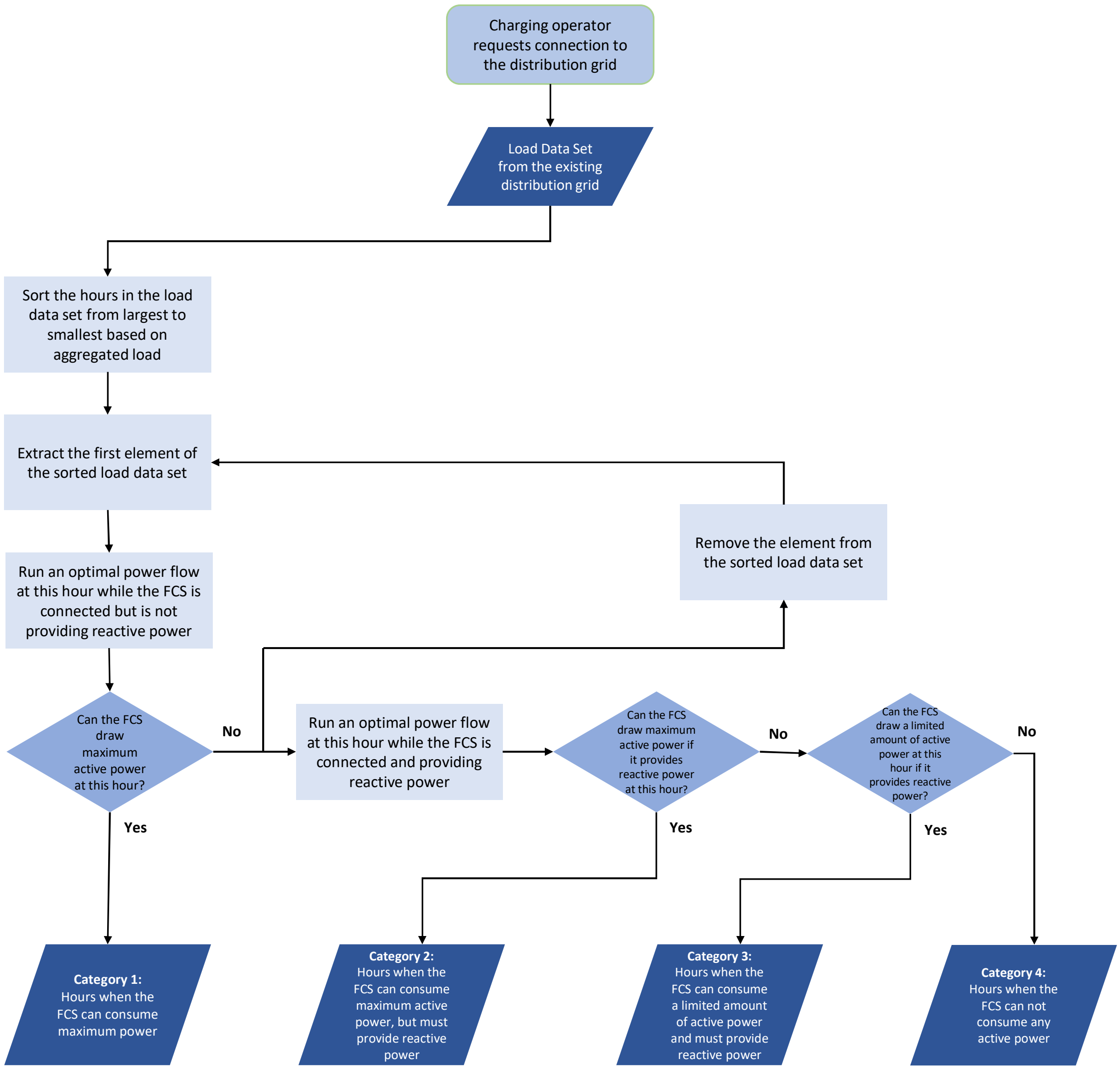



**Figure 3.5:** Methodology for Alternative 4 and Alternative 5

## 3.5 Available active power vs expected consumption

In the methodologies for Alternative 3, Alternative 4, and Alternative 5, the active power the FCS can draw is maximized. Although the FCS can have periods where the available active power is limited, it does not necessarily mean that the FCS would need maximum capacity in those periods. Therefore, comparing available active power and expected consumption is interesting. To do this, it is necessary to have either a load data set for a corresponding fast-charging station in the same area where the connection is requested or to have a description from the charging operator specifying how they predict the load to behave. After the methodologies of Alternative 3, Alternative 4, and Alternative 5 was followed, the active power available in the hours in Category 2 and Category 3 in Alternative 3 and the hours in Category 3 and Category 4 in Alternative 4 and Alternative 5 was compared to the expected consumption in the corresponding hours.

# Chapter 4

# Case study

The methodologies for the different alternatives presented in Chapter 3 were used in a case study on a 124-bus medium voltage reference system which represents a Norwegian medium voltage distribution grid. The different cases represent different connection requests from fast-charging operators, and the cases vary in terms of installed apparent power. In each case, each alternative was evaluated by following the proposed methodologies. Furthermore, the available active power of the FCS in the different cases was compared to a real-world load data set of an FCS. This chapter provides a system description of the 124-bus medium voltage reference system, a description of the load data set of the FCS, and a description of the different cases.

## 4.1 System description

CINELDI has established a 22 kV reference grid with 124 nodes based on real data provided by a Norwegian distribution system operator. The reference system represents a Norwegian medium voltage distribution system. All analysis in this master's thesis is performed on this system. The most relevant features of the system will now be summarized from [33], but for further description and detailed information, see [33].

This paragraph is retrieved from [12], the specialisation project report of the author. The reference system represents a radial medium voltage distribution grid in Norway and is illustrated in Figure 4.1. Table 4.1 provides the main characteristics of the distribution grid. The data is provided by a Norwegian Distribution System Operator but is further anonymized and simplified. The system operates at 22 kV and consists of 124 nodes and 123 lines. The lines are a combination of overhead lines and underground cables. The system has one main feeder connected to node 1 and three backup feeders connected to nodes 36, 42 and 88. It is assumed that the feeders have enough available capacity to cover the total power peak load of the system. In the present system, only 54 of 124 nodes are load points. These 54 nodes are a mix of residential, agricultural, public, industrial and commercial loads, with a maximum aggregated load demand of 5.231 MW. The load data set covers the entire year of 2018, and includes hourly-resolution load values from a Norwegian distribution system.

**Table 4.1:** Main characteristics of the CINELDI reference system [33]

| Parameter | Value |
|---|---|
| Number of nodes | 124 |
| Number of lines | 123 |
| Voltage level | 22 kV |
| Number of load points | 54 |
| Maximum aggregated load | 5.231 MW |

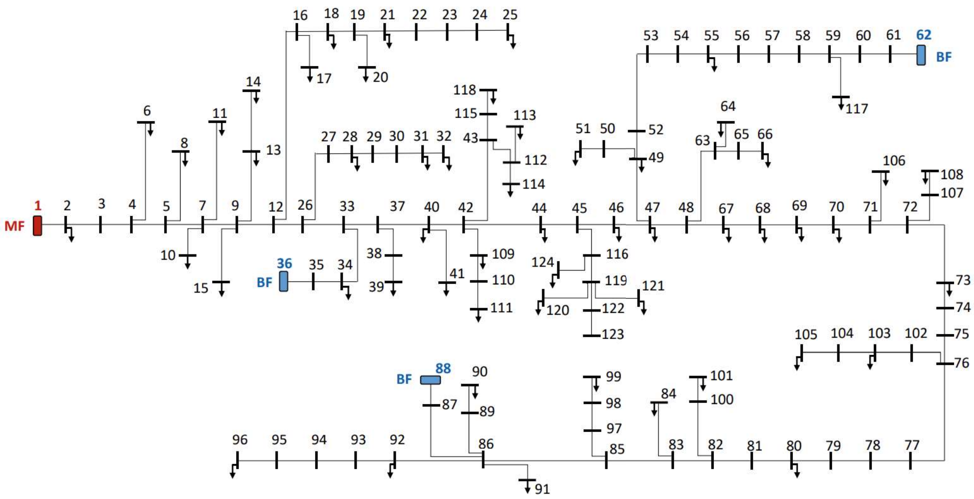



**Figure 4.1:** Illustration of the CINELDI 124-bus medium voltage reference system [33]

Figure 4.2 shows the aggregated load-time series for the reference system throughout the year.

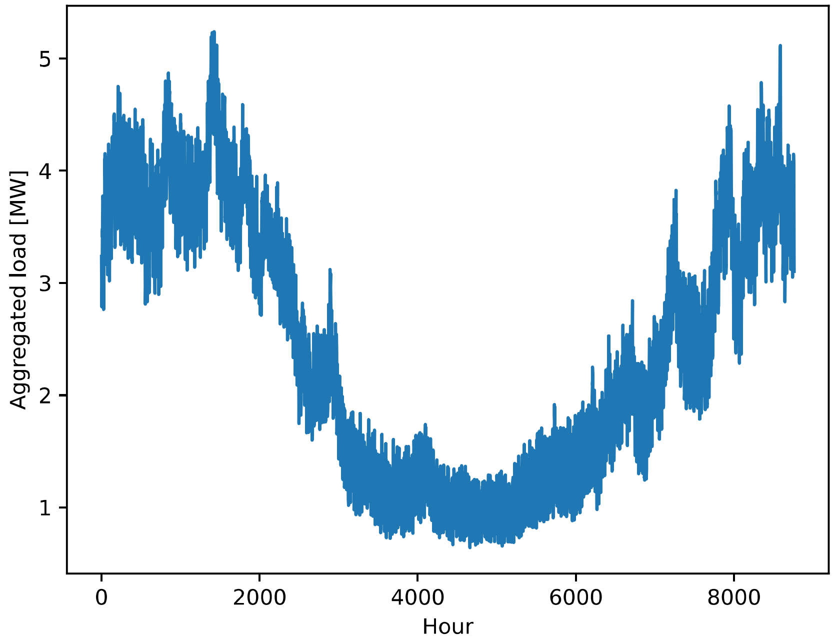



**Figure 4.2:** The aggregated load-time series for the CINELDI reference system throughout the year

## 4.2 Load data set - FCS

A load data set, which is not a part of the CINELDI reference system, was provided by the Norwegian Distribution System Operator, Elvia, representing the load of an FCS located close to a highway in Eastern Norway. The load data set has an hourly resolution and covers the entire year of 2018. To ensure confidentiality, the data set is anonymized, and it is impossible to locate which fast-charging station the data is collected from. Furthermore, the data set was scaled by the author by dividing all values in it by the maximum value. This resulted in values from 0 to 1, representing the relative power demand of the fast-charging station. In order to scale the data set to represent a fast-charging station with a maximum power demand of 2 MW, the relative power demand was multiplied by 2 MW. Figure 4.3 shows the scaled load of the FCS throughout the year.

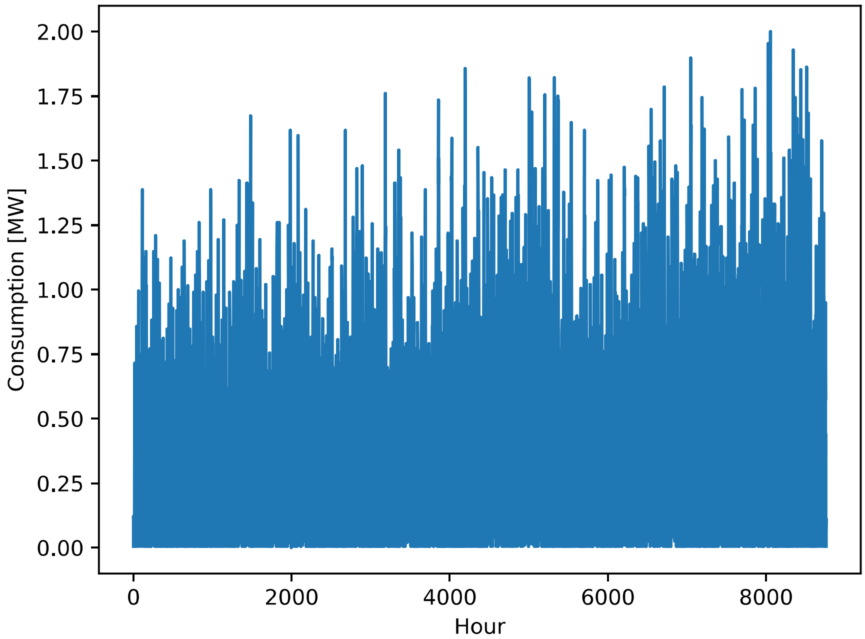



**Figure 4.3:** Load-time series for the FCS throughout the year

## 4.3 Case study description

In the case study, three different cases were studied. Each case represents a grid connection request of an FCS to the CINELDI 124-bus reference system. The different cases vary in terms of installed apparent power. In each case, each of the five alternatives was evaluated by using the proposed methodology for each alternative presented in Chapter 3. In the analysis, it is assumed that the DSO has clarified with the Transmission System Operator that there is sufficient capacity in the transmission grid to connect the new load. Table 4.2 provides an overview of the different cases and their characteristics.

**Table 4.2:** A brief description of the cases in the case study

| Case | Description |
|---|---|
| Case A | 124 bus CINELDI reference system with 54 load points + one FCS connected to node 78 (S=2.5 MVA, P=2 MW) |
| Case B | 124 bus CINELDI reference system with 54 load points + one FCS connected to node 78 (S=3.0 MVA, P=2 MW) |
| Case C | 124 bus CINELDI reference system with 54 load points + one FCS connected to node 78 (S=2.0 MVA, P=2 MW) |

For all three cases, the optimization problem defined in Equations 3.1-3.5 was implemented as follows:

- fcs = node 78
- $P_{78,\mathrm{min}} = 0\,\mathrm{MW}$
- $P_{78,\mathrm{max}} = 2\,\mathrm{MW}$
- $V_{\mathrm{min}} = 0.95\,\mathrm{pu}$
- $V_{\mathrm{max}} = 1.05\,\mathrm{pu}$
- $L_{\mathrm{max},l} = 100\,\%$
- $P_{\mathrm{ext,\ min}} = 0\,\mathrm{MW}$
- $P_{\mathrm{ext,\ max}} = 20\,\mathrm{MW}$

The optimisation problem defined in Equations 3.6-3.11 is identical to the optimisation problem defined in Equations 3.1-3.5, except from Equation 3.8, as this is an additional equation. Thus, the values presented above were also applied to Equations 3.6-3.7 and 3.9-3.11. Equation 3.8 is case specific and will be presented for each case separately.

**Case A**

The converter of the fast-charging station had an installed nominal apparent power of 2.5 MVA. The lower limit of $Q_i$ in Equation 3.8 is thus equal $-\sqrt{2.5^2 - 2^2} = -1.5$ Mvar.

**Case B**

The converter of the fast-charging station had an installed nominal apparent power of 3.0 MVA.The lower limit of $Q_i$ in Equation 3.8 is thus equal $-\sqrt{3^2 - 2^2} = -2.2$ Mvar.

**Case C**

The converter of the fast-charging station had an installed nominal apparent power of 2.0 MVA. The lower limit of $Q_i$ in Equation 3.8 is thus equal $-\sqrt{2^2 - 2^2} = 0$ Mvar.

# Chapter 5

# Results

The results of the case study will be presented in this chapter. The distinguishing factor between Case A, Case B, and Case C is the installed apparent power. Thus, the result of Alternative 1, Alternative 2, and Alternative 3 will be identical in all cases as reactive power provision is not utilized in the three first alternatives. The result of Alternative 1, Alternative 2, and Alternative 3 will first be presented. Subsequently, the result of Alternative 4 and Alternative 5 will be provided for each case separately - respectively Case A, Case B, and Case C. Finally, the chapter studies the effectiveness of active power curtailment versus reactive power provision.

## 5.1 Alternative 1

The methodology presented for Alternative 1 in Chapter 3 was followed, and the result will now be presented. In order to determine whether the fast-charging station can be connected with or without the need for measures, the voltages and the loading of the power lines during the aggregated peak load hour of the other loads in the system were studied. Figure 5.1 shows the voltage at each bus in the system when the FCS was connected and consumed 2 MW during the aggregated peak load hour of the other loads in the CINELDI reference system. The bus indexes in the figure are in accordance with the numbering of the buses in Figure 4.1. As depicted in Figure 5.1, the voltage is below the lower limit of 0.95 per unit (pu) for multiple buses. Figure 5.2 shows the line loading of all power lines in the system when the FCS was connected and consumed 2 MW during the aggregated peak load hour of the other loads in the CINELDI reference system. The line indexes with their corresponding from bus and to bus can be found in Appendix A. Figure 5.2 shows that the loading of the lines is far from being overloaded. The line between bus 5 and bus 7 is the most loaded, with a loading of 66.5%. Based on these observations, the voltage level is the limiting factor in order to connect the fast-charging station to the CINELDI reference system, and not the loading of the lines. Since the new load causes unacceptable voltage levels in the grid, the FCS cannot be connected without the need for measures.

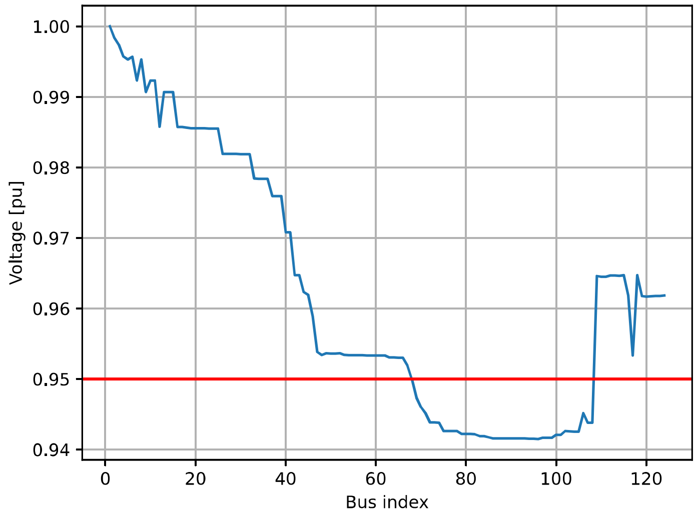



**Figure 5.1:** Voltage at all buses in the system when the FCS is drawing 2 MW during the aggregated peak load hour of the other loads in the system in Alternative 1

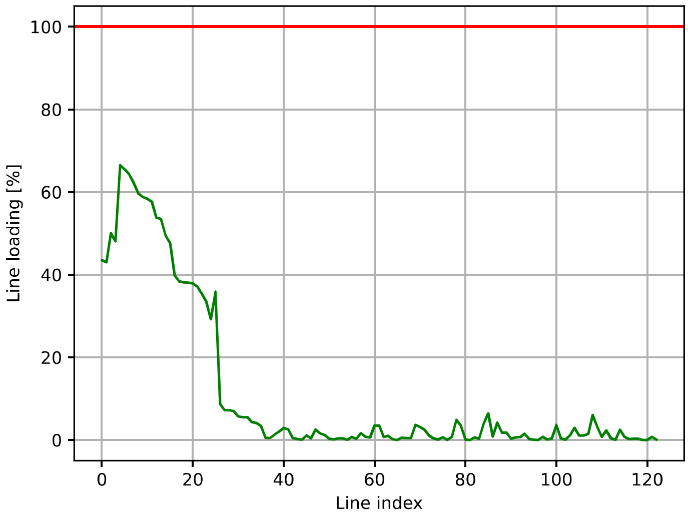



**Figure 5.2:** Line loading of all power lines in the system when the FCS is drawing 2 MW during the aggregated peak load hour of the other loads in the system in Alternative 1

## 5.2 Alternative 2

Since the result in Alternative 1 showed that the voltage level is unacceptable for multiple buses, measures are needed to connect the FCS to the CINELDI reference system. The traditional choice would be to expand or reinforce the existing grid in order to connect the FCS. This will trigger a connection charge the charging operator has to pay.

## 5.3 Alternative 3

The methodology presented for Alternative 3 in Chapter 3 was followed, and the results will be given in this section. Table 5.1 shows the distribution of the hours when the fast-charging station can draw maximum active power, the hours when it can only draw a limited amount, and the hours when it cannot consume any active power. The table shows that Category 1 equals 8368 hours, which signifies that the fast-charging station could have consumed the maximum capacity of 2 MW in 8368 of 8760 hours of the year. Category 2 equals 392 hours, which implies that the FCS have a limited amount of available active power during 392 hours. There were no hours when the fast charging station could not have drawn any active power, as Category 3 equals zero.

**Table 5.1:** The output of the methodology of Alternative 3

| Category | Number of hours |
|---|---|
| Category 1 | 8368 |
| Category 2 | 392 |
| Category 3 | 0 |

When drafting an alternative grid connection agreement, it is crucial that the DSO specifies to the fast-charging operator how much and when the available active power will be restricted. Figure 5.3 shows how much active power the FCS had available in each hour of the year. The available active power in the curtailed hours ranges from 1.17 MW to 1.95 MW.

In order to illustrate that the curtailment of active power in critical hours will enhance the voltage level in the system, it is interesting to compare the voltage at all buses when the FCS is drawing 2 MW and when it is drawing a limited amount of active power during the peak load hour of the other loads in the CINELDI reference system. In Figure 5.4, the voltage at all buses when the FCS is connected and drawing power during the aggregated peak load hour of the other loads in the CINELDI reference system for respectively Alternative 1 and Alternative 3 is compared. The bus indexes in the figure are in accordance with the numbering of the buses in Figure 4.1. In Alternative 3, 1.17 MW of active power was available during the aggregated peak load hour. As shown in the figure, when the active power is curtailed to 1.17 MW during the aggregated peak load hour, the voltage at all buses remains within acceptable levels.

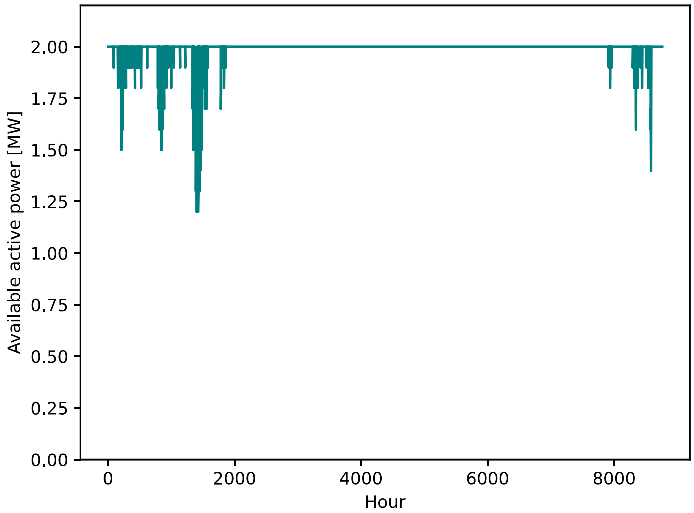



**Figure 5.3:** Hourly available active power for the FCS throughout the year in Alternative 3

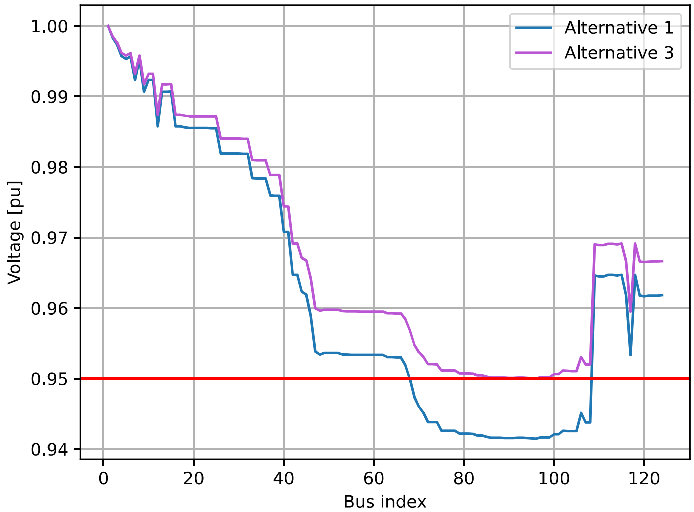



**Figure 5.4:** Comparison of the voltage at all buses in the system when the FCS is drawing power during the aggregated peak load hour of the other loads in the system in Alternative 1 and Alternative 3

Since the analysis is based on historical data, the hours when the active power was curtailed in Figure 5.3 is not necessarily the exact hours when the available active power will be restricted in the following years. Therefore, it is interesting to study the hours when the available active power was limited, sorted by month, day of the week and hour of the day in order to identify trends. Figure 5.5, Figure 5.6 and Figure 5.7 shows the 392 hours when the available active power was limited, respectively sorted by month, day of the week and hour of the day.

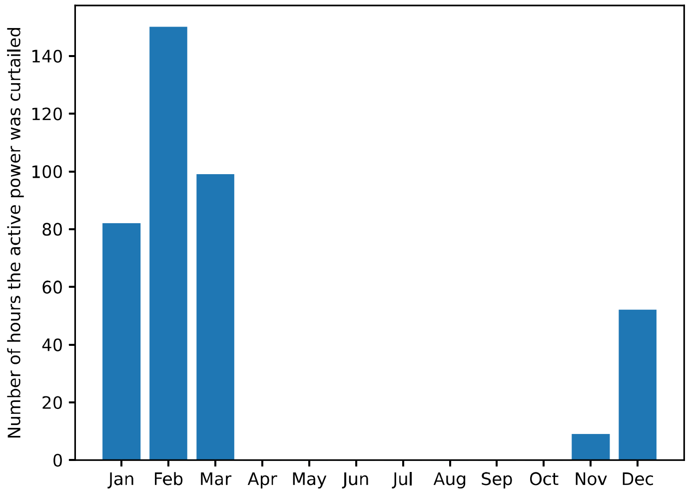



**Figure 5.5:** The hours when the available active power for the FCS was limited sorted by month in Alternative 3

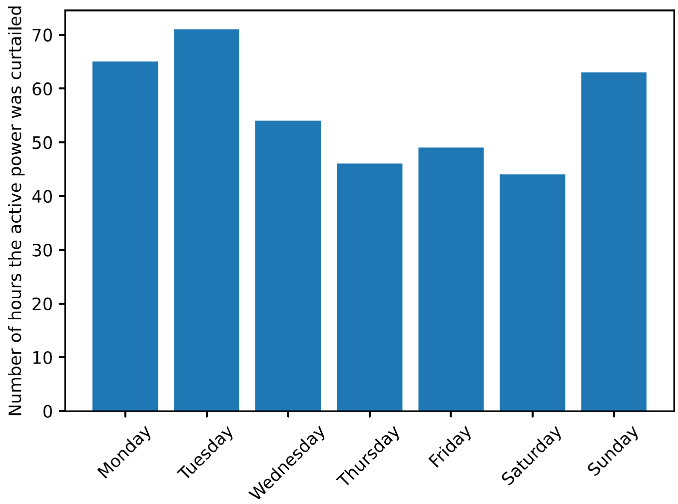



**Figure 5.6:** The hours when the available active power for the FCS was limited sorted by day of the week in Alternative 3

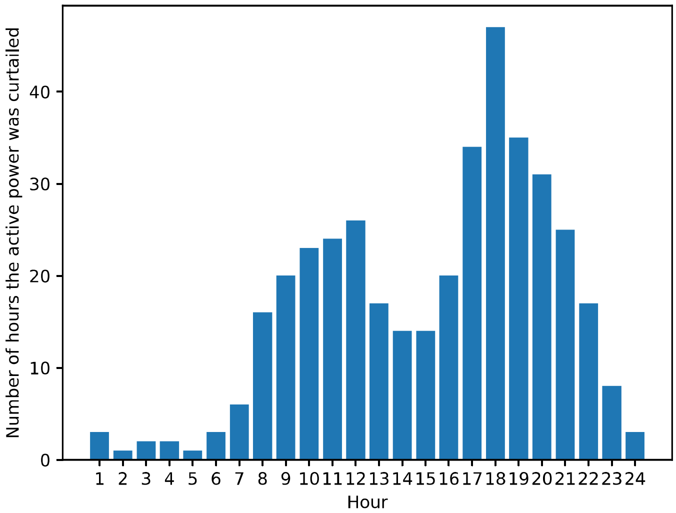
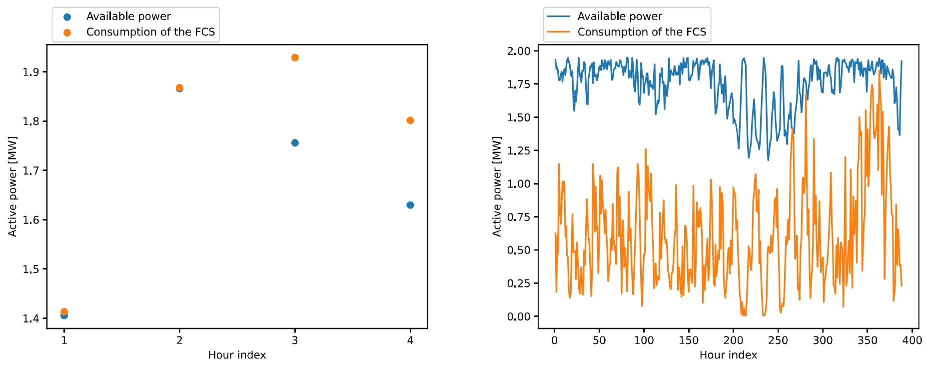



**Figure 5.7:** The hours when the available active power for the FCS was limited sorted by hour of the day in Alternative 3

A comparison was made between the real-world data set of the FCS described in Chapter 4 and the 392 hours when the available active power was lower than 2 MW. The comparison showed that the consumption of the fast-charging station was only greater than the available active power in 4 out of 392 hours. This signifies that in 388 out of 392 hours, the fact that the FCS did not have maximum available active power would not have impacted the FCS. Figure 5.8a shows the comparison between the available power and the consumed power of the FCS in the hours when the available power was lower than the consumption. The hours are depicted in chronological order. Appendix B shows the hour indexes with their corresponding date and hour of the day. When the hour index equals one and two, the available power is just slightly lower than the consumed power. In only two hours of the year was the available power significantly lower than the consumption and would have had an impact on the FCS.

Figure 5.8b displays the comparison of the available power and the consumed power of the FCS in the hours when the available power was higher than the consumption. The hours are presented in chronological order. The hour indexes with their corresponding date and hour of the day can be found in Appendix C. In Figure 5.8b, the available active power generally has a good margin to the consumed power. This indicates that the fast-charging station and the other loads in the CINELDI reference system do not peak simultaneously.




**(a)** when consumption exceeds availability **(b)** when availability exceeds consumption

**Figure 5.8:** Comparison of the available active power and the consumed active power in Alternative 3 in the hours when the available power is lower than the maximum capacity

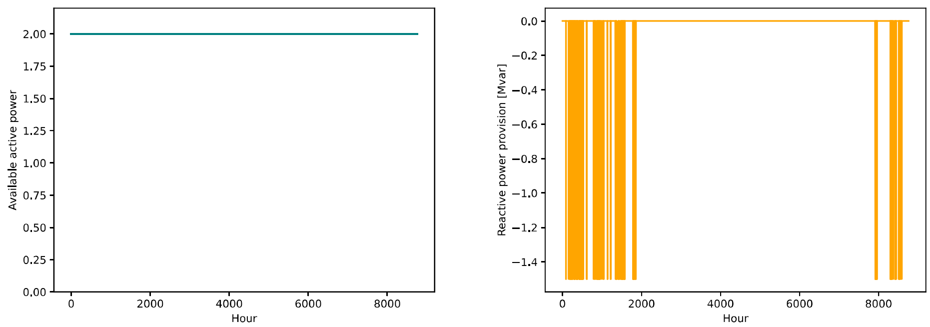
## 5.4 Case A: Alternative 4 and Alternative 5

In Case A, the installed apparent power was 2.5 MVA. The methodology of Alternative 4 and 5 presented and described in Chapter 3 was followed, and the result will now be presented. The output of the methodology of Alternative 4 and 5 for Case A is presented in Table 5.2. As Category 3 and Category 4 do not have content, Alternative 4 is an option in this case. This means that the FCS could have drawn maximum active power every hour of the year. However, since Category 2 equals 392 hours, the FCS must have provided reactive power in 392 hours of the year in order to draw maximum active power in those hours.

**Table 5.2:** Case A: The output of the methodology of Alternative 4

| Category | Number of hours |
|---|---|
| Category 1 | 8368 |
| Category 2 | 392 |
| Category 3 | 0 |
| Category 4 | 0 |

When drafting an alternative grid connection agreement, it is important that the DSO communicates to the charging operator how much and when the FCS potentially needs to provide reactive power and how much and when the available active power potentially needs to be limited. It is thus interesting to plot the available active power for each hour of the year and the reactive power provision for each hour of the year. Figure 5.9a shows the available active power for the FCS for each hour throughout the year. Figure 5.9b shows how much reactive power the FCS needs to supply in each hour of the year. In the majority of the hours, the FCS does not have to provide reactive power. However, in certain hours must the FCS supply -1.5 Mvar.




**(a)** Hourly available active power **(b)** Hourly reactive power provision

**Figure 5.9:** Case A: Hourly available active power and hourly reactive power provision for the FCS throughout the year in Alternative 4

In order to show that the reactive power provision from the FCS increases the voltage level in the grid, a comparison of the voltage at all buses when the FCS was connected and drawing power during the aggregated peak load hour of the other loads in the CINELDI reference system in Alternative 1 and Alternative 4 was made and is shown in Figure 5.10. The bus indexes in the figure are in accordance with the numbering of the buses in Figure 4.1. As can be seen from Figure 5.10, all buses have a voltage level that exceeds the lower limit of 0.95 pu in Alternative 4.

When comparing the voltage levels in Alternative 3 in Figure 5.4 and the voltage levels in Alternative 4 in Figure 5.10, it can be observed that the voltage levels on certain buses in Alternative 3 are exactly equal to the lower limit of 0.95 pu, whereas, in Alternative 4, all buses have a voltage level that is above the limit. This shows that the OPF, as it is implemented, utilises more reactive power than what is necessary for the FCS to access the maximum active power. This implies that the FCS may not necessarily have to provide -1.5 Mvar in the 392 hours as shown in Figure 5.9b; a lower amount may have been sufficient.

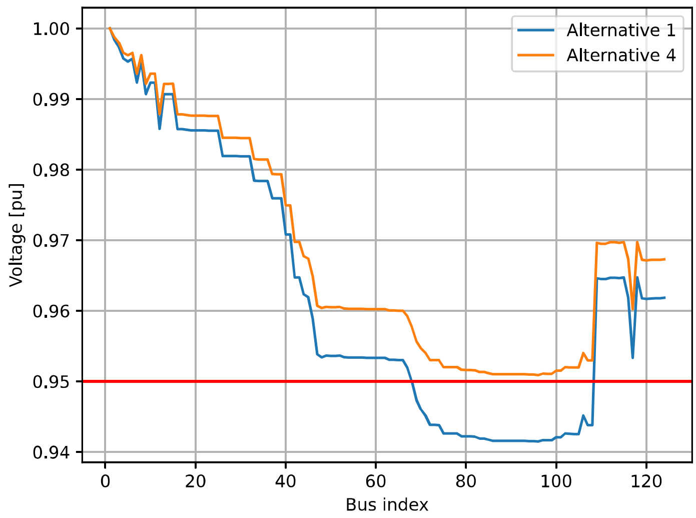



**Figure 5.10:** Case A: Comparison of the voltage at all buses in the system when the FCS was connected and was drawing power during the aggregated peak load hour of the other loads in the system in Alternative 1 and Alternative 4

As the conducted analysis is based on historical data, the hours in Figure 5.9b where $Q < 0$ are not necessarily the exact hours when the FCS needs to provide reactive power as the other loads in the distribution system are influenced by many factors, and will vary from year to year. It is thus interesting to sort the hours when the FCS must provide reactive power by month, day of the week, and hour of the day in order to identify trends. Since the same 392 hours are studied in Alternative 3 and Alternative 4 for Case A, the hours when the FCS needs to provide reactive power sorted by month, day of the week, and hour of the day will be identical to the hours when the FCS in Alternative 3 must be curtailed sorted by month, day of the week and hour of the day, respectively shown in Figure 5.5, Figure 5.6 and Figure 5.7. The figures for Alternative 4 can also be found in section E.1 in Appendix E.

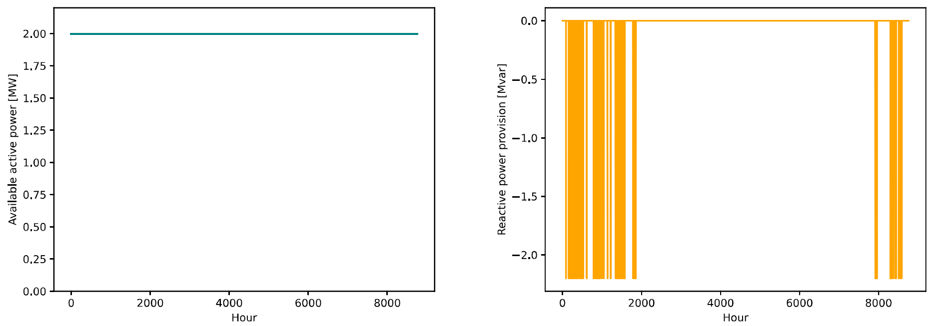
## 5.5 Case B: Alternative 4 and Alternative 5

In Case B, the installed apparent power was increased in comparison to Case A and equalled 3.0 MVA. The methodology for Alternative 4 and Alternative 5 was followed, and the result is presented in Table 5.3. As both Category 3 and Category 4 equals zero, Alternative 4 is an option in this case. This implies that the FCS can draw maximum active power at all hours throughout the year. As Category 2 equals 392 hours, the FCS must provide reactive power in 392 hours of the year in order to always have maximum active power available.

**Table 5.3:** Case B: The output of the methodology of Alternative 4

| Category | Number of hours |
|---|---|
| Category 1 | 8368 |
| Category 2 | 392 |
| Category 3 | 0 |
| Category 4 | 0 |

Figure 5.11a shows the available active power for the FCS for each hour throughout the year. As can be seen from the figure, the available active power is maximum throughout the entire year. Furthermore, Figure 5.11b presents the reactive power provision for the FCS for each hour of the year. In certain hours of the year must the FCS provide -2.2 Mvar, but in most of the hours do the FCS not have to supply reactive power.




**(a)** Hourly available active power **(b)** Hourly reactive power provision

**Figure 5.11:** Case B: Hourly available active power and hourly reactive power provision for the FCS throughout the year in Alternative 4

Figure 5.12 compares the voltage at all buses when the FCS was connected and was drawing power during the aggregated peak load hour of the other loads in the CINELDI reference system in Alternative 1 and Alternative 4. When the FCS provided -2.2 Mvar while it simultaneously was drawing maximum active power in Alternative 4, it can be seen from the figure that the voltage level of all buses in the system was well above the lower limit of 0.95 pu. Comparing the voltage levels in Alternative 3 in Figure 5.4 and the voltage levels in Alternative 4 in Figure 5.12, it can be seen that certain buses have a voltage level of 0.95 in Alternative 3, while the voltage levels in Alternative 4 was well above the limit. This is because the OPF, as it is implemented, uses more reactive power than what is needed in order for the FCS to have maximum available active power. Thus, the FCS must most likely provide less than -2.2 Mvar in the 392 hours in order to access maximum capacity.

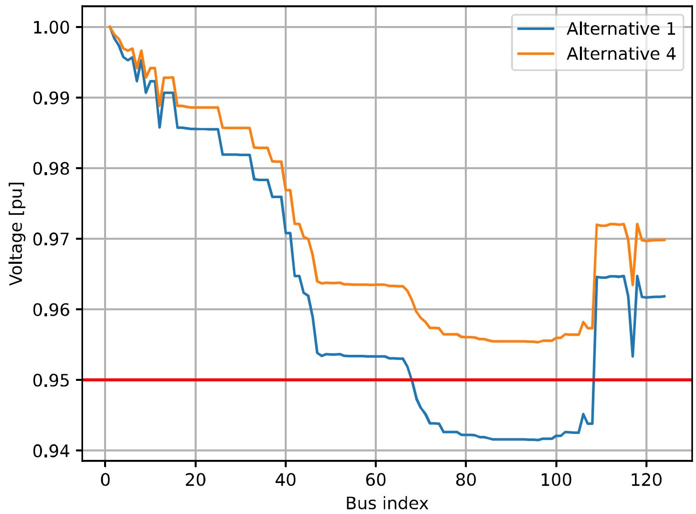



**Figure 5.12:** Case B: Comparison of the voltage at all buses in the system when the FCS was connected and was drawing power during the aggregated peak load hour of the other loads in the system in Alternative 1 and Alternative 4

Since the same hours are studied in Alternative 3 and Alternative 4 for Case B, the distribution of the hours sorted by month, day of the week and hour of the day will be the same. Consequently, Figure 5.5, Figure 5.6, and Figure 5.7 shows respectively the distribution of the hours when the FCS needs to provide reactive power sorted by month, day of the week and hour of the day. The figures can also be found in section E.2 in Appendix E.

## 5.6 Case C: Alternative 4 and Alternative 5

In Case C, the apparent power was decreased in comparison to Case A and equalled 2.0 MVA. The result of Alternative 4 and 5 in Case C is presented in Table 5.4. From the table, it can be seen that in 8368 out of 8760 hours could the FCS draw maximum active power. In 392 hours, the available active power was restricted while the FCS had to provide reactive power simultaneously. Since $S_n = P_{max}$, it is expected that Category 2 equals zero, as there is no reactive power available for the FCS to provide when $P_{fcs} = P_{fcs,\,\mathrm{max}}$. There were no hours when the FCS could not consume any active power. As the available active power was limited during 392 hours, Alternative 5 is an option in this case, whereas Alternative 4 is not.

**Table 5.4:** Case C: The output of the methodology of Alternative 4 and Alternative 5

| Category | Number of hours |
|---|---|
| Category 1 | 8368 |
| Category 2 | 0 |
| Category 3 | 392 |
| Category 4 | 0 |

Figure 5.13 shows the voltage at all buses in the system when the FCS was connected to the CINELDI reference system and was drawing power during the aggregated peak load hour of the other loads in the system in Alternative 1 and Alternative 5. The figure shows that when the active power was curtailed to 1.73 MW and the FCS provided -0.9 Mvar to the grid during the aggregated peak load hour, the voltages at all buses were equal to or above 0.95 pu.

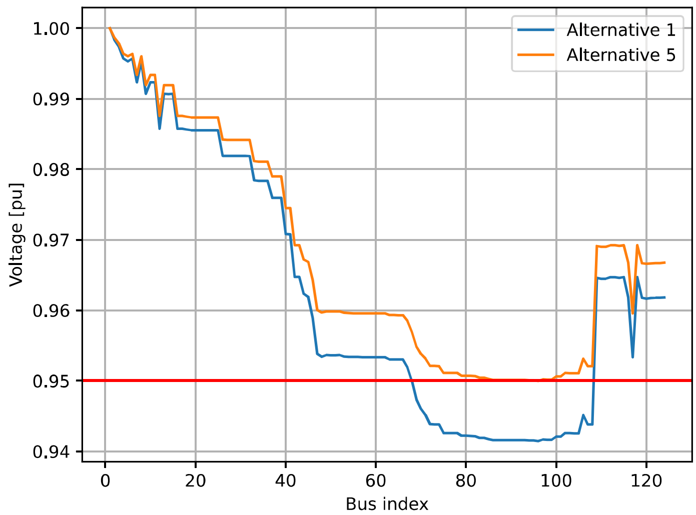
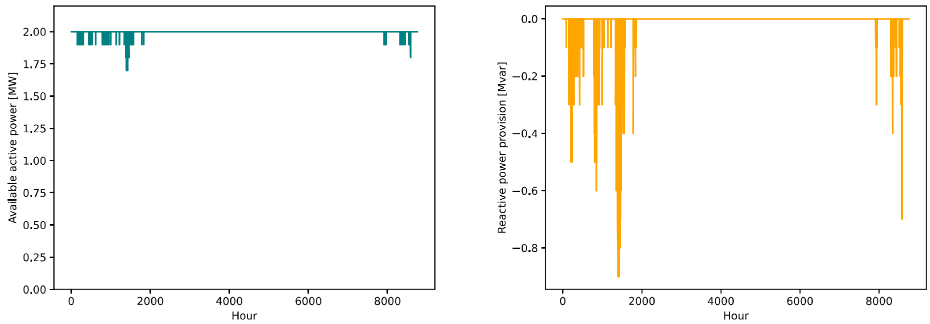



**Figure 5.13:** Case C: Comparison of the voltage at all buses in the system when the FCS was connected to the system and was drawing power during the aggregated peak load hour of the other loads in the system in Alternative 1 and Alternative 5

Figure 5.14a displays the available active power throughout the year. During the 392 hours when the capacity was restricted, the available power ranged from 1.73 MW to 1.99 MW. Figure 5.14b shows the reactive power provision of the

FCS throughout the year. The reactive power provision ranged from -0.1 Mvar to -0.9 Mvar in the hours when it was required. However, since $S_n = P_{fcs,\max}$ in Case C, it triggered the brute force solution; thus, Figure 5.14b displays the approximation of the reactive power provision.




**(a)** Hourly available active power **(b)** Hourly reactive power provision

**Figure 5.14:** Case C: Hourly available active power and hourly reactive power provision for the FCS throughout the year in Alternative 5

Figure 5.15 shows how much the available active power was reduced in comparison to the maximum active power in the hours when the available power was limited. The hours are presented in chronological order. As can be seen from the figure, in the majority of the hours, the available active power was reduced by 0.15 MW or less. In some hours was the available power reduced more, and at its most, it was reduced by 0.27 MW. As written in Chapter 2, a fast charger has a capacity from 50 kW, and an ultra-fast charger has a capacity from 150 kW. In order to get a relationship to the impact of the reduction; a reduction of 0.15 MW would imply that one ultra-fast charger with a capacity of 150 kW or three fast chargers with a capacity of 50 kW each would be unavailable. In practice, this would probably not be the case; the capacity would instead have been reduced equally on all chargers. On the other side, it is not necessarily that the FCS would need maximum capacity in those hours. Thus, the degree of coincidence between the consumption of the FCS and the available active power is interesting to study and will be executed later in the section.

Figure 5.16 shows the reactive power provision from the FCS in the hours when the active power must have been curtailed. The hours are presented in chronological order, and the reactive power provision ranges from -0.1 Mvar to -0.9 Mvar. During a few hours, the FCS is not providing any reactive power. This may be because the reactive power is redundant and does not enhance the conditions in the grid. Alternatively, it could be an undetected weakness in the implementation of the brute-force solution.

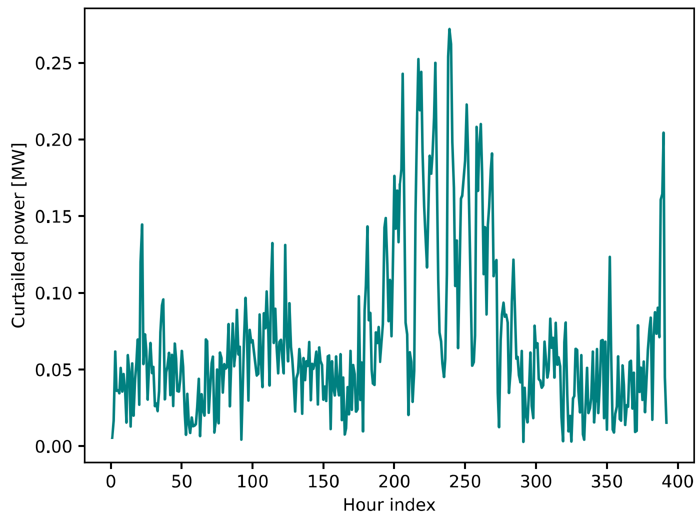



**Figure 5.15:** Case C: Reduction in available active power compared to maximum available power in the limited hours in Alternative 5

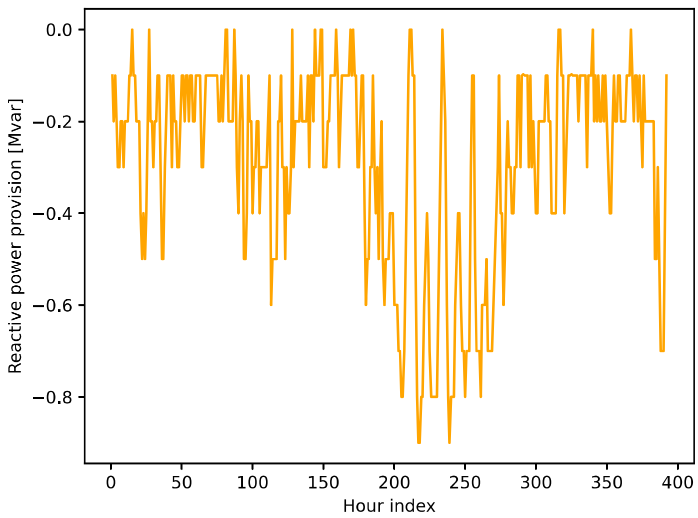



**Figure 5.16:** Case C: Reactive power provision in the limited hours in Alternative 5

Since the same 392 hours are studied in Alternative 3 and Alternative 5 in Case C, the distribution of hours sorted by month, day of the week, and hour of the day will be the same. Due to this, Figure 5.5, Figure 5.6, and Figure 5.7 respectively illustrate the hours when the FCS will have a limited available capacity and needs to provide reactive power to the grid sorted by month, day of the week and hour of the day. The figures can also be found in section E.3 in Appendix E.

The available active power in the 392 hours when the capacity was restricted was compared to the consumed power of the FCS in the load data set and is plotted in Figure 5.17. The hours are plotted in chronological order, and the hour indexes with their corresponding date and hour of the day can be found in Appendix D. From the figure, it is evident that the available power is greater than the consumed power in all 392 hours. This implies that the restricted available active power in certain hours would not impact the FCS.

In order to discuss the most appropriate alternative of Alternative 3 and Alternative 5 in Case C, it is interesting to compare the available active power in the two alternatives. Figure 5.18 compare the available active power for the FCS in Alternative 3 and Alternative 5.

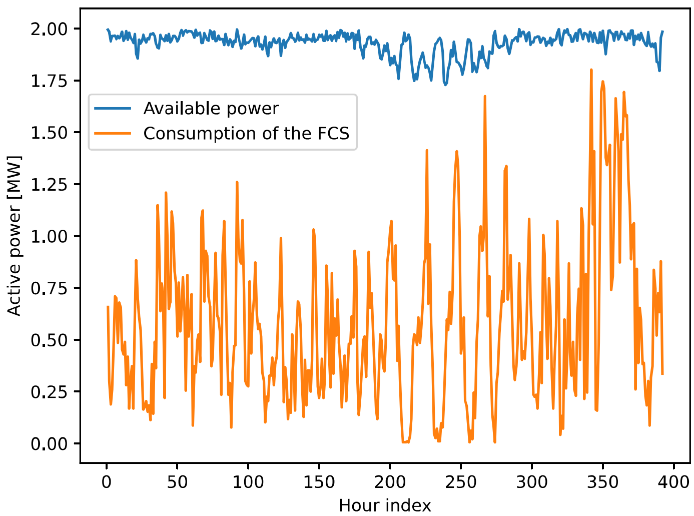



**Figure 5.17:** Case C: Comparison of available active power and consumed active power in Alternative 5

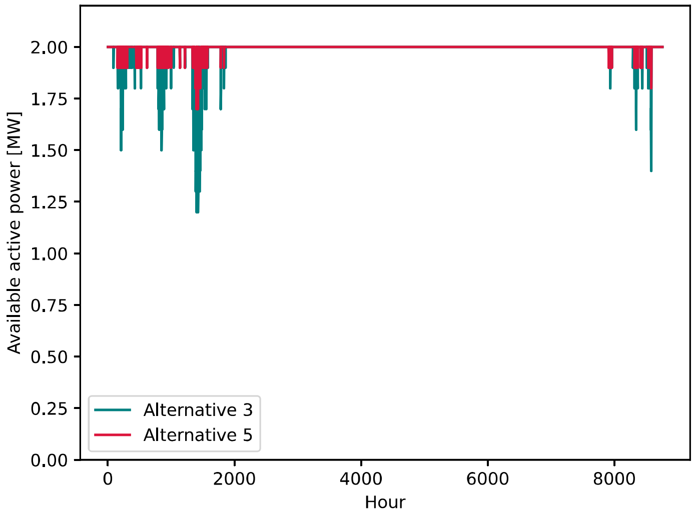



**Figure 5.18:** Case C: Comparison of the available active power in Alternative 3 and Alternative 5

## 5.7 Case study result summary

As stated earlier, the result of Alternative 1, 2 and 3 was equal for all three cases as the only distinguishing factor was the installed apparent power. The case study showed that measures were needed in 392 hours for Alternative 3, Alternative 4 and Alternative 5 in all cases. Table 5.5 provides a summary of the main characteristics of the result of the case study. The table depicts the measures needed in each case and alternative, how much the available power eventually was limited during the 392 hours and how much reactive power the fast-charging station must have provided during the 392 hours.

**Table 5.5:** Summary of the results of the case study

| Case | Alternative | Measure | Available power in limited hours | Reactive power provision |
|---|---|---|---|---|
| A, B, C | 3 | Curtailment of active power | 1.17 - 1.95 MW | - |
| A | 4 | Reactive power provision | 2 MW | -1.5 Mvar |
| B | 4 | Reactive power provision | 2 MW | -2.2 Mvar |
| C | 5 | Curtailment of active power and reactive power provision | 1.73 - 1.99 MW | -0.1 to -0.9 Mvar |

## 5.8 Effectiveness of active power curtailment vs. reactive power provision

As written in Chapter 2, the $\frac{R}{X}$ ratio plays a crucial role in which of the active power curtailment and the reactive power provision who will be the most influencing counteracting factor in terms of voltage drops. Figure 5.19 shows the $\frac{R}{X}$ ratio of the power lines along the main radial in the CINELDI reference system. The lines are displayed in ascending order, where line index 0 represents the line from node 0 to node 1, and line index 40 corresponds to the line between node 95 and node 96. The lines connected to node 78, where the FCS is connected in the case study, are assigned line indexes 28 and 29. As can be seen from the figure, the $\frac{R}{X}$ ratio equals 1 when the line index equals 26, 27 and 28, signifying that the active and reactive power will influence equally. On the other hand, the ratio of the line from node 78 to node 79 equals 2.7.

The total $\frac{R}{X}$ ratio of the main radial was calculated as $\frac{\sum_i R_i}{\sum_i X_i} = 1.6$ where $i$ signifies all power lines in the main radial. A total $\frac{R}{X}$ ratio of 1.6 implies that the curtailment of active power will be more influential than the reactive power provision, according to the theory presented in subsection 2.4.2 in Chapter 2. In order to visualise this, Figure 5.20 shows the voltage at each bus in the CINELDI reference system during the aggregated peak load hour respectively when the FCS is drawing 2 MW, when it is drawing 1.9 MW, and when it is drawing 2 MW and simultaneously supplying -0.1 Mvar to the grid.

As seen from Figure 5.20, both reducing the consumption of the FCS and the provision of reactive power enhanced the voltage levels in the system. However, the reduction of active power had a more significant impact on the voltage levels than reactive power provision. Node 96 had the lowest voltage level during the aggregated peak load hour. When curtailing the active power to 1.9 MW, the voltage at node 96 increased by 0.001044 pu, whereas a reactive power provision of -0.1 Mvar increased the voltage at node 96 by 0.000643 pu. Dividing the change in voltage at node 96 when active power was curtailed by the change in voltage at node 96 when reactive power was provided yields 1.62. This means, if the provision of reactive power is to have the same impact on the voltage at node 96 as the curtailment of active power, the amount of reactive power provision must be 1.62 times the amount of the active power reduction. In this case, it would thus be necessary to supply -0.162 Mvar in order to increase the voltage at node 96 by 0.001044 pu. This shows that the curtailment of active power is 1.62 times more effective than the provision of reactive power, and the efficiency ratio is equal to 1.62, which is approximately equal to the total $\frac{R}{X}$ ratio in the main radial.

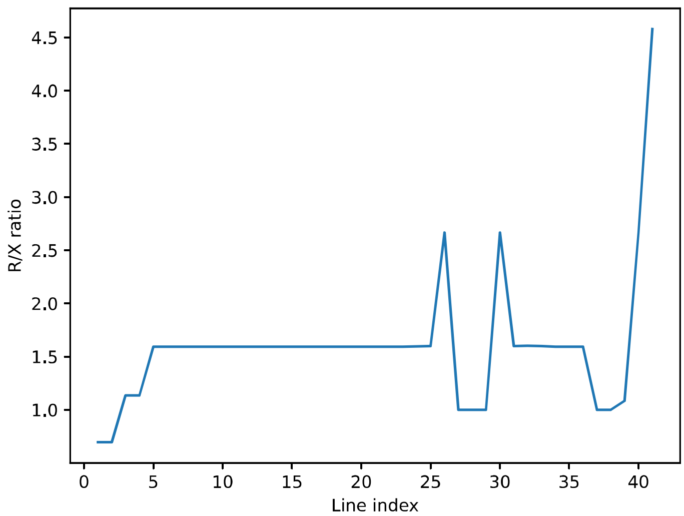



**Figure 5.19:** R/X ratio of the power lines along the main radial of the CINELDI reference system

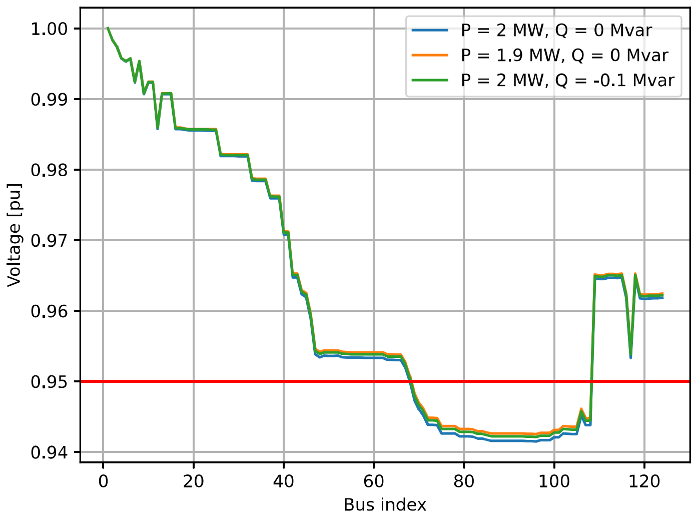



**Figure 5.20:** The voltage at each bus in the CINELDI reference system during the aggregated peak load hour respectively when the FCS is drawing 2 MW, when it is drawing 1.9 MW and when it is drawing 2 MW and simultaneously supplying -0.1 Mvar to the grid

# Chapter 6

# Discussion

This chapter will discuss the results presented in Chapter 5. Firstly, Alternative 3 will be compared to Alternative 4/5 for each case, and secondly, the cases will be compared to each other. Subsequently, the hours when measures were needed will be discussed in terms of months, day of the week and hour of the day. Finally, the most appropriate alternative, thus the most suitable grid connection agreement, for the case study and, in general, will be discussed.

**Case A: Alternative 3 vs Alternative 4**
In Alternative 3, the available active power was limited during 392 hours, while in Alternative 4, the maximum active power was always available. However, the FCS must provide reactive power during 392 hours in Alternative 4 to ensure maximum capacity. As explained in Chapter 2, the provision of reactive power requires a more expensive converter compared to the standard ones used today. It becomes a trade-off for the fast-charging operator to decide on the best alternative; either invest in a more expensive converter and always have maximum active power available or accept that the available active power will be restricted in specific periods of the year, potentially resulting in revenue loss. By choosing the second option, the charging operator can avoid the additional cost of a more expensive converter. The decision-making process should take into account the demand pattern of the FCS. If it is not expected that the FCS will require maximum active power during the 392 hours, there may not be a need to invest in a more expensive converter. However, if maximum active power is anticipated, the charging operator must carefully evaluate and determine the best course of action.

**Case B: Alternative 3 vs Alternative 4**
As Case A and Case B yield the same result regarding available active power and number of hours with reactive power provision in Alternative 4, the same discussion as in the previous paragraph can be applied here.

**Case C: Alternative 3 vs Alternative 5**
It is expected that the number of hours when the FCS have a limited amount of

active power available is equal in Alternative 3 and Alternative 4 as $S_n = P_{fcs,\,\max}$ in Case C. This is because the FCS has no reactive power available to supply when $P_{fcs} = P_{fcs,\,\max}$. The distinction between the alternatives first becomes apparent when $P_{fcs} < P_{fcs,\,\max}$, as the available power in the 392 hours varies between 1.17 MW and 1.95 MW in Alternative 3. In contrast, in Alternative 5, it ranges from 1.73 MW to 1.99 MW. In Figure 5.18, it can be seen that the available active power in Alternative 5 is significantly greater than the available active power in Alternative 3. This shows that the supply of reactive power in Alternative 5 increases the voltage level in the grid, which releases more active power. As written in Chapter 2, the converters used for fast-charging stations today do not have the ability to supply reactive power back to the grid. Therefore, a more expensive converter which also can work in the fourth quadrant is needed in Alternative 5. It is up to the charging operator to determine what is the most convenient; either to invest in a more expensive converter and thus have more available active power to sell throughout the entire year or to have a more limited available active power and thus less power to sell in periods, but do not need to invest in a more expensive converter.

As shown by the figures in Figure 5.8 and Figure 5.17, simultaneity plays a crucial role in deciding the most suitable alternative. From the figures in Figure 5.8, it can be observed that the consumption of the FCS was only greater than the available active power in 4 of the 392 hours in Alternative 3. In two of those four hours, the demand and the available active power were approximately equal, which would not have impacted the FCS considerably. In Alternative 4, the available power was greater than the consumed power in all 392 hours. Information about the expected consumption is thus essential to comprehensively understand how the limiting capacity will impact the fast-charging station.

**Case A vs Case B**

The results obtained in both Case A and Case B show that the fast-charging station can consume maximum active power throughout the entire year, and the number of hours it needs to provide reactive power is similar in both cases. Since the available active power was equal to the maximum throughout the entire year in Case A, an installed apparent power of 2.5 MVA was sufficient to give the fast-charging station access to maximum active power throughout the entire year. This implies that an installed apparent power of 3.0 MVA was unnecessary, considering the goal of maximising the available power. However, it is observed that a higher installed apparent power, and thus more available reactive power, further increased the voltage level in the grid. Comparing the voltage levels at the buses during the aggregated peak load hour for Alternative 4 in Figure 5.10 and Alternative 4 in Figure 5.12, it can be seen that the voltage at the buses during the aggregated peak load hour deviates more from the lower limit of 0.95 pu in Case B, than in Case A. A higher voltage level in the grid may be desirable from the perspective of the DSO according to voltage stability, power quality and losses in the grid.

However, the voltage level of the buses in Figure 5.10 in Case A are all above 0.95 pu, and the extra margin in Case B may be unnecessary.

**Case A vs Case C**

In both Alternative 4 in Case A and Alternative 5 in Case C is a more complex converter needed as both cases use reactive power provision. The converter in Case A has a greater installed apparent power than the converter in Case C, which may require a higher investment. Which of the two cases is the most suitable is up to the charging operator. Maximum active power is always ensured in Case A, but the investment cost is probably higher. In Case C, the investment cost will probably be lower than in Case A, but the available active power will be limited during specific hours of the year. As the result in Case A and Case B is equal in terms of available active power and number of hours with reactive power provision, comparing Case B with Case C, will give the same discussion as comparing Case A and Case C.

**Trends in months, day of the week and hour of the day**

In 8368 hours of the year, the FCS could draw maximum active power without any measures needed in all alternatives and cases. In 392 hours, the FCS was unable to consume maximum active power, and measures had to be taken to increase the voltage during these hours so that the FCS could draw the maximum possible active power. Since the same 392 hours apply for all cases and alternatives, it does not make sense to discuss the trends in terms of months, day of the week and hour of the day case by case, but either it will be discussed once and for all.

Figure 5.5, which exhibits the 392 hours when measures were needed sorted by months, shows that measures were needed in January, February, March, November and December. Furthermore, the figure shows that February was the month where measures were needed most frequently. This is expected as February is typically one of the coldest months in Norway, triggering a high load. No measures were needed in April, May, June, July, August, September and October, and the FCS could draw maximum active power. Based on the load-time series for the CINELDI reference system presented in Figure 4.2, the distribution of hours in terms of months is expected as the figure shows that the aggregated load is low during the summer and higher during the winter. Since many electric vehicle owners have their own chargers at home, the need for fast charging first arises when they are planning to drive long distances. Based on this, it can be assumed that the high season for fast charging is during the summer months when people have summer vacations and more time for longer trips. With this in mind, it is positive that the FCS have maximum available active power during the summer months.

The 392 hours are relatively evenly spread regarding the day of the week, according to Figure 5.6. Although the hours are relatively evenly distributed, the figure shows that Tuesday is the day of the week when measures are needed most frequently. Monday and Sunday also have a high share of hours where measures are needed. As written in the previous paragraph, many electric vehicle owners have a charger at home, and the need for fast charging arises when driving long distances. It is expected that EV owners drive longer distances during the weekends, which requires a higher demand for the FCSs during the weekends. Friday and Saturday have one of the lowest numbers of hours where measures are needed, which is positive, but Sunday has a high share which is unfortunate.

Based on Figure 5.7, it can be observed that the hour of the day when measures are most frequently needed is hour 18. In general, measures are most needed during the evening and late morning. As the existing load in the CINELDI reference system is a mix of residential, agricultural, public, industrial, and commercial loads, it is expected to peak during the morning and the evening, making less capacity available for the FCS.

In an alternative grid connection agreement where the available capacity is variable, like in Alternative 3 and Alternative 5, the capacity curve of the active power should be specified in the agreement as in Figure 5.3 and Figure 5.14a. In the same manner, the reactive power provision in an alternative grid connection agreement, like in Alternative 4 and Alternative 5, should be specified as in Figure 5.9b and Figure 5.11b. However, since the analysis is based on historical data, the load will vary from year to year, and the exact hours and amount of available active power and reactive power provision will vary from year to year. Due to this, a more general capacity curve and reactive power provision plan must be designed based on the number of hours when measures are needed and the distribution of those hours in terms of months, day of the week and hour of the day.

When connecting an FCS to node 78 in the CINELDI reference system, dividing the capability curve in terms of seasons would be natural. During April, May, June, July, August, September and October, there would be no restriction on the available capacity, and no reactive power provision will be required. In the rest of the months of the year should the available active power be specified like in Figure 2.5 with max on-peak capacities and max off-peak capacities. Similarly, the reactive power provision would be specified in steps when it needs to be provided in January, February, March, November and December. The level of detail of the capacity curve is up to each DSO to determine. One alternative could be to have one daily profile with different off-peak capacities and on-peak capacities, which applies to all Mondays, Tuesdays, Wednesdays and Thursdays in one month and another daily profile for the weekends for each month.

As written earlier, it will not be possible to specify precisely when the available capacity will be restricted or when the FCS must supply reactive power due to load variations. Thus, the capacity curves and reactive power provision plans must be designed generally based on the distribution of hours sorted by month, day of the week and hour of the day. A drawback with the capacity curves and plans for reactive power provision is that they do not necessarily reflect the actual situation. As suggested, if a capacity curve is specified for all Mondays to Thursdays in a month, there will probably be situations where the actual available capacity is greater than the specified on-peak capacity. At the end of the day, it is the voltage level of the critical bus which will be the determining factor for how much capacity is available and how much reactive power which must be supplied. For the charging operator, it is valuable to get an estimation of the number of hours when measures are needed. In this case, it could be communicated to the charging operator that it would affect around 400 hours of the year. For the DSO, it is crucial that the capacity curves and reactive power provision plans are general enough to cover all the hours where measures are needed, as they have to pay for the non-delivered power in the hours not specified in the agreement.

**Suitable grid connection agreement**
Figure 5.1 showed that the voltage at several buses was below 0.95 pu when the FCS consumed 2 MW during the aggregated peak load hour of the other loads in the CINELDI reference system. Seen from the worst-case scenario perspective, this would typically trigger a need to reinforce or expand the existing distribution grid before the FCS can be connected. The case study showed that in 95.5 % of the hours of the year, the FCS could draw maximum power without the need for measures, whereas in only 4.5 % of the hours of the year were measures needed. The number of hours where measures are needed is small, which implies a big potential for alternative grid connection agreements.

Which alternative and which case is the most appropriate depends on the needs of the charging operator. If it is essential that the FCS always have maximum active power available, Alternative 2 or Alternative 4 in Case A and Case B would be the best choice. As an installed apparent power of 2.5 MVA in Case A was sufficient in order for the FCS to always have access to maximum active power, an installed apparent power of 3.0 MVA in Case B was unnecessary. Case A would thus be a more economical choice than Case B. What is the best choice between waiting for the grid to be reinforced and paying the connection charge in Alternative 2 or investing in a more expensive converter, as in Alternative 4 Case A, will be a trade-off for the charging operators. It will depend on when the charging operator wants to commission the fast-charging station and the total cost of the alternatives.

Alternative 3 and Alternative 5 in Case C will be the most suitable alternatives if the charging operator does not value maximum active power as the most crucial criterion for connection and accepts that limited access to capacity will exist in specific periods. Although the capacity was considerably limited during certain periods in Alternative 3, the available active power was consistently above 1 MW. In Alternative 5, the available active power was not limited to the same extent. However, a more expensive converter was needed in order to provide reactive power back to the grid. Alternative 3 will be a better choice than Alternative 5 if the charging operator assumes that he will not need more than the available active power in the limited periods in Alternative 3.

Grid connection requests will vary in terms of requested power extraction, installed apparent power of the converter, expected demand from the FCS, placement of the FCS geographically, the available capacity and the operational condition of the grid where the connection is requested. All these factors will influence which of the alternatives is the most suitable. Another factor that will influence this is the $\frac{R}{X}$ ratio of the power lines in the grid. As written in Chapter 2, the $\frac{R}{X}$ ratio influences how much impact the reduction of active power; in this context, the curtailment of active power in Alternative 3 and Alternative 5 has on the voltage, and how much impact the reactive power provision in Alternative 4 and Alternative 5 has on the voltage. The total $\frac{R}{X}$ ratio in the main radial of the CINELDI reference system equalled 1.6, thus implying that curtailment of active power would counteract the voltage drops more than the provision of reactive power. However, the case study showed that the reactive provision in Alternative 4 in Case A and Case B was sufficient to counteract the voltage drops in order to connect the FCS and give it access to maximum capacity.

Since the most appropriate alternative will vary from case to case, one best solution for all cases does not exist. Due to this, it is important to have a technical procedure which investigates the various grid connection agreements. The method developed by the author and presented in Chapter 3 serves as a starting point for determining which grid connection agreement is the most appropriate.

# Chapter 7

# Conclusion

A methodology was developed with the aim of exploring the potential of alternative grid connection agreements between Distribution System Operators (DSOs) and fast-charging operators. The methodology proposes a technical analysis for three alternative grid connection agreements: Alternative 3, Alternative 4 and Alternative 5. In Alternative 3, the active power the fast-charging station (FCS) has available is limited when the grid is suffering congestion or the voltage level in the grid is unacceptably low. In Alternative 4, the FCS provides reactive power while drawing active power in periods when the voltage level is unacceptable low or when the loading of the power lines is too high. Alternative 5 combines Alternative 3 and 4 and uses both active power curtailment and reactive power provision in order to enhance the voltage levels and prevent overloading of the lines.

A case study was conducted where an FCS requested a connection to a 124-bus MV reference system. The cases varied in terms of installed apparent power, and in each case, each alternative grid connection agreement was evaluated through the proposed methodology. The case study showed that the voltage level on multiple buses in the reference system was unacceptable low when the FCS was connected to the system and consumed 2 MW during the aggregated peak load hour of the other loads in the system. Based on this, measures were needed to connect the FCS to the system. In all cases, measures were required during 392 hours of the year to enable a connection. The case study showed that the implementation of active power curtailment, reactive power provision and a combination of both enhanced the voltage level in the system in the 392 hours, enabling the FCS to be connected and draw power. This shows great potential for alternative grid connection agreements.

The most suitable grid connection agreement depends on the connection request and the needs of the charging operator. If the charging operator must be guaranteed to always have maximum capacity available, either Alternative 4 or upgrading the existing grid would be the most appropriate option. However, in Alternative 4, a more complex converter is needed, which triggers an extra investment.

In the case of upgrading the grid, a connection charge payment is required. If the available capacity will be restricted in periods when the maximum capacity most likely is not necessitated, Alternative 3 would be the better option as it does not require expensive extra equipment.

When assessing the potential of alternative grid connection agreements, it is, in general, important that the DSO communicate to the charging operator how the measures will impact them. In the case of curtailment of active power, it must be expressed how much and when the available active power will be limited. The same applies to reactive power provision; how much and when the FCS needs to supply reactive power must be specified.

## 7.1 Further work

For further work, it would be interesting to implement the calculation of the cost of each alternative in order to compare the different alternatives economically. In Alternative 1 and 2, this would be to implement an estimation of the connection charges. In Alternative 1, it would be an estimation of the connection charge when there is sufficient capacity to connect the FCS without the need for any measure. In Alternative 2, it would be an estimation of the connection charge for upgrading the existing distribution grid in order to connect the FCS. In Alternative 3, it would be an approximation of the lost revenue the FCS potentially will have due to limited access to power in certain periods. In Alternative 4, it would be an estimation of the extra investment cost due to the investment of a more complex converter. Additionally, it would be interesting to implement an estimation of the potential income the FCS can have by selling the redundant reactive power as a flexibility to the Distribution System Operator in the periods where it is not required to provide reactive power in order to draw active power. The Distribution System Operator may be interested in buying reactive power for voltage stability and reduction of losses. In Alternative 5, an estimation of the cost of the lost revenue, the extra investment cost for a more advanced converter, and the potential income by selling redundant reactive power must be addressed.

# Bibliography


[1] Statistisk sentralbyrå. *Transport står for 30 prosent av klimautslippene i Norge*. URL: https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/transport-star-for-30-prosent-av-klimautslippene-i-norge (visited on 11/04/2023).

[2] Regjeringen. *Reduserte utslipp fra transport er avgjørende for å nå Norges klimamål*. URL: https://www.regjeringen.no/no/tema/klima-og-miljo/forurensning/innsiktsartikler-forurensning/miljovennlig-transport/id2076774/ (visited on 11/04/2023).

[3] Regjeringen. *Norge er elektrisk*. URL: https://www.regjeringen.no/no/tema/transport-og-kommunikasjon/veg_og_vegtrafikk/faktaartikler-vei-og-ts/norge-er-elektrisk/id2677481/ (visited on 11/04/2023).

[4] R. Rana and B. Nybakk Torsæter. 'Coordinated Voltage Support with Reactive Power from High-power Charging Stations for EVs'. In: *2021 IEEE Madrid PowerTech*. 2021, pp. 1–6. DOI: 10.1109/PowerTech46648.2021.9495041.

[5] I. B. Sperstad, E. Solvang and O. Gjerde. 'Framework and methodology for active distribution grid planning in Norway'. In: *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. 2020, pp. 1–6. DOI: 10.1109/PMAPS47429.2020.9183711.

[6] NOU 2022:6. *Nett i tide*. 2022. URL: https://www.regjeringen.no/contentassets/9dabbb7fb58e4bb297f4388696570460/no/pdfs/nou202220220006000dddpdfs.pdf.

[7] S. Srdic and S. Lukic. 'Toward Extreme Fast Charging: Challenges and Opportunities in Directly Connecting to Medium-Voltage Line'. In: *IEEE Electrification Magazine* 7.1 (2019), pp. 22–31. DOI: 10.1109/MELE.2018.2889547.

[8] Lovdata. *Forskrift om endring i forskrift om nettregulering og energimarkedet*. 2021. URL: https://lovdata.no/dokument/LTI/forskrift/2021-04-07-1072 (visited on 26/01/2023).

[9] F. Gonzalez Venegas, M. Petit and Y. Perez. 'Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services'. In: *Renewable and Sustainable Energy Reviews* 145 (2021), p. 111060. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2021.111060.

[10] FuChar. *FuChar – Grid and Charging Infrastructure of the Future*. URL: https://www.sintef.no/projectweb/fuchar/ (visited on 11/04/2023).

[11] CINELDI. *CINELDI is a centre for environment-friendly energy research*. URL: https://www.sintef.no/projectweb/cineldi/ (visited on 11/04/2023).

[12] A. L. L. Aasen. 'Peak Load Behaviour of Fast-Charging Stations - Correlation and Coincidence With Other Loads in The Distribution System'. Specialisation Project Report. Department of Electric Energy, Norwegian University of Science and Technology (NTNU), Trondheim, Norway, 2022.

[13] European Environment Agency. *New registrations of electric vehicles in Europe*. URL: https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles (visited on 15/04/2023).

[14] Statistisk sentralbyrå. *Tabell*. URL: https://www.ssb.no/381908/bilparken (visited on 15/04/2023).

[15] Norsk elbilforening. *Statistikk elbil - Elbilbestand og markedsandel*. URL: https://elbil.no/om-elbil/elbilstatistikk/ (visited on 15/04/2023).

[16] Norsk elbilforening. *Ladestasjoner*. URL: https://elbil.no/om-elbil/elbilstatistikk/ladestasjoner/ (visited on 15/04/2023).

[17] Statens vegvesen and Miljødirektoratet. *Kunnskapsgrunnlag om hurtigladeinfrastruktur for veitransport*. 2022. URL: https://www.regjeringen.no/contentassets/a07ef2d3142344989dfddc75f5a92365/kunnskapsgrunnlag_1mars.pdf.

[18] H. Tu, H. Feng, S. Srdic and S. Lukic. 'Extreme Fast Charging of Electric Vehicles: A Technology Overview'. In: *IEEE Transactions on Transportation Electrification* 5.4 (2019), pp. 861–878. DOI: 10.1109/TTE.2019.2958709.

[19] A. Ahmad, Z. Qin, T. Wijekoon and P. Bauer. 'An Overview on Medium Voltage Grid Integration of Ultra-Fast Charging Stations: Current Status and Future Trends'. In: *IEEE Open Journal of the Industrial Electronics Society* 3 (2022), pp. 420–447. DOI: 10.1109/OJIES.2022.3179743.

[20] M. Nikkhah Mojdehi and P. Ghosh. 'An On-Demand Compensation Function for an EV as a Reactive Power Service Provider'. In: *IEEE Transactions on Vehicular Technology* 65.6 (2016), pp. 4572–4583. DOI: 10.1109/TVT.2015.2504264.

[21] J. R. A. Klemets and B. N. Torsæter. 'MPC-based Voltage Control with Reactive Power from High-Power Charging Stations for EVs'. In: *2021 IEEE Madrid PowerTech*. 2021, pp. 1–6. DOI: 10.1109/PowerTech46648.2021.9495042.

[22] S. Paudyal, O. Ceylan, B. P. Bhattarai and K. S. Myers. 'Optimal coordinated EV charging with reactive power support in constrained distribution grids'. In: *2017 IEEE Power Energy Society General Meeting*. 2017, pp. 1–5. DOI: 10.1109/PESGM.2017.8274266.

[23] S. Habib, M. M. Khan, F. Abbas and H. Tang. 'Assessment of electric vehicles concerning impacts, charging infrastructure with unidirectional and bidirectional chargers, and power flow comparisons'. In: *International Journal of Energy Research* 42.11 (2018), pp. 3416–3441. DOI: https://doi.org/10.1002/er.4033.

[24] N. Mehboob, M. Restrepo, C. A. Cañizares, C. Rosenberg and M. Kazerani. 'Smart Operation of Electric Vehicles With Four-Quadrant Chargers Considering Uncertainties'. In: *IEEE Transactions on Smart Grid* 10.3 (2019), pp. 2999–3009. DOI: 10.1109/TSG.2018.2816404.

[25] Energifakta Norge. *Strømnettet*. URL: https://energifaktanorge.no/norsk-energiforsyning/kraftnett/ (visited on 11/05/2023).

[26] M. L. Kolstad. *Alternative tiltak for å øke tilknytningskapasitet i distribusjonsnett*. 2016. URL: https://www.ren.no/doc/api/rest/download/open/3e4b6b52-fd22-432b-aace-39f6eca69554?filename=TRA%207561%20Alternative%20tiltak%20for%20tilknytningskapasitet%20i%20distribusjonsnett.pdf.

[27] NVE-RME. *Nettilknytning*. 2021. URL: https://www.nve.no/reguleringsmyndigheten/regulering/nettvirksomhet/nettilknytning/ (visited on 26/01/2023).

[28] NVE-RME. *Tilknytningsplikt*. URL: https://www.nve.no/reguleringsmyndigheten/regulering/nettvirksomhet/nettilknytning/tilknytningsplikt/ (visited on 07/03/2023).

[29] NVE-RME. *Anleggsbidrag*. 2021. URL: https://www.nve.no/reguleringsmyndigheten/regulering/nettvirksomhet/anleggsbidrag/ (visited on 26/01/2023).

[30] M. Z. Degefa, I. B. Sperstad and H. Sæle. 'Comprehensive classifications and characterizations of power system flexibility resources'. In: *Electric Power Systems Research* 194 (2021), p. 107022. ISSN: 0378-7796. DOI: https://doi.org/10.1016/j.epsr.2021.107022.

[31] NVE-RME. *Tilknytning med vilkår om utkobling*. 2021. URL: https://www.nve.no/reguleringsmyndigheten/regulering/nettvirksomhet/nettilknytning/leveringsplikt/tilknytning-med-vilkaar-om-utkobling/ (visited on 26/01/2023).

[32] R. Fonteijn, M. van Amstel, P. Nguyen, J. Morren, G. Maarten Bonnema and H. Slootweg. 'Evaluating flexibility values for congestion management in distribution networks within Dutch pilots'. In: *The Journal of Engineering* 2019.18 (2019), pp. 5158–5162. DOI: https://doi.org/10.1049/joe.2018.9314.

[33] I. B. Sperstad, O. B. Fosso, S. H. Jakobsen, A. O. Eggen, J. H. Evenstuen and G. Kjølle. 'Reference data set for a Norwegian medium voltage power distribution system'. In: *Data in Brief* 47 (2023), p. 109025. ISSN: 2352-3409. DOI: https://doi.org/10.1016/j.dib.2023.109025.

## Appendix A

# Line indexes - Figure 5.2

**Table A.1:** Line indexes with their corresponding from bus and to bus in Figure 5.2

| Line index | From bus | To bus | Line index | From bus | To bus |
|---|---|---|---|---|---|
| 0 | 1 | 2 | 47 | 12 | 16 |
| 1 | 2 | 3 | 48 | 16 | 18 |
| 2 | 3 | 4 | 49 | 18 | 19 |
| 3 | 4 | 5 | 50 | 19 | 21 |
| 4 | 5 | 7 | 51 | 21 | 22 |
| 5 | 7 | 9 | 52 | 22 | 23 |
| 6 | 9 | 12 | 53 | 23 | 24 |
| 7 | 12 | 26 | 54 | 24 | 25 |
| 8 | 26 | 33 | 55 | 16 | 17 |
| 9 | 33 | 37 | 56 | 19 | 20 |
| 10 | 37 | 40 | 57 | 26 | 27 |
| 11 | 40 | 42 | 58 | 27 | 28 |
| 12 | 42 | 44 | 59 | 28 | 29 |
| 13 | 44 | 45 | 60 | 29 | 30 |
| 14 | 45 | 46 | 61 | 30 | 31 |
| 15 | 46 | 47 | 62 | 31 | 32 |
| 16 | 47 | 48 | 63 | 33 | 34 |
| 17 | 48 | 67 | 64 | 34 | 35 |
| 18 | 67 | 68 | 65 | 35 | 36 |
| 19 | 68 | 69 | 66 | 37 | 38 |
| 20 | 69 | 70 | 67 | 38 | 39 |
| 21 | 70 | 71 | 68 | 40 | 41 |
| 22 | 71 | 72 | 69 | 42 | 109 |
| 23 | 72 | 73 | 70 | 109 | 110 |
| 24 | 73 | 74 | 71 | 110 | 111 |
| 25 | 74 | 75 | 72 | 42 | 43 |
| 26 | 75 | 76 | 73 | 43 | 115 |
| 27 | 76 | 77 | 74 | 115 | 118 |
| 28 | 77 | 78 | 75 | 43 | 112 |
| 29 | 78 | 79 | 76 | 112 | 113 |
| 30 | 79 | 80 | 77 | 112 | 114 |
| 31 | 80 | 81 | 78 | 45 | 116 |
| 32 | 81 | 82 | 79 | 116 | 119 |
| 33 | 82 | 83 | 80 | 119 | 122 |
| 34 | 83 | 85 | 81 | 122 | 123 |
| 35 | 85 | 86 | 82 | 119 | 121 |
| 36 | 86 | 92 | 83 | 116 | 124 |
| 37 | 92 | 93 | 84 | 119 | 120 |
| 38 | 93 | 94 | 85 | 47 | 49 |
| 39 | 94 | 95 | 86 | 49 | 52 |
| 40 | 95 | 96 | 87 | 52 | 53 |
| 41 | 4 | 6 | 88 | 53 | 54 |
| 42 | 5 | 8 | 89 | 54 | 55 |
| 43 | 7 | 10 | 90 | 55 | 56 |
| 44 | 7 | 11 | 91 | 56 | 57 |
| 45 | 9 | 13 | 92 | 57 | 58 |
| 46 | 13 | 14 | 93 | 58 | 59 |

| Line index | From bus | To bus | Line index | From bus | To bus |
|---|---|---|---|---|---|
| 94 | 59 | 60 | 109 | 103 | 104 |
| 95 | 60 | 61 | 110 | 104 | 105 |
| 96 | 61 | 62 | 111 | 82 | 100 |
| 97 | 49 | 50 | 112 | 100 | 101 |
| 98 | 50 | 51 | 113 | 83 | 84 |
| 99 | 59 | 117 | 114 | 85 | 97 |
| 100 | 48 | 63 | 115 | 97 | 98 |
| 101 | 63 | 65 | 116 | 98 | 99 |
| 102 | 65 | 66 | 117 | 86 | 89 |
| 103 | 63 | 64 | 118 | 89 | 90 |
| 104 | 71 | 106 | 119 | 86 | 87 |
| 105 | 72 | 107 | 120 | 87 | 88 |
| 106 | 107 | 108 | 121 | 86 | 91 |
| 107 | 76 | 102 | 122 | 9 | 15 |
| 108 | 102 | 103 | | | |

## Appendix B

# Hour indexes - Figure 5.8a

**Table B.1:** Hour indexes with their corresponding date and hour in Figure 5.8a

| Hour index | Date | Hour |
|---|---|---|
| 0 | 01/03/18 | 17 |
| 1 | 14/12/18 | 14 |
| 2 | 14/12/18 | 15 |
| 3 | 14/12/18 | 16 |

## Appendix C

# Hour indexes - Figure 5.8b

**Table C.1:** Hour indexes with their corresponding date and hour in Figure 5.8b

| Hour index | Date | Hour | Hour index | Date | Hour | Hour index | Date | Hour |
|---|---|---|---|---|---|---|---|---|
| 0 | 04/01/18 | 17 | 46 | 12/01/18 | 17 | 92 | 03/02/18 | 16 |
| 1 | 07/01/18 | 10 | 47 | 12/01/18 | 18 | 93 | 03/02/18 | 17 |
| 2 | 07/01/18 | 11 | 48 | 12/01/18 | 19 | 94 | 03/02/18 | 18 |
| 3 | 07/01/18 | 12 | 49 | 13/01/18 | 12 | 95 | 03/02/18 | 19 |
| 4 | 07/01/18 | 13 | 50 | 13/01/18 | 17 | 96 | 03/02/18 | 20 |
| 5 | 07/01/18 | 14 | 51 | 13/01/18 | 19 | 97 | 04/02/18 | 09 |
| 6 | 07/01/18 | 15 | 52 | 14/01/18 | 15 | 98 | 04/02/18 | 10 |
| 7 | 07/01/18 | 16 | 53 | 14/01/18 | 16 | 99 | 04/02/18 | 11 |
| 8 | 07/01/18 | 17 | 54 | 14/01/18 | 17 | 100 | 04/02/18 | 12 |
| 9 | 07/01/18 | 18 | 55 | 14/01/18 | 18 | 101 | 04/02/18 | 13 |
| 10 | 07/01/18 | 19 | 56 | 15/01/18 | 16 | 102 | 04/02/18 | 14 |
| 11 | 07/01/18 | 20 | 57 | 15/01/18 | 17 | 103 | 04/02/18 | 15 |
| 12 | 08/01/18 | 17 | 58 | 16/01/18 | 17 | 104 | 04/02/18 | 16 |
| 13 | 08/01/18 | 19 | 59 | 16/01/18 | 20 | 105 | 04/02/18 | 17 |
| 14 | 08/01/18 | 21 | 60 | 18/01/18 | 08 | 106 | 04/02/18 | 18 |
| 15 | 09/01/18 | 07 | 61 | 18/01/18 | 10 | 107 | 04/02/18 | 19 |
| 16 | 09/01/18 | 08 | 62 | 18/01/18 | 11 | 108 | 04/02/18 | 20 |
| 17 | 09/01/18 | 09 | 63 | 18/01/18 | 16 | 109 | 04/02/18 | 21 |
| 18 | 09/01/18 | 10 | 64 | 18/01/18 | 17 | 110 | 04/02/18 | 22 |
| 19 | 09/01/18 | 15 | 65 | 18/01/18 | 18 | 111 | 05/02/18 | 06 |
| 20 | 09/01/18 | 16 | 66 | 19/01/18 | 16 | 112 | 05/02/18 | 07 |
| 21 | 09/01/18 | 17 | 67 | 19/01/18 | 17 | 113 | 05/02/18 | 08 |
| 22 | 09/01/18 | 18 | 68 | 19/01/18 | 18 | 114 | 05/02/18 | 09 |
| 23 | 09/01/18 | 19 | 69 | 20/01/18 | 16 | 115 | 05/02/18 | 10 |
| 24 | 09/01/18 | 20 | 70 | 20/01/18 | 17 | 116 | 05/02/18 | 11 |
| 25 | 09/01/18 | 21 | 71 | 21/01/18 | 14 | 117 | 05/02/18 | 12 |
| 26 | 09/01/18 | 22 | 72 | 21/01/18 | 17 | 118 | 05/02/18 | 13 |
| 27 | 10/01/18 | 07 | 73 | 21/01/18 | 18 | 119 | 05/02/18 | 14 |
| 28 | 10/01/18 | 08 | 74 | 22/01/18 | 11 | 120 | 05/02/18 | 15 |
| 29 | 10/01/18 | 09 | 75 | 22/01/18 | 16 | 121 | 05/02/18 | 16 |
| 30 | 10/01/18 | 10 | 76 | 22/01/18 | 17 | 122 | 05/02/18 | 17 |
| 31 | 10/01/18 | 11 | 77 | 22/01/18 | 18 | 123 | 05/02/18 | 18 |
| 32 | 10/01/18 | 12 | 78 | 22/01/18 | 19 | 124 | 05/02/18 | 19 |
| 33 | 10/01/18 | 13 | 79 | 22/01/18 | 20 | 125 | 05/02/18 | 20 |
| 34 | 10/01/18 | 15 | 80 | 22/01/18 | 21 | 126 | 05/02/18 | 21 |
| 35 | 10/01/18 | 16 | 81 | 26/01/18 | 18 | 127 | 05/02/18 | 22 |
| 36 | 10/01/18 | 17 | 82 | 02/02/18 | 17 | 128 | 06/02/18 | 07 |
| 37 | 10/01/18 | 18 | 83 | 02/02/18 | 18 | 129 | 06/02/18 | 08 |
| 38 | 10/01/18 | 19 | 84 | 02/02/18 | 19 | 130 | 06/02/18 | 09 |
| 39 | 10/01/18 | 20 | 85 | 02/02/18 | 20 | 131 | 06/02/18 | 10 |
| 40 | 11/01/18 | 08 | 86 | 02/02/18 | 21 | 132 | 06/02/18 | 11 |
| 41 | 11/01/18 | 15 | 87 | 03/02/18 | 09 | 133 | 06/02/18 | 15 |
| 42 | 11/01/18 | 16 | 88 | 03/02/18 | 10 | 134 | 06/02/18 | 16 |
| 43 | 11/01/18 | 17 | 89 | 03/02/18 | 11 | 135 | 06/02/18 | 17 |
| 44 | 11/01/18 | 18 | 90 | 03/02/18 | 12 | 136 | 06/02/18 | 18 |
| 45 | 12/01/18 | 16 | 91 | 03/02/18 | 13 | 137 | 06/02/18 | 19 |

| Hour index | Date | Hour | Hour index | Date | Hour | Hour index | Date | Hour |
|---|---|---|---|---|---|---|---|---|
| 138 | 06/02/18 | 20 | 185 | 26/02/18 | 18 | 232 | 01/03/18 | 00 |
| 139 | 06/02/18 | 21 | 186 | 26/02/18 | 19 | 233 | 01/03/18 | 02 |
| 140 | 07/02/18 | 07 | 187 | 26/02/18 | 20 | 234 | 01/03/18 | 03 |
| 141 | 07/02/18 | 08 | 188 | 26/02/18 | 21 | 235 | 01/03/18 | 05 |
| 142 | 07/02/18 | 09 | 189 | 26/02/18 | 22 | 236 | 01/03/18 | 06 |
| 143 | 07/02/18 | 11 | 190 | 27/02/18 | 06 | 237 | 01/03/18 | 07 |
| 144 | 07/02/18 | 12 | 191 | 27/02/18 | 07 | 238 | 01/03/18 | 08 |
| 145 | 07/02/18 | 16 | 192 | 27/02/18 | 08 | 239 | 01/03/18 | 09 |
| 146 | 07/02/18 | 17 | 193 | 27/02/18 | 09 | 240 | 01/03/18 | 10 |
| 147 | 07/02/18 | 18 | 194 | 27/02/18 | 10 | 241 | 01/03/18 | 11 |
| 148 | 07/02/18 | 19 | 195 | 27/02/18 | 11 | 242 | 01/03/18 | 12 |
| 149 | 08/02/18 | 07 | 196 | 27/02/18 | 12 | 243 | 01/03/18 | 13 |
| 150 | 08/02/18 | 08 | 197 | 27/02/18 | 13 | 244 | 01/03/18 | 14 |
| 151 | 08/02/18 | 09 | 198 | 27/02/18 | 14 | 245 | 01/03/18 | 15 |
| 152 | 08/02/18 | 10 | 199 | 27/02/18 | 15 | 246 | 01/03/18 | 16 |
| 153 | 08/02/18 | 11 | 200 | 27/02/18 | 16 | 247 | 01/03/18 | 18 |
| 154 | 08/02/18 | 17 | 201 | 27/02/18 | 17 | 248 | 01/03/18 | 19 |
| 155 | 08/02/18 | 18 | 202 | 27/02/18 | 18 | 249 | 01/03/18 | 20 |
| 156 | 08/02/18 | 20 | 203 | 27/02/18 | 19 | 250 | 01/03/18 | 21 |
| 157 | 08/02/18 | 21 | 204 | 27/02/18 | 20 | 251 | 01/03/18 | 22 |
| 158 | 09/02/18 | 17 | 205 | 27/02/18 | 21 | 252 | 01/03/18 | 23 |
| 159 | 11/02/18 | 12 | 206 | 27/02/18 | 22 | 253 | 02/03/18 | 00 |
| 160 | 11/02/18 | 14 | 207 | 27/02/18 | 23 | 254 | 02/03/18 | 05 |
| 161 | 11/02/18 | 15 | 208 | 28/02/18 | 00 | 255 | 02/03/18 | 06 |
| 162 | 11/02/18 | 16 | 209 | 28/02/18 | 01 | 256 | 02/03/18 | 07 |
| 163 | 11/02/18 | 17 | 210 | 28/02/18 | 02 | 257 | 02/03/18 | 08 |
| 164 | 11/02/18 | 18 | 211 | 28/02/18 | 03 | 258 | 02/03/18 | 09 |
| 165 | 13/02/18 | 07 | 212 | 28/02/18 | 04 | 259 | 02/03/18 | 10 |
| 166 | 13/02/18 | 08 | 213 | 28/02/18 | 05 | 260 | 02/03/18 | 11 |
| 167 | 13/02/18 | 09 | 214 | 28/02/18 | 06 | 261 | 02/03/18 | 12 |
| 168 | 17/02/18 | 10 | 215 | 28/02/18 | 07 | 262 | 02/03/18 | 13 |
| 169 | 17/02/18 | 11 | 216 | 28/02/18 | 08 | 263 | 02/03/18 | 14 |
| 170 | 20/02/18 | 18 | 217 | 28/02/18 | 09 | 264 | 02/03/18 | 15 |
| 171 | 20/02/18 | 19 | 218 | 28/02/18 | 10 | 265 | 02/03/18 | 16 |
| 172 | 20/02/18 | 20 | 219 | 28/02/18 | 11 | 266 | 02/03/18 | 17 |
| 173 | 25/02/18 | 18 | 220 | 28/02/18 | 12 | 267 | 02/03/18 | 18 |
| 174 | 25/02/18 | 19 | 221 | 28/02/18 | 13 | 268 | 02/03/18 | 19 |
| 175 | 25/02/18 | 20 | 222 | 28/02/18 | 14 | 269 | 02/03/18 | 20 |
| 176 | 25/02/18 | 21 | 223 | 28/02/18 | 15 | 270 | 02/03/18 | 21 |
| 177 | 26/02/18 | 06 | 224 | 28/02/18 | 16 | 271 | 02/03/18 | 22 |
| 178 | 26/02/18 | 07 | 225 | 28/02/18 | 17 | 272 | 03/03/18 | 08 |
| 179 | 26/02/18 | 08 | 226 | 28/02/18 | 18 | 273 | 03/03/18 | 09 |
| 180 | 26/02/18 | 09 | 227 | 28/02/18 | 19 | 274 | 03/03/18 | 10 |
| 181 | 26/02/18 | 10 | 228 | 28/02/18 | 20 | 275 | 03/03/18 | 11 |
| 182 | 26/02/18 | 11 | 229 | 28/02/18 | 21 | 276 | 03/03/18 | 12 |
| 183 | 26/02/18 | 12 | 230 | 28/02/18 | 22 | 277 | 03/03/18 | 13 |
| 184 | 26/02/18 | 17 | 231 | 28/02/18 | 23 | 278 | 03/03/18 | 14 |

| Hour index | Date | Hour | Hour index | Date | Hour | Hour index | Date | Hour |
|---|---|---|---|---|---|---|---|---|
| 279 | 03/03/18 | 15 | 316 | 07/03/18 | 17 | 353 | 15/12/18 | 13 |
| 280 | 03/03/18 | 16 | 317 | 07/03/18 | 18 | 354 | 15/12/18 | 14 |
| 281 | 03/03/18 | 17 | 318 | 16/03/18 | 07 | 355 | 15/12/18 | 15 |
| 282 | 03/03/18 | 18 | 319 | 16/03/18 | 08 | 356 | 15/12/18 | 16 |
| 283 | 03/03/18 | 19 | 320 | 16/03/18 | 09 | 357 | 15/12/18 | 17 |
| 284 | 03/03/18 | 20 | 321 | 16/03/18 | 20 | 358 | 15/12/18 | 18 |
| 285 | 03/03/18 | 21 | 322 | 17/03/18 | 09 | 359 | 15/12/18 | 19 |
| 286 | 04/03/18 | 09 | 323 | 17/03/18 | 10 | 360 | 17/12/18 | 16 |
| 287 | 04/03/18 | 10 | 324 | 17/03/18 | 19 | 361 | 17/12/18 | 17 |
| 288 | 04/03/18 | 11 | 325 | 18/03/18 | 08 | 362 | 18/12/18 | 15 |
| 289 | 04/03/18 | 16 | 326 | 18/03/18 | 09 | 363 | 18/12/18 | 16 |
| 290 | 04/03/18 | 17 | 327 | 18/03/18 | 10 | 364 | 18/12/18 | 17 |
| 291 | 04/03/18 | 19 | 328 | 18/03/18 | 11 | 365 | 18/12/18 | 19 |
| 292 | 04/03/18 | 20 | 329 | 19/03/18 | 09 | 366 | 21/12/18 | 17 |
| 293 | 05/03/18 | 10 | 330 | 26/11/18 | 17 | 367 | 22/12/18 | 17 |
| 294 | 05/03/18 | 11 | 331 | 26/11/18 | 19 | 368 | 23/12/18 | 11 |
| 295 | 05/03/18 | 16 | 332 | 27/11/18 | 07 | 369 | 23/12/18 | 12 |
| 296 | 05/03/18 | 17 | 333 | 27/11/18 | 16 | 370 | 23/12/18 | 13 |
| 297 | 05/03/18 | 18 | 334 | 27/11/18 | 17 | 371 | 23/12/18 | 14 |
| 298 | 05/03/18 | 19 | 335 | 27/11/18 | 19 | 372 | 23/12/18 | 15 |
| 299 | 05/03/18 | 20 | 336 | 27/11/18 | 20 | 373 | 23/12/18 | 16 |
| 300 | 05/03/18 | 21 | 337 | 28/11/18 | 07 | 374 | 23/12/18 | 17 |
| 301 | 06/03/18 | 07 | 338 | 28/11/18 | 16 | 375 | 23/12/18 | 18 |
| 302 | 06/03/18 | 08 | 339 | 12/12/18 | 17 | 376 | 23/12/18 | 19 |
| 303 | 06/03/18 | 09 | 340 | 13/12/18 | 16 | 377 | 23/12/18 | 20 |
| 304 | 06/03/18 | 10 | 341 | 13/12/18 | 17 | 378 | 24/12/18 | 09 |
| 305 | 06/03/18 | 11 | 342 | 13/12/18 | 18 | 379 | 24/12/18 | 10 |
| 306 | 06/03/18 | 15 | 343 | 14/12/18 | 08 | 380 | 24/12/18 | 11 |
| 307 | 06/03/18 | 16 | 344 | 14/12/18 | 09 | 381 | 24/12/18 | 12 |
| 308 | 06/03/18 | 17 | 345 | 14/12/18 | 10 | 382 | 24/12/18 | 13 |
| 309 | 06/03/18 | 18 | 346 | 14/12/18 | 11 | 383 | 24/12/18 | 14 |
| 310 | 06/03/18 | 19 | 347 | 14/12/18 | 13 | 384 | 24/12/18 | 13 |
| 311 | 06/03/18 | 20 | 348 | 14/12/18 | 17 | 385 | 24/12/18 | 14 |
| 312 | 06/03/18 | 21 | 349 | 14/12/18 | 18 | 386 | 24/12/18 | 15 |
| 313 | 07/03/18 | 08 | 350 | 14/12/18 | 19 | 387 | 24/12/18 | 16 |
| 314 | 07/03/18 | 10 | 351 | 15/12/18 | | | | |
| 315 | 07/03/18 | 11 | 352 | 15/12/18 | | | | |

# Appendix D

# Hour indexes - Figure 5.17

**Table D.1:** Hour indexes with their corresponding date and hour in Figure 5.17

| Hour index | Date | Hour | Hour index | Date | Hour | Hour index | Date | Hour |
|---|---|---|---|---|---|---|---|---|
| 0 | 04/01/18 | 17 | 47 | 12/01/18 | 18 | 94 | 03/02/18 | 18 |
| 1 | 07/01/18 | 10 | 48 | 12/01/18 | 19 | 95 | 03/02/18 | 19 |
| 2 | 07/01/18 | 11 | 49 | 13/01/18 | 12 | 96 | 03/02/18 | 20 |
| 3 | 07/01/18 | 12 | 50 | 13/01/18 | 17 | 97 | 04/02/18 | 09 |
| 4 | 07/01/18 | 13 | 51 | 13/01/18 | 19 | 98 | 04/02/18 | 10 |
| 5 | 07/01/18 | 14 | 52 | 14/01/18 | 15 | 99 | 04/02/18 | 11 |
| 6 | 07/01/18 | 15 | 53 | 14/01/18 | 16 | 100 | 04/02/18 | 12 |
| 7 | 07/01/18 | 16 | 54 | 14/01/18 | 17 | 101 | 04/02/18 | 13 |
| 8 | 07/01/18 | 17 | 55 | 14/01/18 | 18 | 102 | 04/02/18 | 14 |
| 9 | 07/01/18 | 18 | 56 | 15/01/18 | 16 | 103 | 04/02/18 | 15 |
| 10 | 07/01/18 | 19 | 57 | 15/01/18 | 17 | 104 | 04/02/18 | 16 |
| 11 | 07/01/18 | 20 | 58 | 16/01/18 | 17 | 105 | 04/02/18 | 17 |
| 12 | 08/01/18 | 17 | 59 | 16/01/18 | 20 | 106 | 04/02/18 | 18 |
| 13 | 08/01/18 | 19 | 60 | 18/01/18 | 08 | 107 | 04/02/18 | 19 |
| 14 | 08/01/18 | 21 | 61 | 18/01/18 | 10 | 108 | 04/02/18 | 20 |
| 15 | 09/01/18 | 07 | 62 | 18/01/18 | 11 | 109 | 04/02/18 | 21 |
| 16 | 09/01/18 | 08 | 63 | 18/01/18 | 16 | 110 | 04/02/18 | 22 |
| 17 | 09/01/18 | 09 | 64 | 18/01/18 | 17 | 111 | 05/02/18 | 06 |
| 18 | 09/01/18 | 10 | 65 | 18/01/18 | 18 | 112 | 05/02/18 | 07 |
| 19 | 09/01/18 | 15 | 66 | 19/01/18 | 16 | 113 | 05/02/18 | 08 |
| 20 | 09/01/18 | 16 | 67 | 19/01/18 | 17 | 114 | 05/02/18 | 09 |
| 21 | 09/01/18 | 17 | 68 | 19/01/18 | 18 | 115 | 05/02/18 | 10 |
| 22 | 09/01/18 | 18 | 69 | 20/01/18 | 16 | 116 | 05/02/18 | 11 |
| 23 | 09/01/18 | 19 | 70 | 20/01/18 | 17 | 117 | 05/02/18 | 12 |
| 24 | 09/01/18 | 20 | 71 | 21/01/18 | 14 | 118 | 05/02/18 | 13 |
| 25 | 09/01/18 | 21 | 72 | 21/01/18 | 17 | 119 | 05/02/18 | 14 |
| 26 | 09/01/18 | 22 | 73 | 21/01/18 | 18 | 120 | 05/02/18 | 15 |
| 27 | 10/01/18 | 07 | 74 | 22/01/18 | 11 | 121 | 05/02/18 | 16 |
| 28 | 10/01/18 | 08 | 75 | 22/01/18 | 16 | 122 | 05/02/18 | 17 |
| 29 | 10/01/18 | 09 | 76 | 22/01/18 | 17 | 123 | 05/02/18 | 18 |
| 30 | 10/01/18 | 10 | 77 | 22/01/18 | 18 | 124 | 05/02/18 | 19 |
| 31 | 10/01/18 | 11 | 78 | 22/01/18 | 19 | 125 | 05/02/18 | 20 |
| 32 | 10/01/18 | 12 | 79 | 22/01/18 | 20 | 126 | 05/02/18 | 21 |
| 33 | 10/01/18 | 13 | 80 | 22/01/18 | 21 | 127 | 05/02/18 | 22 |
| 34 | 10/01/18 | 15 | 81 | 26/01/18 | 18 | 128 | 06/02/18 | 07 |
| 35 | 10/01/18 | 16 | 82 | 02/02/18 | 17 | 129 | 06/02/18 | 08 |
| 36 | 10/01/18 | 17 | 83 | 02/02/18 | 18 | 130 | 06/02/18 | 09 |
| 37 | 10/01/18 | 18 | 84 | 02/02/18 | 19 | 131 | 06/02/18 | 10 |
| 38 | 10/01/18 | 19 | 85 | 02/02/18 | 20 | 132 | 06/02/18 | 11 |
| 39 | 10/01/18 | 20 | 86 | 02/02/18 | 21 | 133 | 06/02/18 | 15 |
| 40 | 11/01/18 | 08 | 87 | 03/02/18 | 09 | 134 | 06/02/18 | 16 |
| 41 | 11/01/18 | 15 | 88 | 03/02/18 | 10 | 135 | 06/02/18 | 17 |
| 42 | 11/01/18 | 16 | 89 | 03/02/18 | 11 | 136 | 06/02/18 | 18 |
| 43 | 11/01/18 | 17 | 90 | 03/02/18 | 12 | 137 | 06/02/18 | 19 |
| 44 | 11/01/18 | 18 | 91 | 03/02/18 | 13 | 138 | 06/02/18 | 20 |
| 45 | 12/01/18 | 16 | 92 | 03/02/18 | 16 | 139 | 06/02/18 | 21 |
| 46 | 12/01/18 | 17 | 93 | 03/02/18 | 17 | 140 | 07/02/18 | 07 |

| Hour index | Date | Hour | Hour index | Date | Hour | Hour index | Date | Hour |
|---|---|---|---|---|---|---|---|---|
| 141 | 07/02/18 | 08 | 188 | 26/02/18 | 21 | 235 | 01/03/18 | 05 |
| 142 | 07/02/18 | 09 | 189 | 26/02/18 | 22 | 236 | 01/03/18 | 06 |
| 143 | 07/02/18 | 11 | 190 | 27/02/18 | 06 | 237 | 01/03/18 | 07 |
| 144 | 07/02/18 | 12 | 191 | 27/02/18 | 07 | 238 | 01/03/18 | 08 |
| 145 | 07/02/18 | 16 | 192 | 27/02/18 | 08 | 239 | 01/03/18 | 09 |
| 146 | 07/02/18 | 17 | 193 | 27/02/18 | 09 | 240 | 01/03/18 | 10 |
| 147 | 07/02/18 | 18 | 194 | 27/02/18 | 10 | 241 | 01/03/18 | 11 |
| 148 | 07/02/18 | 19 | 195 | 27/02/18 | 11 | 242 | 01/03/18 | 12 |
| 149 | 08/02/18 | 07 | 196 | 27/02/18 | 12 | 243 | 01/03/18 | 13 |
| 150 | 08/02/18 | 08 | 197 | 27/02/18 | 13 | 244 | 01/03/18 | 14 |
| 151 | 08/02/18 | 09 | 198 | 27/02/18 | 14 | 245 | 01/03/18 | 15 |
| 152 | 08/02/18 | 10 | 199 | 27/02/18 | 15 | 246 | 01/03/18 | 16 |
| 153 | 08/02/18 | 11 | 200 | 27/02/18 | 16 | 247 | 01/03/18 | 17 |
| 154 | 08/02/18 | 17 | 201 | 27/02/18 | 17 | 248 | 01/03/18 | 18 |
| 155 | 08/02/18 | 18 | 202 | 27/02/18 | 18 | 249 | 01/03/18 | 19 |
| 156 | 08/02/18 | 20 | 203 | 27/02/18 | 19 | 250 | 01/03/18 | 20 |
| 157 | 08/02/18 | 21 | 204 | 27/02/18 | 20 | 251 | 01/03/18 | 21 |
| 158 | 09/02/18 | 17 | 205 | 27/02/18 | 21 | 252 | 01/03/18 | 22 |
| 159 | 11/02/18 | 12 | 206 | 27/02/18 | 22 | 253 | 01/03/18 | 23 |
| 160 | 11/02/18 | 14 | 207 | 27/02/18 | 23 | 254 | 02/03/18 | 00 |
| 161 | 11/02/18 | 15 | 208 | 28/02/18 | 00 | 255 | 02/03/18 | 05 |
| 162 | 11/02/18 | 16 | 209 | 28/02/18 | 01 | 256 | 02/03/18 | 06 |
| 163 | 11/02/18 | 17 | 210 | 28/02/18 | 02 | 257 | 02/03/18 | 07 |
| 164 | 11/02/18 | 18 | 211 | 28/02/18 | 03 | 258 | 02/03/18 | 08 |
| 165 | 13/02/18 | 07 | 212 | 28/02/18 | 04 | 259 | 02/03/18 | 09 |
| 166 | 13/02/18 | 08 | 213 | 28/02/18 | 05 | 260 | 02/03/18 | 10 |
| 167 | 13/02/18 | 09 | 214 | 28/02/18 | 06 | 261 | 02/03/18 | 11 |
| 168 | 17/02/18 | 10 | 215 | 28/02/18 | 07 | 262 | 02/03/18 | 12 |
| 169 | 17/02/18 | 11 | 216 | 28/02/18 | 08 | 263 | 02/03/18 | 13 |
| 170 | 20/02/18 | 18 | 217 | 28/02/18 | 09 | 264 | 02/03/18 | 14 |
| 171 | 20/02/18 | 19 | 218 | 28/02/18 | 10 | 265 | 02/03/18 | 15 |
| 172 | 20/02/18 | 20 | 219 | 28/02/18 | 11 | 266 | 02/03/18 | 16 |
| 173 | 25/02/18 | 18 | 220 | 28/02/18 | 12 | 267 | 02/03/18 | 17 |
| 174 | 25/02/18 | 19 | 221 | 28/02/18 | 13 | 268 | 02/03/18 | 18 |
| 175 | 25/02/18 | 20 | 222 | 28/02/18 | 14 | 269 | 02/03/18 | 19 |
| 176 | 25/02/18 | 21 | 223 | 28/02/18 | 15 | 270 | 02/03/18 | 20 |
| 177 | 26/02/18 | 06 | 224 | 28/02/18 | 16 | 271 | 02/03/18 | 21 |
| 178 | 26/02/18 | 07 | 225 | 28/02/18 | 17 | 272 | 02/03/18 | 22 |
| 179 | 26/02/18 | 08 | 226 | 28/02/18 | 18 | 273 | 03/03/18 | 08 |
| 180 | 26/02/18 | 09 | 227 | 28/02/18 | 19 | 274 | 03/03/18 | 09 |
| 181 | 26/02/18 | 10 | 228 | 28/02/18 | 20 | 275 | 03/03/18 | 10 |
| 182 | 26/02/18 | 11 | 229 | 28/02/18 | 21 | 276 | 03/03/18 | 11 |
| 183 | 26/02/18 | 12 | 230 | 28/02/18 | 22 | 277 | 03/03/18 | 12 |
| 184 | 26/02/18 | 17 | 231 | 28/02/18 | 23 | 278 | 03/03/18 | 13 |
| 185 | 26/02/18 | 18 | 232 | 01/03/18 | 00 | 279 | 03/03/18 | 14 |
| 186 | 26/02/18 | 19 | 233 | 01/03/18 | 02 | 280 | 03/03/18 | 15 |
| 187 | 26/02/18 | 20 | 234 | 01/03/18 | 03 | 281 | 03/03/18 | 16 |

| **Hour index** | **Date** | **Hour** | **Hour index** | **Date** | **Hour** | **Hour index** | **Date** | **Hour** |
|---|---|---|---|---|---|---|---|---|
| 282 | 03/03/18 | 17 | 319 | 16/03/18 | 07 | 356 | 15/12/18 | 12 |
| 283 | 03/03/18 | 18 | 320 | 16/03/18 | 08 | 357 | 15/12/18 | 13 |
| 284 | 03/03/18 | 19 | 321 | 16/03/18 | 09 | 358 | 15/12/18 | 14 |
| 285 | 03/03/18 | 20 | 322 | 16/03/18 | 20 | 359 | 15/12/18 | 15 |
| 286 | 03/03/18 | 21 | 323 | 17/03/18 | 09 | 360 | 15/12/18 | 16 |
| 287 | 04/03/18 | 09 | 324 | 17/03/18 | 10 | 361 | 15/12/18 | 17 |
| 288 | 04/03/18 | 10 | 325 | 17/03/18 | 19 | 362 | 15/12/18 | 18 |
| 289 | 04/03/18 | 11 | 326 | 18/03/18 | 08 | 363 | 15/12/18 | 19 |
| 290 | 04/03/18 | 16 | 327 | 18/03/18 | 09 | 364 | 17/12/18 | 16 |
| 291 | 04/03/18 | 17 | 328 | 18/03/18 | 10 | 365 | 17/12/18 | 17 |
| 292 | 04/03/18 | 19 | 329 | 18/03/18 | 11 | 366 | 18/12/18 | 15 |
| 293 | 04/03/18 | 20 | 330 | 19/03/18 | 09 | 367 | 18/12/18 | 16 |
| 294 | 05/03/18 | 10 | 331 | 26/11/18 | 17 | 368 | 18/12/18 | 17 |
| 295 | 05/03/18 | 11 | 332 | 26/11/18 | 19 | 369 | 18/12/18 | 19 |
| 296 | 05/03/18 | 16 | 333 | 27/11/18 | 07 | 370 | 21/12/18 | 17 |
| 297 | 05/03/18 | 17 | 334 | 27/11/18 | 16 | 371 | 22/12/18 | 17 |
| 298 | 05/03/18 | 18 | 335 | 27/11/18 | 17 | 372 | 23/12/18 | 11 |
| 299 | 05/03/18 | 19 | 336 | 27/11/18 | 19 | 373 | 23/12/18 | 12 |
| 300 | 05/03/18 | 20 | 337 | 27/11/18 | 20 | 374 | 23/12/18 | 13 |
| 301 | 05/03/18 | 21 | 338 | 28/11/18 | 07 | 375 | 23/12/18 | 14 |
| 302 | 06/03/18 | 07 | 339 | 28/11/18 | 16 | 376 | 23/12/18 | 15 |
| 303 | 06/03/18 | 08 | 340 | 12/12/18 | 17 | 377 | 23/12/18 | 16 |
| 304 | 06/03/18 | 09 | 341 | 13/12/18 | 16 | 378 | 23/12/18 | 17 |
| 305 | 06/03/18 | 10 | 342 | 13/12/18 | 17 | 379 | 23/12/18 | 18 |
| 306 | 06/03/18 | 11 | 343 | 13/12/18 | 18 | 380 | 23/12/18 | 19 |
| 307 | 06/03/18 | 15 | 344 | 14/12/18 | 08 | 381 | 23/12/18 | 20 |
| 308 | 06/03/18 | 16 | 345 | 14/12/18 | 09 | 382 | 24/12/18 | 09 |
| 309 | 06/03/18 | 17 | 346 | 14/12/18 | 10 | 383 | 24/12/18 | 10 |
| 310 | 06/03/18 | 18 | 347 | 14/12/18 | 11 | 384 | 24/12/18 | 11 |
| 311 | 06/03/18 | 19 | 348 | 14/12/18 | 13 | 385 | 24/12/18 | 12 |
| 312 | 06/03/18 | 20 | 349 | 14/12/18 | 14 | 386 | 24/12/18 | 13 |
| 313 | 06/03/18 | 21 | 350 | 14/12/18 | 15 | 387 | 24/12/18 | 14 |
| 314 | 07/03/18 | 08 | 351 | 14/12/18 | 16 | 388 | 24/12/18 | 15 |
| 315 | 07/03/18 | 10 | 352 | 14/12/18 | 17 | 389 | 24/12/18 | 16 |
| 316 | 07/03/18 | 11 | 353 | 14/12/18 | 18 | 390 | 24/12/18 | 17 |
| 317 | 07/03/18 | 17 | 354 | 14/12/18 | 19 | 391 | 24/12/18 | 18 |
| 318 | 07/03/18 | 18 | 355 | 15/12/18 | 11 | 130 | 06/02/18 | 09 |

# Appendix E

# Hours sorted by month, day of the week and hour of the day

## E.1 Case A: Alternative 4

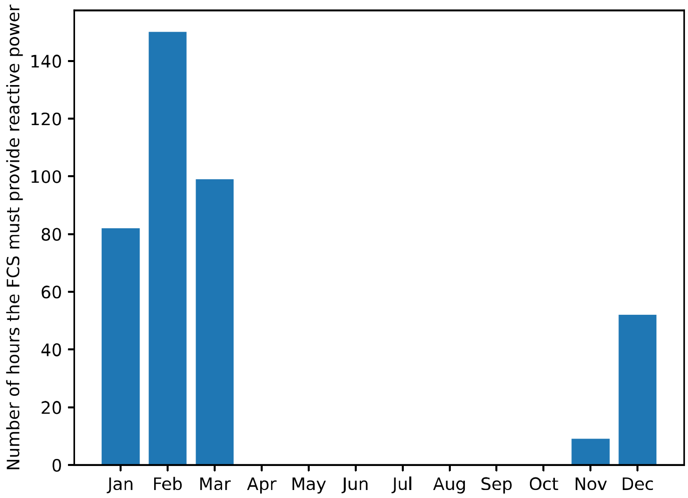



**Figure E.1:** Case A: The hours when the FCS must provide reactive power sorted by month in Alternative 4

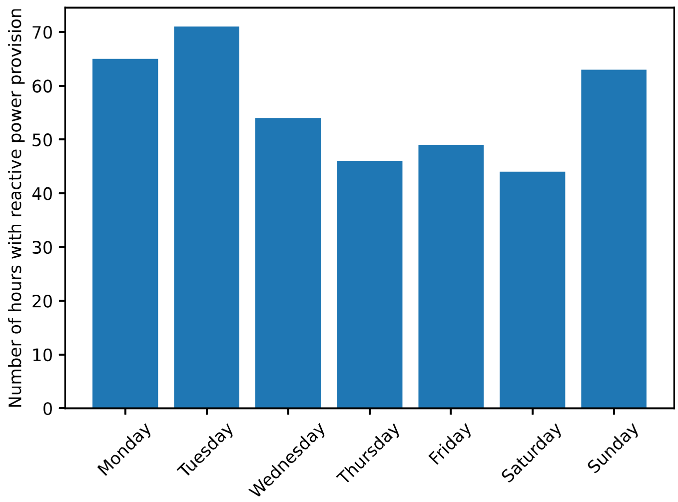



**Figure E.2:** Case A: The hours when the FCS must provide reactive power sorted by day of the week in Alternative 4

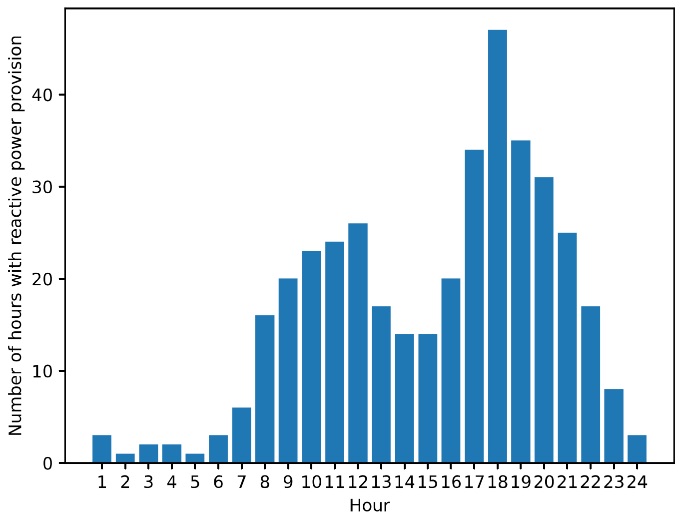



**Figure E.3:** Case A: The hours when the FCS must provide reactive power sorted by month in Alternative 4

## E.2 Case B: Alternative 4

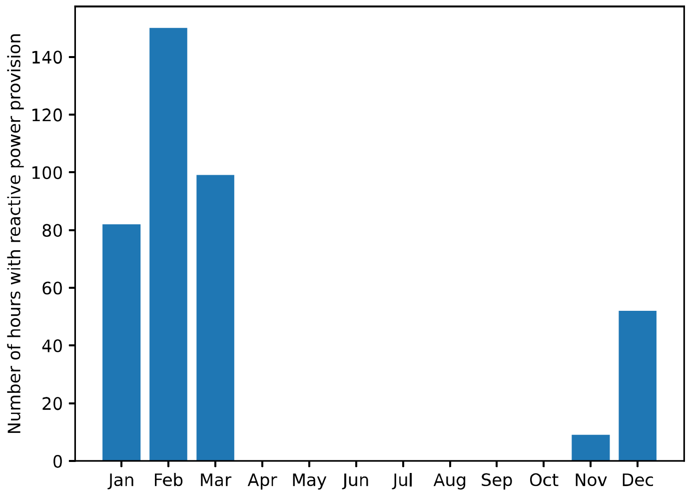



**Figure E.4:** Case B: The hours when the FCS must provide reactive power sorted by month in Alternative 4

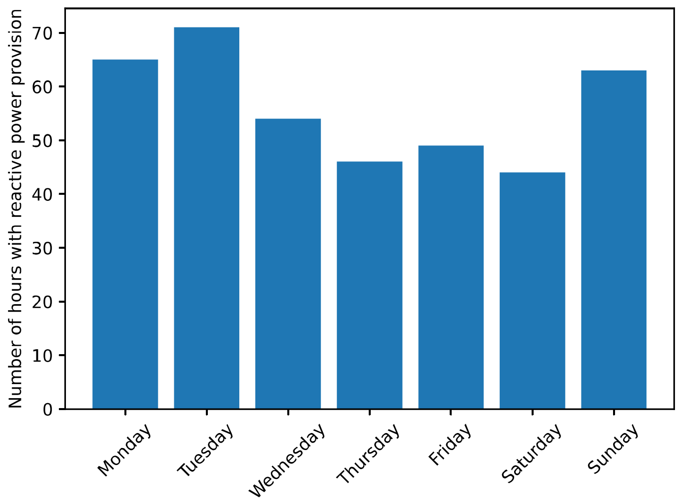



**Figure E.5:** Case B: The hours when the FCS must provide reactive power sorted by day of the week in Alternative 4

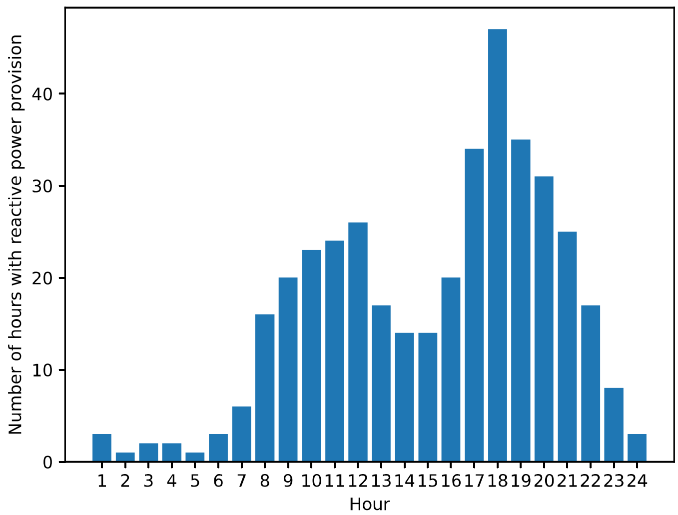



**Figure E.6:** Case B: The hours when the FCS must provide reactive power sorted by hour of the day in Alternative 4

## E.3 Case C: Alternative 5

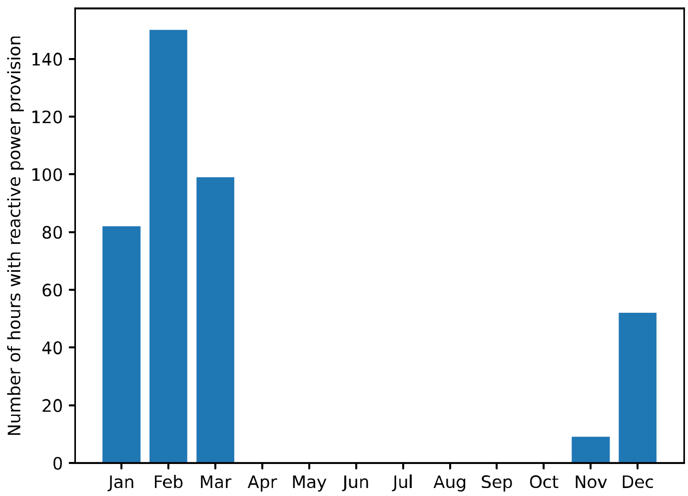



**Figure E.7:** Case C: The hours when the FCS must provide reactive power sorted by month in Alternative 5

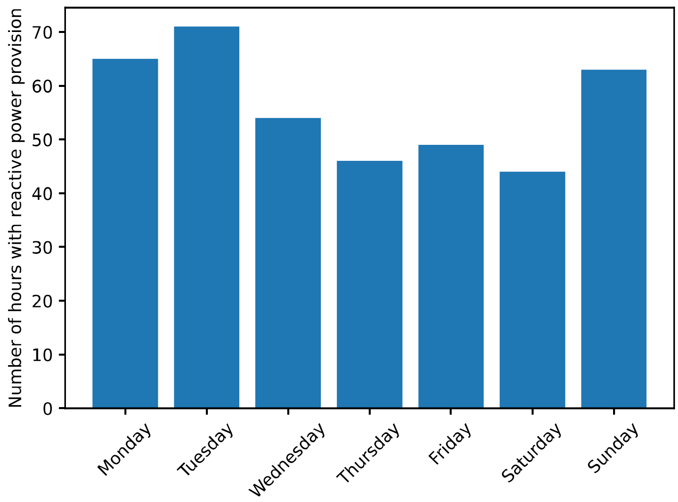



**Figure E.8:** Case C: The hours when the FCS must provide reactive power sorted by day of the week in Alternative 5

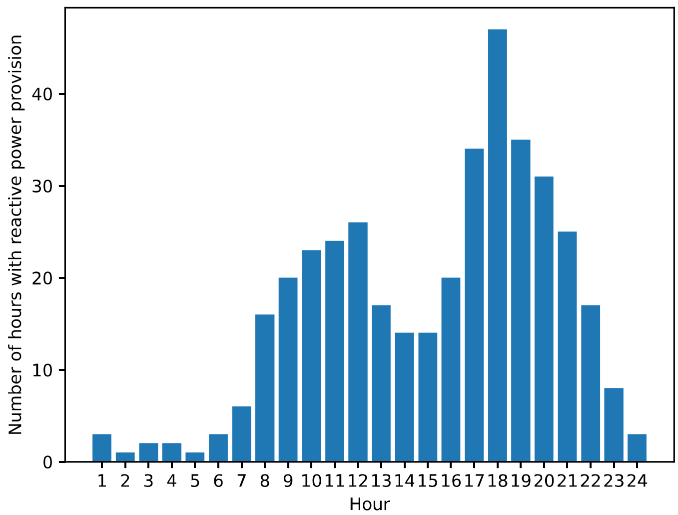



**Figure E.9:** Case C: The hours when the FCS must provide reactive power sorted by hour of the day in Alternative 5

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