Georgios Cheimonas

Master's Thesis Report

Design of an electric vehicle fleet model for service provision in Bornholm power system

Master's Thesis, June 2019
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Author(s):
Georgios Cheimonas

Supervisor(s):
Mattia Marinelli, Associate professor; Antonio Zecchino, Postdoc; Lisa Calearo, Research assistant; Hans Henrik Ipsen, Project manager

Department of Electrical Engineering
Centre for Electric Power and Energy (CEE)
Technical University of Denmark
Elektrovej 325
DK-2800 Kgs. Lyngby
Denmark

www.elektro.dtu.dk/cee
Tel: (+45) 45 25 35 00
Fax: (+45) 45 88 61 11
E-mail: cee@elektro.dtu.dk

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PREFACE

This MSc thesis report was elaborated at the Department of Electrical Engineering of the Technical University of Denmark (DTU Elektro) as the final prerequisite for receiving the Master of Science in Engineering degree focusing on Sustainable Energy, study line Electric Energy Systems. Additionally, this thesis aims to build on work previously performed as part of the Across Continents Electric Vehicle Services (ACES) project.

Supervisors of the work were Mattia Marinelli, Antonio Zecchino and Lisa Calearo from DTU and Hans Henrik Ipsen from Bornholms Energi og Forsyning (BEOF), while the thesis investigation took place from January until June 2019. Finally, the work corresponds to 30 ECTS.
AKNOWLEDGEMENTS

I would like to thank my supervisors for giving me the opportunity to improve my knowledge in a topic that I am interested in. Their competence and support were very important during the past five months and I am glad that I worked with them.

Moreover, I would like to express my gratitude to the people who supported me, family and friends. Their happy faces made those two years pass so quickly and made them full of fun. My choice to study and work in Denmark was totally worth it.

Georgios Cheimonas
ABSTRACT

Purpose of this work is to design an electric vehicle (EV) fleet model and investigate the effects on the power system from providing frequency regulation services along with services required for battery plants. Initially a single bus power system is modelled at 10kV, as equivalent of the power system of the Danish island of Bornholm, operating in islanded configuration. First analysis is conducted by replacing units providing primary frequency regulation with the designed EV fleet and assessing the response of the fleet by implementing various response times for the EVs and the respective hardware. Subsequently, the single bus model performance is validated in the complete 60 kV power system model where more simulations are executed in order to assess the performance of the fleet in providing active power / frequency services and reactive power services. This is performed through implementing various response times, EV shares and voltage dependencies. It is concluded that the response time is important and can lead to instabilities, while different services require different response times before frequency instability occurs, while voltage dependencies can help stabilising the system in some cases of reactive power control.
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<tr>
<td></td>
<td>A power factory files ...............................................................................</td>
<td>79</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

1.1 Background and motivation

In recent years, awareness is raised against global warming with the goal to contain global greenhouse gas emissions and thus global average temperature below 2°C above pre industrial levels as the Paris agreement concluded [1]. This agreement sets commitments for the parties, which are implemented by the European Union (EU), through the 2030 climate & energy framework [2]. The framework sets key targets for reducing the greenhouse gas emissions at least 40% compared to 1990, increasing the share of renewables to 32% at least and improving energy efficiency at least by 32.5%. These goals are based on previous frameworks as the 20/20/20 targets and Kyoto protocol. On top of that the Danish Government aims to reach independence from fossil fuels under the guidelines of Energy Strategy 2050 [3]. One way of achieving this is by setting a goal of 100% renewable produced electricity, which is also reflected in the development of the share of wind in electricity generation according to the Danish Energy Agency as shown in Figure 1.1. Therefore, renewables are of significant importance towards stabilising the global warming effect, therefore Many countries are development of support schemes to increase the share of such kind of sources in the energy mix.

Regarding transportation, the transition to green energy is also reflected in the goals set for the transport sector, aiming to a fossil fuel free transportation. Major factor towards this transition will be electric power as it enables the use of electric motors, which are more efficient than combustion engines. Moreover, the need to increase the number of electric cars and charging stations, through tax exemptions and subsidies as incentive, is also expressed along with the need for harmonisation rules and regulation applicable across the EU. Backbone of
this transition is the integration of electric vehicles (EVs) into the power system through providing ancillary services, enabling flexible electricity consumption and contributing to the security of supply [3].

Security of supply maintenance in a power system with highly fluctuating generation, as the one from renewables such as wind, is paramount and electricity storage can contribute to that [3].

Electric vehicles (EVs) powered by batteries are considered a promising source of services to the power system, since the active power that they absorb or release to that can be modulated [4]. Additionally, the use of battery based and hybrid EVs is expected to increase dramatically as shown in Figure 1.2. These scenarios have taken into account both existing policies and improved policies contributing to climate goals [5]. Thus, proper aggregation of the EVs willing to provide services to the power system is crucial, in order for a safe and stable operation to be secured [4].
Owners of EVs will not only benefit from the primary use of an EV, which is transportation, but also through participating in the electricity markets. Specifically, EVs along with the utilisation of bidirectional and unidirectional chargers, which allow both for modulated charging and discharging, can be part of a concept referred as Vehicle to Grid (V2G) [6]. From the provision of these services, specifically primary frequency regulation, profits can be achieved, therefore making EVs economically attractive for the consumers. Profits can vary based on frequency profile of the synchronous area thus they are different from place to place [7], while the battery is not significantly compromised by the provision of frequency regulation services [8]. Charger efficiency profile, especially of the bidirectional chargers, is also an important aspect towards maximising profit, as it varies based on the operation point of the charger [6].

As discussed, the future power system of Denmark is characterised by high penetration of renewables. Bornholm island located south of Sweden provides an excellent experimental and demonstration platform given that its power system resembles one with high renewable source penetration, when it is operated disconnected from Sweden, thus being a synchronous area on its own. This feature, which can well resembles the concept of the future Danish power system, thus providing an experimental facility for developing new electricity
markets for ancillary service provision and utilisation of energy storage for system balancing and ancillary services [9].

The aforementioned characteristics of the Bornholm power system and its ability to run intentionally in islanded mode, allow to perform research related to EV integration, specifically related to frequency regulation service provision. It is proven that part of the conventional units providing primary frequency regulation to the islanded power system of Bornholm can be replaced by a homogeneous EV fleet, when specific recommendations related to regulation power share and response times of the EV chargers are fulfilled [4]. More specifically, the significance of response time between requesting and ultimately providing the power to the system and the share of regulation power provided from EVs over the total regulation power of the power system is stressed when it comes to frequency stability. Other works conclude that the granularity in the response of unidirectional chargers imposed by the IEC 61851 standard, may induce oscillations in the output power depending also on the droop characteristic and the operation set-point [10].

The in integrations of EVs in the power system requires research in order to avoid instabilities in the power system when contingencies occur. This work is based on work previously carried out under the scope and the objectives of the ACES project which contribute in to the EV integration direction. A full scale penetration scenario of electrical vehicles at Bornholm will be simulated in order to assess how new aggregating functionalities - both technically and economically - can support a successful integration of electric vehicles into the energy system. It will also initiate a small scale pilot project involving up to 50 publicly and privately owned Nissan vehicles and V2G chargers for proving that EVs can be used for effectively balance the system. [11].

1.2 Thesis goals
This master’s thesis aims to develop a novel heterogeneous EV fleet and conclude whether it can provide ancillary services for the Bornholm power system. The aspects related to the EV fleet modelling and performance within a
power system, that this thesis will investigate are along with the research questions to be answered are:

1. Types of chargers implemented into the model. Specifically, not only commercial fleets connected to 10 kW bidirectional chargers will be examined, but also private EVs connected to 3.7 kW slow, 11 and 22 kW unidirectional chargers will be assessed. Therefore, the total number of EVs providing services to the grid can be 9% of the total EVs, thus increased compared to [4], while keeping the total EV penetration at 50% of all vehicles. Thus, are these chargers combined into one model provide successfully frequency regulation services?

2. Response time of the EVs. As private vehicles are standing alone and commercial fleets can be controlled either in a centralized or in a distributed manner, various response times can be implemented, reflecting the smaller delay of the decentralised contrary to the centralised. Thus can all services be provided successfully with the same response time or some services require for faster response?

3. Share of renewables in the power system. The share can be as high as 50%, while a part of the type A Wind turbines (WTs) can contribute to primary frequency regulation along with the EVs and therefore decreasing the share of EVs providing that service. How the share of renewables and specifically those contributing to the inertia of the power system affect the performance of the EVs providing frequency regulation services?

4. Ancillary services’ requirements imposed by the Transmission System Operator (TSO). The local TSO Energinet requires that battery power plants must be able to provide specific ancillary services depending on their size. Which ancillary services must be provided and suggestions can be made for changes in existing regulation?

5. Load dependencies. Load dependency on voltage in terms of active power, can significantly lower the load of the system when the voltage drops. How is load dependencies affects frequency response?

Finally, results are analysed and conclusions are extracted based on the frequency response of the power system for different scenarios of droop characteristics for frequency regulation requirements as well as reactive power
control. Sensitivity analysis of delays and power factor (PF) are investigated for the respective scenarios.

1.3 Report structure

Following the introduction, the second Chapter 2 gives an overview of the ancillary service requirements in Denmark along with technical requirements for battery power plants as an aggregated EV fleet is considered a battery plant.

In Chapter 3 the methodology for modelling the EV fleet is developed, describing how the charging dynamics are expressed and how the model is implemented in PowerFactory.

In Chapter 4 a description of the Bornholm power system is given both for its normal and its islanded operation mode, along with a description of the single bus model developed.

In Chapter 5 the EV fleet model and the Bornholm power system are put together, and simulation results from PowerFactory are presented.

Finally, in Chapter 6 conclusions are extracted and further work is suggested.
2 ANCILLARY SERVICES AND POWER PLANT TECHNICAL REQUIREMENTS

Being able to operate a power plant necessitates complying with regulation steering the operation of the power system that the plant is connected to. This means that, plant operators, plant owners and electricity supply undertakings, that is companies to whose grid the plant is electrically connected, must comply both to market regulation and technical regulation, including system operation. Technical regulation is relevant to metering data for system operation purposes, electricity metering, ancillary services and technical regulation for power plants, that is battery plants in the case of this thesis [12]. This thesis deals with technical regulation for battery plants, with focus on system operation and ancillary service provision.

In this chapter ancillary services and battery plants’ technical regulation is summarized.

2.1 Ancillary services in Denmark

As a result of the increased renewable penetration, new challenges and opportunities are set for the power system operators, which are responsible for keeping balance between generation and consumption of active and reactive power [13], [14]. The main Indicator of this balance is the electrical frequency of the power system [13], which must be kept within a given window defined in transmission system operation agreements between Transmission System Operators (TSOs) of the same synchronous area [15], [16]. Relevant frequency limitations are provided in Table 2.1 [17]. In order to achieve this the TSO buys ancillary services from electricity generators and consumers. Specifically, in Denmark two sets of tender conditions are to be covered as the Danish transmission system consists of two synchronous areas, one east of the Great
Belt (DK2) and one west of it (DK1). DK2 is part of the ENTOS-E RG Nordic synchronous area and DK1 of the ENTOS-E RG Continental Europe area [18]. In Figure 2.1 DK1 is depicted with purple and DK2 with blue [19].

Table 2.1 Normal state frequency range [17]

<table>
<thead>
<tr>
<th>Synchronous Area</th>
<th>Frequency limits for standard frequency deviation range [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continental Europe Region</td>
<td>49.95 – 50.05</td>
</tr>
<tr>
<td>Nordic Region</td>
<td>49.9 – 50.1</td>
</tr>
</tbody>
</table>

The concept of frequency regulation can be divided in three consecutive steps: the first aims to stabilize the frequency after a deviation occurs, the second is to bring the frequency back to the nominal value and the third is to relieve and make available the units that provided frequency regulation in the first two steps.

Figure 2.1 Synchronous Areas of North Sea Region [19, 20]
The ancillary services to be delivered both in DK1 and DK2 are covered by the following tender conditions [18]:

- Primary reserve, FCR
- Secondary reserve, aFRR
- Manual reserves, mFRR
- Properties required to maintain power system stability.

Similarly, for DK2 the services to be provided are [18]:

- Frequency-controlled disturbance reserve, FCR-D
- Frequency-controlled normal operation reserve, FCR-N
- Manual reserves, mFRR
- Properties required to maintain power system stability.

An overview of the activation and interactions between the operational reserves following a disturbance, along with the frequency response is depicted in Figure 2.2. The frequency dependency of the load is also appreciated as it drops as frequency diminishes helping the system to stabilise faster.

Figure 2.2 Primary and secondary reserves and respective frequency response [21]
### 2.1.1 Primary reserve, FCR for DK1

Purpose of the primary reserve also called Frequency Containment Reserve (FCR) is to ensure that the generation and consumption of electrical power is balanced after a contingency occurs and therefore the frequency disturbance is stabilised. The Danish TSO, Energinet is obliged to supply 20 MW of both upward and downward primary reserves to the Continental Europe region.

The reserve is decentralised and automatically provided from the generation or consumption units based on frequency deviations of +/- 200 mHz from the reference frequency of 50 Hz in a linear way, meaning frequencies between 49.8 and 50.2 Hz. A small deadband of +/- 20 mHz is allowed.

This type of power frequency control must be possible to be provided for a minimum of 15 minutes until other automatic and manual reserves take over.

### 2.1.2 Secondary reserve, aFRR for DK1

Secondary reserve or Automatic Frequency Restoration Reserve (aFRR) aims to indirectly restore the frequency to nominal, thus 50 Hz by means of power frequency control. Ultimately, primary reserve is released and any imbalances in the interconnections are restored, as aFRR considers the Area Control Error (ACE). ACE takes into account tie-line deviation from plan and frequency deviation [16].

Secondary reserve is automatic and is provided both from generating and consuming units, which are triggered by control signals received from Energinet. It is a symmetrical service of both up and down regulation for all participating units.

aFRR providing units must provide the requested power within 15 minutes and be able to maintain regulation continuously.
2.1.3 Frequency-controlled normal operation reserve, FCR-N for DK2

Similar to primary reserve described in 2.1.1, frequency-controlled normal operation reserve (FCR-N) aims to restore balance between generation and consumption after a contingency takes place. Energinet was required to provide 23 MW of FCR-N to the Nordic transmission system.

The reserve must be supplied symmetrically, that is both upward and downward, and linearly responding to frequency deviations of +/- 100 mHz, while no deadband is allowed. Both production and consumption units offering this service are operating automatically and decentralised.

The activation time of the reserve must be less than 150 s, while units must be able to maintain regulation continuously.

2.1.4 Frequency-controlled disturbance reserve, FCR-D for DK2

In case of major system disturbances, such as an outage of major production units or lines, frequency-controlled disturbance reserve (FCR-D) regulates the frequency. Energinet was required to provide 150-180 MW of this reserve type to the Nordic transmission system.

FCR-D is an automatic upward frequency regulation operational reserve provided by generating and consuming units. It is decentralized, thus control actions are calculated and performed by each participating unit and is based on responding to frequency deviations. The reserve must be activated when frequency drops below 49.9 Hz and remain active until power balance has been restored or manual reserve takes over power generation.

FCR-D activates for frequencies between 49.9 to 49.5 Hz and must be fully activated within 30 s.

2.1.5 Manual reserve, mFRR for DK1 and DK2

Manual Frequency Restoration Reserve, mFRR is activated manually by Energinet’s Control Centre and they are requested to meet demand during individual hours via the regulating power market.
Ancillary services and power plant technical requirements

mFRR is centralised and can be both and upward and downward regulation from the participating suppliers. The reserve relieves the aFRR and FCR-N operational reserves in the event of minor imbalances and ensures power balance during outages and constraints relevant to generation and interconnections.

Manual reserve must be fully supplied within 15 minutes after the TSO demands it.

2.1.6 Short-circuit power, inertia, reactive reserves and voltage control for DK1 and DK2

Apart from the operational reserves described in sections 2.1.1 to 2.1.6, other properties are also required so that a safe and stable operation of the power system is secured. These properties include short-circuit power, inertia, reactive reserves and voltage control and are required only from central power plants connected to the high-voltage system.

Energinet requests for tenders in a time basis varying from a month before the operational day until the operational day.

2.2 Technical regulation for battery plants

A battery plant can comprise both permanently and temporarily connected battery plants, which include several separate inverters and batteries. This implies that a set of electric vehicle charging stations able to provide grid services can be defined as a battery plant [12].

Technical regulations are technical minimum requirements applied to power plants which enables them to be connected to the public electricity supply grid, while requirements vary based on the size of the plant. Specifically, the battery plant categories are defined based on the rated power $P_n$ at the Point of Connection (POC) of the power plant to the grid as it can be seen in Table 2.2. In case of more than one battery, the sum of the rated power in the POC
determines the plant category. It should also be mentioned that rated power can be delivered ($P_{nl}$) or absorbed ($P_{no}$).

Table 2.2 Plant categories based on rated power

<table>
<thead>
<tr>
<th>Plant category</th>
<th>Rated power $P_n$ [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>$P_n \leq 0.011$</td>
</tr>
<tr>
<td>A2</td>
<td>$0.011 &lt; P_n \leq 0.050$</td>
</tr>
<tr>
<td>B</td>
<td>$0.050 &lt; P_n \leq 1.5$</td>
</tr>
<tr>
<td>C</td>
<td>$1.5 &lt; P_n \leq 25$</td>
</tr>
<tr>
<td>D</td>
<td>$25 \leq P_n$ or connected to over 100 kV</td>
</tr>
</tbody>
</table>

Reference points relevant to power plants as POC are illustrated in Figure 2.3

Figure 2.3 Overview of the various points relevant to power plants [18]

Technical regulation requires that the battery power plants must operate not only under normal frequency and voltage normal conditions but also be able to withstand specific frequency gradients and voltage dips without being disconnected. Moreover, power quality is considered and limitations relevant to DC component, asymmetry, flickering and harmonics are set for the battery.
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plant. Protection requiring compliance with relevant tripping times and exchange of signals and data are also included in the regulation.

For this thesis, control related requirements are mostly relevant as they are referring to control actions with a view of counteracting to frequency deviations, thus contributing to ancillary service requirements as described in 2.1. Depending on the category of the plant a plethora of control functions must be implemented as minimum while the transmission system operator activates or deactivates them after agreement with the plant owner. Activated functions and the respective parameters are determined by the electricity supply undertaking as per regulation set by the transmission system operator. Of the control functions given in Table 2.3 frequency control and voltage control must not be activated unless agreed with the transmission system operator, while Q control, power factor control and automatic power factor control must be agreed with electricity supply undertaking beforehand.

Table 2.3 Control functions of battery plants [12]

<table>
<thead>
<tr>
<th>Category Control function</th>
<th>A1</th>
<th>A2</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency response – LFSM-O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Frequency response – LFSM-U</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Frequency control</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Absolute power limit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ramp rate limit</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Q control</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Power Factor control</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Automatic Power Factor control</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Voltage control</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>System protection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(X)</td>
<td>(X)</td>
</tr>
</tbody>
</table>
The various control functions may be implemented in each battery, combined into one battery plant or a combination of them, while the communication interface is only one as shown in Figure 2.3. This means that all batteries must function as one battery plant with the sum of all connected batteries being equal to the rated power of the plant at the point of connection. Actions imposed by the control functions are executed based on signal exchange between the plant operator and the energy supplying undertaking in the park through the point of communication (PCOM). Such signals activate, deactivate or set values implementing the functions in each case.

### 2.2.1 Active power and frequency control

Battery plants must be able to modulate active power in the POC implementing the frequency response, frequency control, power limitation and active power ramp rate limitation functions, while relevant to the objectives of this thesis are frequency response and frequency control.

#### 2.2.1.1 Frequency response (LFSM-U and LFSM-O)

In case of frequency disturbance in the electricity supply grid the battery plant must contribute automatically to the stabilisation of the frequency through modulating the active power output as a function of the grid frequency, which is alternatively called droop and is performed locally in the plant. Activation time must be commenced no later than 2 s after the frequency change and must be completed within 15 s. Moreover, the respective response frequencies of the droop are set by the transmission system operator. The droop and the frequency settings are shown in Figure 2.4, Table 2.4 and Table 2.5.
As depicted when frequency increases above \( f_2 \) frequency response by overfrequency (LFSM-O) is taking action and the droop \( f_2-f_3 \) is followed decreasing active power production or even absorbing active power. After the frequency is stabilised, power must be maintained as frequency drops until \( f_4 \). Then droop \( f_4-f_0 \) is followed until \( f_0 \) is reached concluding the control action.

Similar actions are performed when frequency drops below \( f_1 \) with the frequency response by underfrequency (LFSM-U) is taking action increasing power generation until \( f_6 \). Then power is maintained as frequency increases until \( f_5 \) and drops following the droop \( f_5-f_0 \) until \( f_0 \) is reached.

The service must commence no later than 2 s after the disturbance and must be completed within 15 s.

For each plant category frequency response requirements can be seen in Table 2.3

<table>
<thead>
<tr>
<th>( f_x )</th>
<th>( f_{\text{min}} )</th>
<th>( f_{\text{max}} )</th>
<th>( f_0 )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( f_3 )</th>
<th>( f_4 )</th>
<th>( f_5 )</th>
<th>( f_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Hz]</td>
<td>47.00</td>
<td>52.00</td>
<td>50.00</td>
<td>49.80</td>
<td>50.20</td>
<td>50.05</td>
<td>49.95</td>
<td>47.00</td>
<td></td>
</tr>
</tbody>
</table>
2.2.1.2 Frequency control (FSM)

Similar to frequency response, frequency control aims to stabilise or restore the frequency. The operation of the function is based on the droop depicted in Figure 2.5 and can be used for both absorbed and delivered power. Values and limits used for setting the control functions are given in Table 2.7 and Table 2.8. It should be mentioned that frequency control is utilized to provide the primary frequency ancillary services FCR, FCR-N and FCR-D to the grid as they are described in 2.1. It must be stressed that no frequency control actions should be undertaken without prior agreement with the TSO.

The actions of the droop are to change the active power output of the power plant having the frequency as input.

![Figure 2.5 Frequency control (FSM) requirement](image)

The accuracy of the regulation must be ±5% of the setpoint value or ±0.5% of the rated power of the plant.

---

### Table 2.5 Standard frequency response setting values for DK2

<table>
<thead>
<tr>
<th>( f_x )</th>
<th>( f_{\min} )</th>
<th>( f_{\max} )</th>
<th>( f_0 )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( f_3 )</th>
<th>( f_4 )</th>
<th>( f_5 )</th>
<th>( f_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Hz]</td>
<td>47.00</td>
<td>52.00</td>
<td>50.00</td>
<td>49.50</td>
<td>50.10</td>
<td>52.00</td>
<td>50.05</td>
<td>49.95</td>
<td>47.00</td>
</tr>
</tbody>
</table>
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Table 2.6 Standard frequency control setting values for DK1 (FCR)

<table>
<thead>
<tr>
<th>( f_x )</th>
<th>( f_{\text{min}} )</th>
<th>( f_{\text{max}} )</th>
<th>( f_0 )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Hz]</td>
<td>47.00</td>
<td>52.00</td>
<td>50.00</td>
<td>49.80</td>
<td>50.20</td>
</tr>
</tbody>
</table>

Table 2.7 Standard frequency control setting values for DK2 (FCR-N)

<table>
<thead>
<tr>
<th>( f_x )</th>
<th>( f_{\text{min}} )</th>
<th>( f_{\text{max}} )</th>
<th>( f_0 )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Hz]</td>
<td>47.00</td>
<td>52.00</td>
<td>50.00</td>
<td>49.90</td>
<td>50.10</td>
</tr>
</tbody>
</table>

Table 2.8 Standard frequency control setting values for DK2 (FCR-D)

<table>
<thead>
<tr>
<th>( f_x )</th>
<th>( f_{\text{min}} )</th>
<th>( f_{\text{max}} )</th>
<th>( f_0 )</th>
<th>( f_1 )</th>
<th>( f_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Hz]</td>
<td>47.00</td>
<td>52.00</td>
<td>50.00</td>
<td>49.90</td>
<td>49.50</td>
</tr>
</tbody>
</table>

2.2.2 Reactive power and voltage control

Technical requirements impose that the battery plant must be able to provide also Q control, power factor control and voltage control at the point of connection, with only one function activated at a time. Q control and power factor control are considered in this thesis.

2.2.2.1 Q control

Q control modulates the reactive power in the POC without taking the voltage and the active power into account, as shown in Figure 2.6. It is necessary that every battery plant is equipped with the Q control function set at 0 VAr.
2.2.2.2 Power factor control

The power factor control sets the reactive power at POC proportionally to the active power at the same point, as depicted in Figure 2.7.

Figure 2.6 Reactive power control function
2.2.2.3 Requirements for reactive power properties of the plant

Apart from the fact that every battery plant must be able to implement the reactive power related control functions, it must be able to operate within the hatched area limiting the power factor to 0.9 lagging and leading, as shown in Figure 2.8.

It must be stressed that when active power is absorbed by the plant, then the power factor must be set to 1.
Figure 2.8 Requirements for reactive power working points for A1, A2, B (left) and C (right) battery plant categories.
With a view to provide a better understanding of the EV related systems an overview of the electrical components is given initially. An electric vehicle comprises various components and assemblies aiming to control power flow from and to the battery and the wheels as seen in Figure 3.1, where green is used for controllers, yellow for batteries, grey for grid and circuit breakers, and orange for power electronic components.

![Diagram](image)

**Figure 3.1 EV connected to EVSE [22]**

Additionally, depending on the Electric Vehicle Supply Equipment (EVSE) configuration the EV can be charged through AC or DC charging as is can be seen in Figure 3.2 and Figure 3.3.
Main difference between the two is the power electronics regulating the charging power and converting it from AC to DC. In the case of AC charging they are located in the EV, while in the case of DC charging, they are located in the charger, that is EVSE. It is worth mentioning that if the charger is bidirectional power can additionally flow the opposite direction.

Primary purpose of the fleet model developed in this thesis is to provide insights on how aggregated electric vehicles can provide frequency regulation, through EVSEs of different types and capacities. Specifically, for this thesis two types and four capacities for chargers were assumed as seen in Table 3.1. Moreover, primary frequency regulation is energy neutral as active power behavior of the charger is symmetric around the nominal frequency of the system, while the EV is not dispatched to provide active power for prolonged periods. Additionally, time periods investigated for the purpose of this thesis are not exceeding one minute and thus it can be safely assumed that the State of Charge (SOC) of the battery model can be neglected.
Eventually, it is the model of the charger that is considered for the model purposes, which is absorbing or generating power at the point of connection. It is worth mentioning that efficiency of the power electronics resulting in higher or lower active power from the battery point of view, compared to the grid setpoint is neglected.

### Table 3.1 Charger types and sizes

<table>
<thead>
<tr>
<th>EVSE types</th>
<th>EVSE Capacities [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidirectional</td>
<td>10</td>
</tr>
<tr>
<td>Unidirectional</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>

For each of the four charger types taken into account for the purposes of this work, an aggregated model has been designed. As depicted in Figure 3.4 the model is divided in four parts, each one contributing to the aspects of controlling the output of the EVs, implementing signal delays, aggregating similar types of chargers along with battery response to power output changes and scaling the output depending on the number of chargers in the model. As frequency control is realized by the model, frequency measurement is the input and active and/or reactive power is the output of the model.

![Figure 3.4 EV aggregation model](image)
3.1 **Types of chargers**

The chargers considered are both single phase and three-phase, uni- and bidirectional, while the sizing is based on current and voltage values implying the active power capacities given in Table 3.1. As the setpoints are referring to the POC with the AC grid, voltage values represent phase to phase voltage and current values represent phase current. An overview of the charging power of top-selling battery EVs can be seen in Figure 3.5. Additionally, are able to provide reactive power both based on active power through Power Factor (PF) and constantly without considering active power. It should be noticed that the chargers are not limited in terms of apparent power, instead only active power limits are considered.

<table>
<thead>
<tr>
<th>Brand</th>
<th>Model</th>
<th>Model year</th>
<th>Battery warranty (years)</th>
<th>Battery energy capacity (kWh)</th>
<th>Standard AC charging power (kW)</th>
<th>DC charging power (kW)</th>
<th>Range NEDC¹ (km)</th>
<th>Range EPA combined cycle² (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>i3</td>
<td>2014</td>
<td>8</td>
<td>22</td>
<td>7.4</td>
<td>50</td>
<td>190</td>
<td>130</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Spark EV</td>
<td>2015</td>
<td>8</td>
<td>18.4</td>
<td>3.3</td>
<td>50</td>
<td>150</td>
<td>132</td>
</tr>
<tr>
<td>Citroen</td>
<td>C-Zero</td>
<td>2014</td>
<td>8</td>
<td>14.5</td>
<td>3.2</td>
<td>50</td>
<td>150</td>
<td>132</td>
</tr>
<tr>
<td>Fiat</td>
<td>500e</td>
<td>2015</td>
<td>8</td>
<td>24</td>
<td>6.6</td>
<td>50</td>
<td>212</td>
<td>150</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus electric</td>
<td>2015</td>
<td>8</td>
<td>23</td>
<td>6.6</td>
<td>162</td>
<td>122</td>
<td>132</td>
</tr>
<tr>
<td>Honda</td>
<td>FIT EV</td>
<td>2014</td>
<td>5</td>
<td>20</td>
<td>6.6</td>
<td>162</td>
<td>122</td>
<td>132</td>
</tr>
<tr>
<td>Kia</td>
<td>Soul EV</td>
<td>2015</td>
<td>10</td>
<td>27</td>
<td>6.6</td>
<td>50</td>
<td>212</td>
<td>150</td>
</tr>
<tr>
<td>Mercedes</td>
<td>B-class electric</td>
<td>2015</td>
<td>8</td>
<td>36</td>
<td>10</td>
<td>200</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>i-MiEV</td>
<td>2014</td>
<td>8</td>
<td>16</td>
<td>3.7</td>
<td>160</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf (Visia)</td>
<td>2015</td>
<td>5</td>
<td>24</td>
<td>3.6</td>
<td>50</td>
<td>199</td>
<td>135</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf (Acenta)</td>
<td>2016</td>
<td>8</td>
<td>30</td>
<td>3.6</td>
<td>50</td>
<td>250</td>
<td>172</td>
</tr>
<tr>
<td>Nissan</td>
<td>e-NV200</td>
<td>2015</td>
<td>5</td>
<td>24</td>
<td>3.6</td>
<td>170</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peugeot</td>
<td>iOn</td>
<td>2014</td>
<td>5</td>
<td>14.5</td>
<td>3.2</td>
<td>50</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Renault</td>
<td>Zoe</td>
<td>2015</td>
<td>5</td>
<td>22</td>
<td>4.3</td>
<td>240</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smart</td>
<td>fortwo ED</td>
<td>2014</td>
<td>4</td>
<td>17.6</td>
<td>3.3</td>
<td>145</td>
<td>109</td>
<td>150</td>
</tr>
<tr>
<td>Tesla</td>
<td>Model S</td>
<td>2015</td>
<td>8</td>
<td>85</td>
<td>10</td>
<td>120</td>
<td>502</td>
<td>426</td>
</tr>
<tr>
<td>Volkswagen</td>
<td>e-Golf</td>
<td>2015</td>
<td>8</td>
<td>24.2</td>
<td>22</td>
<td>50</td>
<td>190</td>
<td>134</td>
</tr>
<tr>
<td>Volkswagen</td>
<td>e-Up!</td>
<td>2013</td>
<td>8</td>
<td>18.7</td>
<td>3.7</td>
<td>40</td>
<td>160</td>
<td>132</td>
</tr>
</tbody>
</table>

¹ New European Driving Cycle is defined in United Nations ECE R101
² U.S. Environmental Protection Agency combined cycle is a weighted average considering 55% of the city consumption and 45% of the highway consumption

Figure 3.5 Top-selling battery EV models [23]

3.1.1 **Bi 315**

The bidirectional 10 kW charger, named as bi315, is modelled based on load convention and is able to operate between 0 A and 15 A phase current, under nominal voltage of 400 V and is three-phase. The nominal power is given in (3.1) and is equal to 10.4 kW.
\[ P_{\text{nominal bl315}} = 3 \cdot I_{\text{max bl315}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{max bl315}} = 15 \, A \]  
\[ V = 400 \, V \]  

As it is bidirectional, it is able to provide the AC grid and absorb from it power varying as shown in (3.2).

\[ -P_{\text{nominal bl315}} \leq P_{\text{bi315}} \leq P_{\text{nominal bl315}} \] (3.2)

Considering reactive power, the bi315 charger can provide constant reactive power or based on power factor given the active power setpoint. Reactive power setpoint calculations are given in (3.3).

\[ Q_{\text{bi315}} = \text{constant} \]  
\[ Q_{PF_{bi315}} = \tan(\cos(PF_{bi315})) \] (3.3)

### 3.1.2 Uni 116

The unidirectional 3.7 kW charger, named as uni116, is modelled based on load convention and is able to operate between 6 A and 16 A phase current, under nominal phase to phase voltage of 400 V and is single phase. The nominal power is given in (3.4) and is equal to 3.7 kW and it is considered a slow EV charger for private or public use [24].

\[ P_{\text{nominal uni116}} = I_{\text{max uni116}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{max uni116}} = 16 \, A \]  
\[ V = 400 \, V \]  

Minimum power absorbed by the charger in calculated as given in (3.5)

\[ P_{\text{min uni116}} = I_{\text{min uni116}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{min uni116}} = 6 \, A \] (3.5)
The total operational active power window of the 3.7 kW charger is shown in (3.6).

\[ P_{\text{min\text{uni116}}} \leq P_{\text{uni116}} \leq P_{\text{nominal\text{uni116}}} \]  

(3.6)

In terms of reactive power, the uni116 charger can provide constant reactive power or based on power factor given the active power setpoint. Reactive power setpoint calculations are given in (3.7).

\[ Q_{c_{\text{uni116}}} = \text{constant} \]  
\[ Q_{PF_{\text{uni116}}} = \tan(\arccos(PF_{\text{uni116}})) \]  

(3.7)

### 3.1.3 Uni 316

Similar to uni116 the unidirectional 11 kW charger, named as uni316, is modelled based on load convention and is able to operate between 6 A and 16 A phase current, under nominal voltage of 400 V and is three-phase. The nominal power is given in (3.8) and is equal to 11.1 kW and it is considered a slow EV charger for private or public use similar to uni116 [24].

\[ P_{\text{nominal\text{uni316}}} = 3 \cdot I_{\text{max\text{uni316}}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{max\text{uni316}}} = 16 \text{ A} \]  
\[ V = 400 \text{ V} \]  

(3.8)

Minimum power absorbed by the charger in calculated as given in (3.9).

\[ P_{\text{min\text{uni316}}} = 3 \cdot I_{\text{min\text{uni316}}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{min\text{uni316}}} = 6 \text{ A} \]  
\[ V = 400 \text{ V} \]  

(3.9)
The total operational active power window of the 11 kW charger is shown in (3.10).

\[ P_{\text{min uni316}} \leq P_{\text{uni316}} \leq P_{\text{nominal uni316}} \]  

(3.10)

In terms of reactive power, the uni316 charger can provide constant reactive power or based on power factor given the active power setpoint. Reactive power setpoint calculations are given in (3.11).

\[ Q_{\text{c uni316}} = \text{constant} \]  
\[ Q_{PF \text{ uni316}} = \tan(\cos(PF_{\text{uni316}})) \]  

(3.11)

### 3.1.4 Uni 332

Similar to uni116 the unidirectional 22 kW charger, named as uni316, is modelled based on load convention and is able to operate between 6 A and 16 A phase current, under nominal voltage of 400 V and is three-phase. The nominal power is given in (3.12) and is equal to 22.2 kW.

\[ P_{\text{nominal uni332}} = 3 \cdot I_{\text{max uni332}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{max uni332}} = 32A \]  
\[ V = 400V \]  

(3.12)

Minimum power absorbed by the charger in calculated as given in (3.13).

\[ P_{\text{min uni332}} = 3 \cdot I_{\text{min uni332}} \cdot \frac{V}{\sqrt{3}} \]  
\[ I_{\text{min uni332}} = 6A \]  
\[ V = 400V \]  

(3.13)

The total operational active power window of the 22 kW charger is shown in (3.14).

\[ P_{\text{min uni332}} \leq P_{\text{uni332}} \leq P_{\text{nominal uni332}} \]  

(3.14)
Concerning reactive power, the uni332 charger can provide constant reactive power or based on power factor given the active power setpoint. Reactive power setpoint calculations are given in (3.15).

\[
Q_{c_{\text{uni332}}} = \text{constant} \\
Q_{PF_{\text{uni332}}} = \tan(\cos(PF_{\text{uni332}})
\]

### 3.2 Aggregated electric vehicle model
Purpose of aggregating the EVs into a model is to represent their response to a change in their power output. This is achieved through a transfer function given in (3.16). In this function \( k_{EV} \) represents the charging controller’s gain, \( T_{EV} \) the first order time constant which models the EV battery dynamics and \( \tau \) is the time delay representing the time required for measurement, communication and activation of the power converters [25, 4]. The aforementioned values are average values approximating similar response of the \( N \) EV chargers of the fleet.

\[
H(s) = N \frac{k_{EV}}{1 + T_{EV} \cdot s} e^{-\tau \cdot s}
\]

It can be seen that the Delay, Aggregation and Scaling blocks shown in Figure 3.4 are implemented in (3.16)

### 3.3 Control strategy
In this section the Control block as given in Figure 3.4 is described. As aim of this work is to provide primary frequency control and frequency control is implemented through a droop function as the ones given in 2.2.1, the respective control actions are driven by the equation (3.17) [26, 4].

\[
\frac{\Delta f}{f_{\text{nom}}} = k_{\text{droop}} \frac{\Delta P}{P_{\text{res}}}
\]
Similarly, the relationship between frequency and current is given by (3.18) [26].

$$\frac{\Delta f}{f_{\text{nom}}} = k_{\text{droop}} \frac{\Delta I}{I_{\text{res}}}$$

(3.18)

The frequency variation $\Delta f$ referred to the nominal frequency $f_{\text{nom}}$ of the system is a function of the relative power or current change referred to the power or current allocated for primary frequency regulation, while $k_{\text{droop}}$ defines the sensitivity of the frequency regulation provider to the frequency changes and its contribution to frequency regulation.

As an example, in the case of primary frequency regulation in DK2 the droop function (3.17) implementing the requirements given in 2.2.1.2, is depicted in Figure 3.6.

![Droop characteristic for FSM provision using the generation convention](image)

Figure 3.6 Droop characteristic for FSM provision using the generation convention
Concerning the bidirectional charger, the respective regulation power is equal to the nominal power, as it normally operates at 0 W, being able to absorb or provide active power equal to its nominal. On the other hand, the current active power setpoint is implemented differently as they are only able to absorb active power. For this reason, when frequency regulation is provided, the current active power setpoint is in the middle of the power range of the chargers as given in 3.1. The respective initial current setpoints, corresponding to frequency equal to the nominal frequency of the system, are given in Table 3.2.

### Table 3.2 Initial current setpoint for $f = f_{\text{nom}}$

<table>
<thead>
<tr>
<th>Charger</th>
<th>Initial Current setpoint [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi315</td>
<td>$I_{\text{init}_{\text{Bi315}}} = 0$</td>
</tr>
<tr>
<td>Uni116</td>
<td>$I_{\text{init}_{\text{Uni116}}} = 11$</td>
</tr>
<tr>
<td>Uni316</td>
<td>$I_{\text{init}_{\text{Uni316}}} = 11$</td>
</tr>
<tr>
<td>Uni332</td>
<td>$I_{\text{init}_{\text{Uni332}}} = 19$</td>
</tr>
</tbody>
</table>

Setting the initial current in the middle of the active power operational window of the charger allows for equal power regulation both upwards and downwards. The respective amount of current and by extension power define the reserve current $I_{\text{res}}$ and the respective power $P_{\text{res}}$ as used in (3.17) and (3.18). The amount of reserves in terms of current are given in Table 3.3, while the respective power can be calculated similar to (3.1), (3.4), (3.8) and (3.12) through setting this current in the equations.

### Table 3.3 Reserve current for each charger type

<table>
<thead>
<tr>
<th>Charger</th>
<th>Reserve Current [A]</th>
</tr>
</thead>
</table>

At this point it should be mentioned that since only reserves are considered in
the droop control function (3.18), the active power setpoint is not reflected in
that equation. For this reason, the initial current in Table 3.2 can be seen as
offset $I_{offset}$ leading to maximum active power setpoint for the unidirectional
chargers, when the regulation power $\Delta P$ is maximum. Contrary to that, for
bidirectional chargers the operational window is reflected in the frequency
regulation window, as the regulation power is equal to the rated power of the
charger.

An overview of how the control block is implemented is given in Figure 3.7.
System frequency is measured and variation from the nominal frequency is
calculated. The derived delta frequency is the input of the droop implementing
equation (3.17) and thus deriving the delta $P$, subsequently the respective
power offset for each charger, as derived from the current values in Table 3.2,
is added. The total is limited based on the equations given in (3.2), (3.6), (3.10)
and (3.14) representing the active power setpoint $P$ of the charger. Moreover, a
dead band is also implemented so that droop functions with shape similar to
Figure 2.4 can be implemented.
3.4 The complete model

Finally, the full model comprising aggregated EV fleets charging and providing V2G services through the same charger type and size is depicted in Figure 3.8. The model allows for customization of parameters for every block and can additionally provide power factor and Q control if needed as described in 2.2.2.

Figure 3.7 Control block implementation

Figure 3.8 Aggregated EV fleet model
3.5 **Software utilised**

For the simulations and validation of the model the DigSilent PowerFactory software platform was utilised. PowerFactory is a tool capable of performing Root Mean Square (RMS) analysis and thus enables the dynamic examination of the system when a contingency takes place. The ability to create composite models and models definitions is also important when it comes to designing elements of the grid in order to simulated their dynamic behavior, as it allows for modifications of the performance of existing elements in PowerFactory libraries.

3.6 **Implementation of the EV fleet model in Power Factory**

The implementation in PowerFactory is realised by utilising a three-phase load element, a phase measurement device (PLL) and a composite model in order to modulate the external active and reactive power signals of the element based on frequency measurements from the PLL. The composite frame referring to the composite model is shown in Figure 3.9.

![Figure 3.9 EV fleet composite frame](image)

As it can be seen it comprises three slots with the aim to realise the fleet model shown in 3.4. “Fmeas” slot provides the “EV fleet model” slot with frequency measurements derived from the PLL, then “EV fleet model” realises all calculations relevant to the model and finally the “EV fleet” is defining the behaviour of a three phase load, which is a network element playing the role of an EV charger in the power system of interest.
The block definition applied to the fleet model is shown in Figure 3.10 and is based on the model shown in Figure 3.8. For every block reference several parameters and equations are applied as the ones given in the model description, enabling the model to be customized.

Specifically, for “DeltaF” block definition, where the frequency variation is calculated, equation (3.19) is utilised for all charger models respectively. Concerning the equation’s parameters $f_{nom}$ is the system’s nominal frequency and $f_{offset}$ allows for asymmetrical frequency regulation. $f_{meas}$ represents the frequency measurements input from the PLL.

$$\Delta F = f_{meas} - (f_{nom} + f_{offset}) \quad (3.19)$$

Figure 3.10 Model definition for the “EV fleet model” slot

For the “Droop” block definition, equation (3.20) is applying the droop control referred in 3.3 for the respective chargers, while $P_{res}$ is given by (3.21) for the single phase charger and by (3.22) for the three-phase chargers. Parameters $V_{pp}$
and \( I_{\text{res}} \) are the nominal phase to phase voltage of the system and the reserve current described in 3.3 respectively.

\[
\Delta P = \frac{\Delta F}{f_{\text{nom}}} \cdot P_{\text{res}} \cdot \frac{1}{k_{\text{droop}}} \tag{3.20}
\]

\[
P_{\text{res1ph}} = I_{\text{res1ph}} \cdot \frac{V_{pp}}{\sqrt{3}} \tag{3.21}
\]

\[
P_{\text{res3ph}} = 3 \cdot I_{\text{res3ph}} \cdot \frac{V_{pp}}{\sqrt{3}} \tag{3.22}
\]

The “ZERO” or “Offset” block definition implements the offset power concept with its values deriving from the parameters \( I_{\text{offset}} = I_{\text{init}} \) given in Table 3.2. Equations applied are given in (3.23) and (3.24) for single and three-phase chargers respectively.

\[
P_{\text{offset1ph}} = I_{\text{offset1ph}} \cdot \frac{V_{pp}}{\sqrt{3}} \tag{3.23}
\]

\[
P_{\text{offset3ph}} = 3 \cdot I_{\text{offset3ph}} \cdot \frac{V_{pp}}{\sqrt{3}} \tag{3.24}
\]

Following that, the “Summation” block definition simply sums the output of the droop and the power offset (3.25).

\[
P_{\text{sum}} = \Delta P + P_{\text{offset}} \tag{3.25}
\]

Then power limited through the “Limiter” block which implements the equations (3.2), (3.6), (3.10) and (3.14).

“Tdel” block definition represents the time delay, “\( K_{\text{EV}}/(1+sT_{\text{EV}}) \)” block definition applies the 1st order delay and “scaling” multiplies the power of a single EV with the total amount of EVs connected to the same type of chargers and providing frequency regulation. The aforementioned concepts were discussed in 3.2 and their response is given in (3.26), (3.27) and (3.28). The
parameters shown were discussed in 3.2. For this thesis it is assumed that $T_{EV} = 0.1 \, s$ and $k_{EV} = 1$.

\[ P_{det} = P(t - t_{det}) \]  \hspace{1cm} (3.26)

\[ H_{agg}(s) = \frac{k_{EV}}{1 + sT_{EV}} \]  \hspace{1cm} (3.27)

\[ P_{scaled} = P_{EV} \cdot N \]  \hspace{1cm} (3.28)

Finally, the total active power signal is calculated through the “P_sum” block definition which adds the aggregated power signals from all aggregated charger types of the fleet. Moreover, the “Q_sum” block definition receives the active power signal from each aggregated model and calculates the respective reactive power based on the equations (3.3), (3.7), (3.11) and (3.15), while it sums the total reactive power and provides the signal.

The model interacts with the power system through a three-phase load element, which receives the $P_{ext}$ and $Q_{ext}$. A point of interest relevant to model realisation that should be considered is that despite the fact the three-phase load is used as element, it realises the behaviour of a single-phase charger along with the others. In terms of power it is assumed that the single-phase chargers are equally spread in all phases of the power system and thus the same amount of power can be delivered through a three-phase load. Additionally, all parameters taken into account are given in Ampere and Volt meaning the result is in Watt when it comes to active power. The “P_sum” block on the other have converts the total active power in MW, as this is required by the load element, while “Q_sum” applies similar logic.
4
THE TEST GRID: BORNHOLM POWER SYSTEM

Bornholm power system is located in the Baltic Sea south of Sweden and east of Denmark and is a Danish territory. It is interconnected to the Nordic region synchronous area specifically with the Swedish transmission system, implying that electricity markets and regulation policies relevant to RG Nordic and DK2 are applied as discussed in Chapter 2. Bornholms Energi & Forsyning (BEOF) is the local Distribution System Operator (DSO), which also has balancing responsibilities when the interconnection with Sweden is not operational.

4.1 The complete system
The complete Bornholm power system consists of three voltage levels 60 kV, 10 kV and 0.4 kV, while it is interconnected with the Swedish transmission system through a 43.5 km long cable operating at 60 kV with a capacity of 63 MVA coupling electrically the distribution network of Bornholm to the Nordic area [27, 9, 4]. The interconnection is realised with the help of a 132/60 kV substation located in Sweden. Occasionally, the cable is becoming inoperative due to maintenance reasons or because of incidents forcing the island’s power system to operate in islanded mode. That is when BEOF has to provide frequency regulation relying on conventional generating units (CGUs), while disconnecting most of the WT [4]. It should also be mentioned that the system can operate islanded for testing and research [27, 9]. For the purpose of this work, the islanded operation scenario is investigated for which a conventional unit providing frequency regulation is replaced by the developed fleet of EVs and provides that service instead. During that period the inertia of the system is lower, thus frequency is more subject to variations [27].
Figure 4.1 depicts the Fourier Transform of a 37 day sample of the Bornholm’s power system electrical frequency with a sampling frequency of 2 Hz. This enables the appreciation of variations both electrical and mechanical imposing changes to the electrical frequency. It can be seen that the DC component of the frequency is close to 50 Hz, while higher harmonic components with significantly lower amplitude at 0.4 Hz and 0.8 Hz are observed reflecting possible mechanical oscillations of rotors or actions related to primary frequency regulation.

In terms of infrastructure the grid is modelled with aggregated loads, CGUs, wind turbines and photovoltaics (PV), while the aggregated EV fleets are through loads connected to 10 kV buses. Only the medium voltage (MV) 60 kV grid is modelled with real models for the lines and 60/10 kV substations lines, while the 10 kV grid is not modelled in detail since no overloading issues occur. For the research purposes of this work, the detailed 60 kV grid model is sufficient to provide valid results, since EV penetration is high [4]. The 60 kV grid is shown in Figure 4.2 where some generation units and 60/10 kV
substations are depicted. The grid comprises 16 60/10 kV substations, 23 60/10 kV transformers with on-load voltage regulation capability and 22 cables and lines being 131 km long [4].

Concerning the generation set this depends on whether the island is interconnected with Sweden or runs in islanded mode. In the following sections 4.1.1 and 4.1.2 the generation portfolios are given [4].

4.1.1 Interconnected operation
The generation installed on the island during its normal interconnected operation includes:

- A 16 MW biomass combined heat and power plant (CHP) with steam turbine, named Block 6, with inertia constant 2H=6.4 s and apparent power S=46.8 MVA. Moreover, it can provide primary frequency regulation with a 2% droop.
The test Grid: bornholm power system

- Two 1 MW biogas CHP gas turbine, with inertia constant $2H=5.6$ s and apparent power $S=1$ MVA not able to provide primary frequency regulation.
- 37 MW of wind, with 17 WTs being rated above 1 MW, 16 between 0.1 and 1 MW and 24 below 0.1 MW.
- 23 MW of PVs, with 8 MW being on the rooftops at 0.4 kV and 15 MW at 10 kV

4.1.2 Islanded operation

When the power system runs disconnected from Sweden, some additional units are dispatched only for this case, with a total amount of reserve equal to 58 MW. One these CGUs will be replaced with EV fleets so that in order to investigate the primary frequency regulation capabilities of the fleet.

Primary reserves include the following plants:

- A 25 MW oil-powered steam turbine, named Block 5, with apparent power $S=29.4$ MVA, inertia constant $2H=8.6$ s and 2% primary frequency droop. Block 5 is generally not used together Block 6 for frequency regulation due to hunting issues.
- Four 4.5 MW diesel generators, with apparent power $S=5.8$ MVA for the two of them and $S=6.3$ MVA for the others. The inertia constant is $2H=8s$ and the primary frequency droop is 2%.
- Ten 1.5 MW diesel generators, named block 7 with apparent power $S=2$ MVA and inertia constant $2H=1.1$ s. They are not able to provide primary frequency droop.

4.2 Software utilised

For the simulations and validation of the model the DigSilent PowerFactory software platform was utilised. PowerFactory is a tool capable of performing Root Mean Square (RMS) analysis and thus enables the dynamic examination of the system when a contingency takes place. The ability to create composite models and models definitions is also important when it comes to designing elements of the grid in order to simulated their dynamic behavior, as it allows for modifications of the performance of existing elements in PowerFactory libraries.
4.3 **The single bus equivalent system**

The single bus system is designed in order to investigate the Bornholm’s power system during the islanded operation. It is developed with a view to first analyse the effects of replacing a CGU with EV fleets of the same primary frequency regulation power as the CGU in the context of a power system with minimal complexity, before validating the model in the complete system. This simplified power system consists only of a single bus, at which some of the generation units described in 4.1.1 and 4.1.2 are connected along with aggregated loads and an EV fleet and implemented in power factory as shown in Figure 4.3.

![Image](single_bus_equivalent.png)

**Figure 4.3 Single bus equivalent implemented in PowerFactory**

The model consists of a single bus with a nominal voltage of 10 kV on which the following units with total inertia $2H=3.6$ s are connected [4]:

- One Diesel generator with apparent power $S=5.8$ MVA as in 4.1.2.
- Two Biogas powerplant models as described in 4.1.1.
- Block 5 powerplant model as in 4.1.2.
- Block 5 powerplant model as in 4.1.1.
- One aggregated WT model implementing the total amount of Type C WT installed, in terms of active power [28].
- One aggregated WT model implementing the total amount of Type A WT installed, in terms of active power, with inertia $2H=1$ s [4].
- One model WT Type A model used for realising power disruption events.
- One load model implementing the aggregated behaviour of the EV fleets providing V2G services as modelled in 0.
- One load model implementing the aggregated load on the power system. In terms of active power it shows linear dependency on voltage, while in terms of reactive power it has quadratic dependency on voltage [4].

As it can be seen no transformers, lines and multiple voltage levels were taken into account. Moreover, despite the policy of the DSO to disconnect wind generation during the islanded operation, the single bus system includes wind generation, while no PV generation is considered as it is assumed that simulations will be performed for an evening time. It should be mentioned that the diesel generator and the EV fleet are not operating at the same time as the diesel is replaced by the EVs and their individual performance in providing frequency regulation is examined and compared.
5 RESULTS

In this section the scenarios considered along with the respective simulation and validation results are presented and discussed. Initially, the single system is utilized to verify that the diesel generator can be replaced with an EV fleet when providing frequency regulation. Subsequently, the results obtained from the single bus system simulations are validated by performing similar simulations in the complete system model. Furthermore, scenarios relevant to technical regulation for battery power plants are investigated with the use of the complete system model.

5.1 Scenario overview

The scenario investigated in this work includes Bornholm power system operating in islanded configuration along with a 50% EV penetration based on 2040 EV penetration scenario, meaning 8500 EVs present in Bornholm [4]. Some of these EVs are able to provide V2G services and this percentage can be 9% or 740 EVs which are distributed in the four chargers of the model depicted in Figure 3.8. The performance of the EVs in terms of active power is shown in Table 5.1 were it is noticed that the total upward and downward regulation power of the fleet is 4.5 MW, while the total steady state power is 4 MW, positive meaning absorption.
Concerning the generation units, wind is contributing with full power of 37 MW despite the fact that BEOF normally disconnects the majority of wind generation, no PV generation is considered due to evening hour operation as also discussed in 4.3. The two biogas units are generating at 0.8 MW each, block 6 power plant operates at 8 MW and block 5 at 20 MW, while the diesel generator is connected but not generating ready to produce 4.5 MW. In terms of power consumption including the offset power of the EVs given in Table 5.1, it equals the generation at 66 MW. In this realistic configuration during islanded operation [4], primary frequency regulation is provided by block 5 with a reserve capacity of 5 MW over 6 Hz, implying a 12% droop relative to the active power reserve capacity, and 4.5 MW over 1.3 Hz either from the diesel or from the chargers, equal to 2.57 % droop relative to the reserve capacity. This allows for the replacement of the diesel generator with the EVs in order to compare their performance, with a share of EVs contributing to primary frequency regulation equal to 0.47 as in (5.1), where $P_{\text{resEV_total}}$ corresponds to the total active power reserve of the EV fleets and $P_{\text{res_total}}$ the total active power reserve of the power system.

$$\alpha = \frac{P_{\text{resEV_total}}}{P_{\text{res_total}}} = \frac{4.5}{9} = 0.47 \quad (5.1)$$
In terms of simulation, initially the single bus system is utilized to compare the performance of the diesel generator and the EV fleet providing primary frequency regulation. Subsequently the complete system model is utilized with same configuration in order to validate the performance of the single bus system. Additionally, various cases with the EVs realising the frequency regulation functions mentioned in 2.2 are examined utilising the complete grid model and discussions are made. Different time delays as described in Section 3.2 are implemented based on literature [4] and various power factors, as explained in Section 3.1, specifically for the reactive power control are applied. The contingency event resulting in frequency destabilisation is a 2MW wind turbine loss.

5.2 Single bus equivalent system results

Results obtained from the single bus system are given in Figure 5.1, where the configuration with the diesel generator providing part of the reserve capacity, thus a=0, is compared to the case were the EV fleets are providing the same reserve, implying a=0.47, with a time delay of 1 s, 4 s, 7 s, 10 s and a droop of 2.57%. It can be seen that frequency oscillations are not dampened, the higher the delay becomes, leading to instability.
5.2.1 Discussion of single bus system results

As the single bus system in only taking into consideration the generation and consumption units, excluding overhead lines, cables, transformers and substations from affecting the response of the power system. Presence of such elements can lead to faster damping of oscillations, while the steady state frequency is not affected significantly or is unaffected, given the low active power losses of a MV grid. Results obtained from the complete system simulations will be compared to single bus system simulations in Section 5.3.

5.3 Complete system

For the complete system simulations, the following cases are investigated:

- EVs replacing the diesel generator with the same droop of 2.57% as in the single bus system simulation in order to validate the results.
• EVs providing the frequency response service, LFSM as described in Section 2.2.1.1. Seen as whole the rated active power of the aggregated EV model is 8.51 MW (Table 5.1), implying category C battery power plant requirements apply and LFSM provision ability is required [12]. As it is required by most of the plant category, it considered more than the other services in the following simulations.

• EVs providing the frequency control service as, FSM as described in Section 2.2.1.2, not required by regulation by any battery plant but only implemented after agreement with the TSO.

• EVs providing power factor control as described in Section 2.2.2.2, not required by regulation unless agreed with the electricity supply undertaking.

It should also be mentioned the for the complete system implementation the EV charges are spread in four substations over the Bornholm power system. Specifically, each aggregated charger is set at specific a substation as shown in Table 5.2, similar to relevant literature [4].

<table>
<thead>
<tr>
<th>Substation</th>
<th>Charger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hasle</td>
<td>bi315</td>
</tr>
<tr>
<td>Nexø</td>
<td>uni116</td>
</tr>
<tr>
<td>Svanøke</td>
<td>uni316</td>
</tr>
<tr>
<td>Rønne</td>
<td>uni332</td>
</tr>
</tbody>
</table>

Table 5.2 V2G charger locations

5.3.1 EVs replacing the diesel generator

For this simulation the same scenario as for the single bus system in Section 5.2 is implemented. In Figure 5.2 the results are depicted, while the influence of the time delay can be appreciated, since the higher it become the higher the frequency oscillations become increasing to slow damping and increasing slightly for the 10 s delay case.
Results

Moreover, the response of the diesel generator and the aggregated EV chargers is given Figure 5.3. The response of the bi315 charger generating power is noted along with the reduction of power consumption from the unidirectional chargers, after the WT outage. The diesel generator responds as expected increasing its output from an initial zero generation. Another point to be stressed is that total active power difference before and after the contingency is the same as both the diesel and the EVs as total change their active power output by approximately 1.2 MW. The diesel plant output increases while the
EVs decreases, as they are considered generator and load respectively.

![Graph of active power response](image1)

**Figure 5.3** Active power response of the diesel and the EV chargers

Additionally, a standard droop value of 4% is also simulated and the results can be seen in Figure 5.4. It is clear the steady state frequency is lower compared to the case of 2.57% droop, while the oscillations are slowly dampened for the same time delays used previously. This is expected as a higher droop value implies a system less sensitive to frequency deviations.
5.3.2 **EVs providing the frequency response service**

This simulation implements the LFSM function as given in Section 2.2.1.1. The droop function implemented is shown in Figure 2.4 the droop for underfrequency being 5% along with a dead band. Results are shown in Figure 5.5 along the hypothetical response of the diesel responding with the same droop. It can be seen that the diesel response is unstable, while the EVs are able to provide that service successfully for smaller delays while for higher time delays the system registers slowly dampened oscillations.

Figure 5.4 EVs providing frequency regulation with 4% droop
In Figure 5.6 the frequency response the frequency control band of the LFSM service is given, implementing a droop of 0.1%. In this simulation it can be seen that the time delays used are much smaller namely 0.1 s and 0.2 s without resulting in instabilities. When implementing 1s delay the system is oscillating while, for the LFSM-U band of the service was stable for the same delay. The hypothetical response of the diesel can be also appreciated, as it slowly dampens the oscillations.
5.3.3 EVs providing the frequency control service

Figure 5.7 depicts the response of the total of the EVs providing the FSM service, implementing a droop of 0.2%. Similar to Section 5.3.2 concerning the frequency control band, small time delays are used, 0.1 s and 0.2 s, without instabilities, while higher delays result in continuous oscillations. For comparison the theoretical response of the diesel performing the same droop is given.
In this section varying time delays are allocated to a specific share of the EVs providing frequency regulation. While to total amount of EVs providing the service is the same as before \( a = 0.47 \), varying delays are only applied to a specific share of this vehicles. For the rest of the vehicles the time delay is kept constant and equal to 1s. The shares of EVs with varying time delays are \( b = 0.063, 0.23 \) and 0.41 corresponding to the share of the aggregated active power reserves of the uni116 along with uni316, uni316 along with uni332 and uni332 along with bi315 respectively. The definition of \( b \) is given in (5.2) with an overview of the EV shares performance in Table 5.3. It can be seen that for \( b = 0.0063 \), the small single phase and three phase chargers are concerned, which as discussed in Section 3.1 are slow private charges. Simulations for this analysis are executed for the diesel replacement and LSFM service provision cases.
\[ \beta = \frac{P_{resEV_{partial}}}{P_{res_{total}}} \]  

(5.2)

Table 5.3 EV shares performance for time delay allocation simulation

<table>
<thead>
<tr>
<th>( b ) [p.u.]</th>
<th>Corresponding chargers</th>
<th>Corresponding reserve [MW]</th>
<th>EV population share</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.063</td>
<td>uni116, uni316</td>
<td>0.6</td>
<td>46%</td>
</tr>
<tr>
<td>0.23</td>
<td>uni316, uni332</td>
<td>2.2</td>
<td>40%</td>
</tr>
<tr>
<td>0.41</td>
<td>uni332, bi315</td>
<td>3.9</td>
<td>54%</td>
</tr>
</tbody>
</table>

5.3.4.1 Replacing the diesel generator time delay analysis

In Figure 5.8 the delay is only applied to the slow private chargers, while the delay applied to the rest of the chargers is kept to 1 s. Despite the fact they represent 46% of the EV population providing frequency regulation, their effect in the system frequency response is minimal, due to low active power reserve share. In Figure 5.11 and Figure 5.12 the same trend follows, meaning that the higher the power reserve of the EV share the delay is applied to, the higher the influences it has over the frequency response. For \( b=0.41 \) the results are closer to those presented in Figure 5.2.
Figure 5.8 Various delays applied only to 6.3% of the EV reserves (diesel case)

Figure 5.9 Various delays applied only to 23% of the EV reserves (diesel case)
5.3.4.2 Frequency response provision time delay analysis

In Figure 5.11 the delay is only applied to the slow private chargers, while the delay applied to the rest of the chargers is kept to 1 s. Again, their effect in the system frequency response is minimal, due to low active power reserve share. In Figure 5.12 and the same trend follows, meaning that the higher the power reserve of the EV share the delay is applied to, the higher the influences it has over the frequency response, resembling Figure 5.5.
Figure 5.11 Various delays applied only to 6.3% of the EV reserves (LFSM case)

Figure 5.12 Various delays applied only to 41% of the EV reserves (LFSM case)
\textbf{5.4 Power factor control provision}

Power factor control can be provided only when active power is provided to the grid, implying that only the bi315 charger can perform this type of control. In Figure 5.13 the performance of the bi315 aggregated charger is depicted, with effects being minimal. It is noted the steady state frequency is slightly slower for the same droop applied, meaning that the load has increased. Indeed, the load is voltage dependent and as the EVs provided reactive power to the grid the voltage increases along with load.

![LFSM 1 s delay - bi315](image)

In Figure 5.14 the substation is shown when power factor control is provided by all EVs and it can be seen that it is lower when the reactive power is absorbed by the EVs. This implies that the active power load will be lower as a result of the linear voltage dependency on the voltage.
In order to investigate the effects of the load dependencies on voltage, power factor control is implemented when all EVs are providing LFSM service with the load being both voltage dependent and independent on voltage in terms of active power. The results are shown in Figure 5.15 and Figure 5.16 where it can be seen the voltage dependencies can lead to a higher steady state frequency when reactive power is absorbed by the chargers and the opposite it is a provided. Contrary to that, a load that is voltage independent in terms of active power leads to lower steady state frequency as the voltage drop has no effect on the active power absorbed by the load. It can also be seen that when the system frequency dampens slowly, load dependencies are registering minimal effects.

Figure 5.14 Substation voltage for power control provision by all EVs
Results

Figure 5.15 Load voltage dependency effects

Figure 5.16 Power factor sensitivity analysis
5.4.1 Discussion of complete system results

To begin with, the results obtained from the single bus system are comparable with the results obtained from the complete system and from the literature [4] when the replacement of the diesel generator is concerned. The effects of the overhead lines and transformers in the complete power system are noted as they are able to dampen the frequency’s oscillations faster for the same delay.

Concerning the frequency response service LFSM, it is of great importance to take into account that two droops are implemented for providing it and as shown much faster response time, in the order of tenths of seconds, is required for the LFSM frequency control band before system becomes unstable. Contrary to that, in LFSM-U band, higher delays will cause slow dampened low amplitude oscillations. These aspects are to be considered when this control function is designed for a battery plant.

The FSM service provision requires very fast responses in the order of tenths of seconds, because of the sensitive droop setting requirements.

When it comes to reactive power control, it could only be provided by the bidirectional chargers when they are providing active power to the grid. A very important factor to take into account is the load voltage dependencies, as they can be beneficial in the case of reactive power absorption by the EVs. Nonetheless, power factor control is not allowed to be performed from all types of chargers according to the regulation, unless a category D power plant is considered, which can operate in all four quadrants of active vs reactive power diagram.
6
CONCLUSIONS AND FUTURE WORK

To conclude, the goals of this work have been achieved, as is was proven that a heterogenous EV fleet can provide frequency regulation services both in terms of replacing existing CGUs offering identical services and in terms of regulatory compliance when requirements relevant to the droop function and the response time of the V2G chargers are considered. Much attention should be given to the response time between measurement and activation of the set point at the charger as it can lead to slowly dampened oscillations before reaching a state-state condition in terms of frequency or even worse to instability of the power system with growing oscillations of the frequency. For each frequency service provision, different delays can lead to instability. In fact, this aspect could be also further investigated and incorporated into the battery plant technical requirements.

In terms of reactive power and voltage regulation the technical requirements are preventing unidirectional chargers from providing any type of reactive regulation unless they are aggregated into a category D power plant. As the load dependency on voltage and thus to reactive power can be in some cases beneficial for the power system’s frequency stability, it is suggested that relevant requirements can be also implemented for smaller power plants, so that they are able to absorb reactive power after TSO’s or DSO’s request.

Moreover, since the assumption was made that all single-phase chargers are equally distributed into the three phases, this aspect could be also investigated. Specifically, unbalanced operation can be studied by assigning incrementally higher share of single-phase chargers to one of the three phases. Additionally, larger shares of EVs and delays can be examined in future works, as in this study only one CGU was replaced by EV fleets.
Conclusions and future work

Finally, the share of renewables taken into account is higher than 50% of the total generation, implementing Type A and Type C wind turbines. PV generation was not considered, while the inertia of Type A WT contributes to the frequency response of the system. Thus it is worth investigating various WT Type shares and PVs in future works.

Due to lack of time, the questions raised in this chapter were not able to be investigated during for this thesis and can be research questions answered within relevant future works.
REFERENCES


A
POWER FACTORY FILES

The PowerFactory files used are listed below:

- Bornholm SingleBus.pfd
  - Implements the single bus equivalent system
- Bornholm_Complete Diesel Rep 2.57-4%.pfd
  - Implements the diesel replacement simulations
- Bornholm_Complete Diesel Rep_VarDelay.pfd
  - Implements the various delays for various EV shares for the diesel replacement case
- Bornholm_Complete LFSM-UO.pfd
  - Implements the LFSM-UO band simulations
- Bornholm_Complete LFSM-FC.pfd
  - Implements the frequency control band of the FSM
- Bornholm_Complete LFSM-UO_VarDelay.pfd
  - Implements the various delays for various EV shares for LFSM case
- Bornholm_Complete FSM.pfd
  - Implements the frequency control function FSM
- Bornholm_Complete LFSM-UO_PFctrl.pfd
  - Implements the power factor control during the LFSM service provision