Jared Balavender, s125114

Ancillary services analysis and provision by Electric Vehicles in a Danish distribution grid

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This thesis was completed in the Electrical Engineering Department at the Technical University of Denmark (DTU) in partial fulfillment for acquiring a Master of Science in Engineering, MSc (Eng.) degree in Electrical Engineering, with a specialization in the Electric Energy Systems study line. This thesis was completed with collaboration from the Nikola Research Project.

Acknowledgement

The author wishes to express his sincere gratitude to his thesis supervisors for their dedicated and thorough supervision throughout this thesis.
ABSTRACT

The Danish power system is undergoing significant changes. Among these is the changing landscape of the power supply. As conventional fossil fuel based power plants are phased out of the system and decommissioned, the grid services they provided in order to ensure the proper security and stability of the power system also go offline. As such, Denmark is revisiting and updating its ancillary services (AS) strategy and associated markets in order to procure these same or analogous services through the increasing amounts of distributed energy resources (DERs) that are being integrated into the Danish power grid. Chief among these DERs are electric vehicles (EVs).

The electrification of transport in Denmark will impact the operation of distribution grid networks. If the status quo is left as is, and EVs continue become more commonplace in Danish society, their high power consumption could introduce challenges to low voltage networks. This is particularly so in unbalanced distribution grids. However, the intelligent integration of EVs has the potential to remediate these potential power quality problems that EVs could otherwise introduce.

This thesis addresses these considerations in a twofold manner. First, this thesis provides a succinct summary on the current state of AS in the Danish context, as well as an indication of how AS are developing in Denmark. Secondly, the thesis simulates how the impact that large scale EV integration would have on a model of a specific Danish low voltage distribution grid. The modelling analysis focuses on three considerations; the most stressed cable in the analyzed system and two power quality aspects – the system’s voltage profile and level of voltage unbalance. These results are completed in a progressive manner via a set of cases. In the first case the impact uncontrolled integration of EVs was quantified in the modelled system. After which three different droop controllers were tested in the simulated network and the aforementioned power system considerations are quantified on a per case basis. Additionally, a basic economic analysis is conducted determining a potentially appropriate level of compensation that could be provided for EV owners to allow their vehicle’s charging behavior to be modified through the analyzed methodologies in order to improve local voltage quality. The simulated results quantify the system benefits that could be potentially obtained if the implemented intelligent EV charging approach was implemented in an unbalanced distribution grid.

From the evaluation of the implemented control methodologies in the simulated low voltage grid, this thesis concludes that the implemented droop control strategies are able to fully reduce congestion issues along the critical cable in the system and partially remedy the additional low voltage deviations uncoordinated EV charging would otherwise introduce to the system.
1 INTRODUCTION

1.1 Background

Since humans learned how to create and harness fire, humanity has burned carbon-based fuels to extract utility from their consumption. The rate which humanity began releasing greenhouse gases (GHG) vastly accelerated during the first and second industrial revolutions. In the first industrial revolution, the invention of the Boulton and Watt steam engine, and specifically through the reliance of coal as its primary fuel source, led to tremendous increase in the release of GHG. This was further accelerated in the second industrial revolution by the advent of the internal combustion engine and the accelerated adoption of petroleum as a fuel source.

While the two industrial revolutions were unequivocally tremendously beneficial to humanity, they were not without negative consequences that persist to the present day. The primary global consequence of creating modern society dependent upon the consumption of fossil fuels (FF) is that in their consumption, vast quantities of GHG are released into Earth’s atmosphere. This is leading to long-lasting changes in all components of the planet’s climate system [1]. If, and more appropriately when (based on current emission rates and most emission scenarios) the rate of climate change exceeds the ability of populations to adapt to the changes, there will be unparalleled consequences to the quality of human life around the planet. Increased resource scarcity, the decrease in arable land, sea level rise and increasing ocean acidification are but a small subset of the tremendously adverse effects that await humanity if the global community fails to significantly reduce GHG emissions [1, 2].

It is with these considerations that scalable alternatives to FF dependent products must be designed, created and deployed as fast as possible. There is no one-size fits all solution to a problem of this size, scope and complexity. Therefore, multiple viable solutions must be investigated and implemented simultaneously. Chiefly among humanity’s solutions to the extremely severe threat posed by ACC is the rapid, widespread deployment of renewable energy systems to transition the global community away from FF energy sources.

While this transition of the energy system is essential to mitigate against the threats posed by the impacts of ACC, it is not without its own significant challenges. There has been tremendous development throughout the 21st century in the increased rates of deployment of renewable energy based resources. As the primary renewable energy resources (RES) today, i.e. wind and solar power, are intermittent, the integration of

---

[1] Primarily coal, petroleum and natural gas
large amounts of these energy resources into a power system creates a new set of additional challenges. These challenges are connected to the challenge of transforming the transportation sector away from its dependency on petroleum. Electrification of transportation is currently the most prominent viable alternative to supplant transportation by vehicles with internal combustion engines. As a greater volume of Electric Vehicles (EVs) become present in society, the intelligent integration of EVs offers a progressively more flexible and potentially helpful tool to accelerate the integration of higher amounts of RES as well as provide critical grid services to ensure sufficient security and reliability of supply of the power system.

The overarching aim of this thesis is to provide a succinct characterization of the current Ancillary Services (AS) framework in the Danish power system and to model how one ancillary service can be provided by currently commercially available EVs.
1.2 The Nikola Research Project

This work has been completed in collaboration with the Nikola Research Project. The Nikola Research Project is led by Peter Bach Andersen at DTU, and is conducted in partnership with the Danish distribution grid operator SEAS-NVE, NUVVE, an electric vehicle vehicle-to-grid (V2G) aggregation service provider [3] and EURISCO, a Danish independent software development company [4]. The Nikola Research Project is an intelligent EV integration research and demonstration project that focuses on the synergies between EVs and the power system [5]. Nikola is divided into four main focus areas, denoted with their main topics and assets in Figure 1.

<table>
<thead>
<tr>
<th>Focus Areas</th>
<th>Topics</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>System-wide</td>
<td>Market Integration, Renewable</td>
<td>PowerLabDK, Bornholm Power System</td>
</tr>
<tr>
<td>Distribution Grid</td>
<td>Grid Services, Local DER Mix</td>
<td>Field Tests and Demonstrations, EURISCO, Electric Lab, SmartGrid, Test-</td>
</tr>
<tr>
<td>EV User</td>
<td>Usage Patterns, Added Value Service</td>
<td>an-EV, EV Users Driving Data, PowerLabDK, PowerLabDK, SYSLAB, EV Fleet</td>
</tr>
<tr>
<td>Technology</td>
<td>Enabling technologies and standardization</td>
<td>EURISCO, SmartGrid, PowerLabDK, SYSLAB, EV Fleet</td>
</tr>
</tbody>
</table>

Figure 1: Overview of the Nikola Research Project [6].

The Nikola Research Project focuses its analysis on the various services EVs can provide to the power system. Nikola defines a service as [6]:

“The act of influencing the timing, rate and direction of the power and energy exchanged between the EV battery and the grid to yield benefits for user, system and society.”

A full list of the services classified and analyzed in the Nikola Research Project is shown in Figure 2. This thesis work is conducted under work package (WP) 2 in Nikola. In WP2, Distribution Grid Services, Nikola investigates the integration of EVs in distribution grids as part of the operational and strategical targets of the distribution system operator (DSO) [7].
## Definition

<table>
<thead>
<tr>
<th>Type</th>
<th>Groups</th>
<th>Name</th>
<th>Short description</th>
<th>Power &amp; energy behavior</th>
<th>Stakeholders &amp; potential benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power and energy services</td>
<td>System-wide services</td>
<td>Frequency regulation</td>
<td>Keeps the frequency in an interval around 50 Hz</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Market earnings TSO: Larger, more competitive market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frequency regulation - very fast</td>
<td>Frequency regulation with ramping times and precision that go beyond what traditional generators can provide</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Market earnings TSO: New/Improved service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary regulation</td>
<td>Replaces frequency regulation and restores the frequency to 50 Hz</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Market earnings TSO: Larger, more competitive market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tertiary regulation</td>
<td>Replaces secondary regulation and fulfills a higher requirement to energy capacity and delivery timescale</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Market earnings TSO: Larger, more competitive market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Synthetic inertia</td>
<td>Mimics rotational inertia by taking advantage of the fast chemical reaction of batteries</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Market earnings TSO: New/Improved service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adaptive charging</td>
<td>Delays or advances charging in time based on e.g. energy costs or renewable contents</td>
<td>Adaptive*</td>
<td>Aggregator/EV Owner: Energy cost or CO2 savings</td>
</tr>
<tr>
<td>Distribution grid services</td>
<td></td>
<td>MORE – Mother of all regulation</td>
<td>Includes all the abovementioned traditional types of regulation in one – assuming a large fleet of EVs.</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Market earnings TSO: New/Improved service + Larger, more competitive market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inalned micro grid and black start</td>
<td>Enables one or a set of EVs to sustain a small power system</td>
<td>Energy backup**</td>
<td>EV owner: Security of supply</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV network balancing</td>
<td>Mitigates unbalances between phases of LV network</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Unknown DSO: New service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV overvoltage management</td>
<td>Mitigates overvoltage of LV feeders</td>
<td>Balancing***</td>
<td>Aggregator/EV Owner: Unknown DSO: New service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MV-LV transformer and lines overloading</td>
<td>Mitigates overloading of transformers and cables of LV network</td>
<td>Adaptive*</td>
<td>Aggregator/EV Owner: Unknown DSO: New service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV congestion due to fast charging stations</td>
<td>Manages LV fast charging to keep within operational limits of LV network</td>
<td>Adaptive*</td>
<td>Aggregator/EV Owner: Unknown DSO: New service</td>
</tr>
<tr>
<td>ICT Services</td>
<td>User added services</td>
<td>Charging management</td>
<td>Simplifies EV service participation for the EV owner by using historical data</td>
<td>Aggregator/EV Owner: Added simplicity for service participation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charging flexibility assessment</td>
<td>Estimates whether sufficient charging flexibility exists in order to participate in services.</td>
<td>Aggregator/EV Owner: Knowledge on charging flexibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charging information</td>
<td>Presents to the EV user the information that is most relevant when controlling (dis)charging of the EV</td>
<td>NA</td>
<td>Aggregator/EV Owner: Improved information service</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vehicle –to-X</td>
<td>Enables the EV to supply electric energy to the EV user in places where access to the general electric grid is impossible or impractical</td>
<td>NA</td>
<td>EV Owner: New electric energy services</td>
</tr>
</tbody>
</table>

**Figure 2:** Overview of the Nikola Research Project's Services description [6].
1.3 Thesis Objective

The objective of this thesis project is twofold. The first objective is to conduct a succinct technical overview of ancillary services in Denmark. This overview provides the foundation for the second portion of this thesis, which is to implement a simple, autonomous droop control strategy into a simulation of a Danish distribution grid with a high penetration of EVs and quantify the impact this control strategy has on local bus voltages, the voltage balance in the analyzed system, and how the control strategies impact the level of stress of the heaviest loaded cable in the analyzed system.

To achieve these objectives this thesis project includes the following main tasks:

- Complete a technical review and characterization of the current set of ancillary services in the Danish power system.
- Incorporate the experimentally tested droop control strategy into a power system model of a real Danish low voltage (LV) grid.
- Conduct a week long root mean square (RMS) simulation of the modelled system and extract the pertinent results.
- Analyze and report the results of the established cases.
- Discuss and evaluate the implications of the modelled control strategy.

1.4 Methodology

The main methods used to complete the two main objectives are briefly described in this section.

To facilitate a technical overview of ancillary services in Denmark the relevant Danish literature and policies were researched and summarized.

In order to analyze the control strategy implemented in the experimental test, five cases were modelled in PowerFactory, the chosen power system simulation environment. The Borup grid under consideration had been subsequently developed through past research completed under the Nikola research project and this model was modified to suit the research aims of this thesis project. A further elaboration on the chosen simulation environment is subsequently provided.

1.4.1 The simulation environment: DIGSILENT PowerFactory

System modelling for stability analysis is one of the most critical issues in the field of power system analysis [8]. One aspect of the complexity involved is that depending on the accuracy of the implemented model, the various system parameters implemented and tests or applied fault situations conducted, nearly any result could be produced and a subsequent explanation could be found to justify these results.

The power system modelling software Digitial Simulation and Electrical Network calculation program (DigSILENT) is a windows-based integrated power systems modelling and analysis software package. PowerFactory uses a strictly hierarchical
system modelling approach, using a combination of graphical and script-based modelling methods [8]. There are four main categories of modelling components in PowerFactory. They are:

1. The *composite frame* (*.BlkDef), which is a block diagram which defines the connections between the inputs and outputs of various models.

2. The *composite model* (*.ElmComp), which is an element built based upon a composite frame. The *composite model* has three structural levels. They are the:
   - Top level: the composite frame, which determines the structure of the model such as the connections of individual functional blocks (common models).
   - Mid-level: built-in models, elements, common models or even another composite model.
   - Bottom level: DIgSilent Simulation Language (DSL) block definition to represent the transfer function(s) or differential equations for e.g. transient models.

3. The *block definition* (*.BlkDef), which is a representation of a transfer function, which produces an output signal(s) as a function of an input signal(s). This is where the unit/controller type is defined.

4. The *common model* (*.ElmDsl), which is an element built based on a block definition.

PowerFactory was created by DIgSILENT GmbH, a leading supplier in power system analysis software. PowerFactory is widely used among industry and academia. For more information about PowerFactory the reader is referred to [8].
1.5 Scope and limitations

To meet the thesis objectives described above, several assumptions and limitations were imposed.

The term “ancillary services” can be characterized as an umbrella term used to describe the various grid services used to ensure the proper operation of the power system. While the specific definition of ancillary services varies among different operating regions [9-12], the key underlying concept is that ancillary services encompasses the additional services beyond generation and transmission that are necessary to ensure that the electric power system can continue to supply the continuous flow of electricity while meeting all system operating requirements. In this thesis, the definitions and categorizations of ancillary services will be based on those definitions providing by the Danish Transmission Service Operator (TSO), Energinet.dk for the Eastern Denmark balancing region (DK2). Definitions outside this scope are not integrated into this report.

For the modelling component of the thesis, the scope was limited based on numerous parameters based on the following criteria. The author’s decision to assist the Nikola research group, and assist in furthering their research aims’ was the main motivating factor for the latter portion of thesis work. As such, the implemented decentralized, autonomous droop control strategy in the modelled network was selected to be the same as the real-world experimental work concurrently conducted at DTU Risø, in order to model and receive information about the implications of such a control strategy being scaled up from a single test case with a set of 3 EVs, to a model of a real Danish distribution grid. As such this work was limited to this control strategy. Additionally, the base model of the distribution grid as well as the associated load datasets for the modelled grid under consideration were provided by the Nikola research group from [13] and by their industrial partner SEAS-NVE, respectively, further narrowing the scope. This maintained consistency in comparing the obtained modelling results and enabled the author to prioritize focusing on the research tasks aforementioned in the thesis objective. For reporting of the results of the modelling work, the scope was narrowed to the most important line in the system, as well as the voltage quality and level of voltage unbalance in the detailed portion of the analyzed grid.

Furthermore, an emphasis was placed on currently commercially available technology, and as such concepts that currently require aftermarket modifications, such as modelling V2G, were not incorporated into the modelling component of this thesis.
1.6 Thesis Outline

Chapter 2 provides the overarching literature review associated with the main concepts in this thesis project. In it, ancillary services are defined in general as well as in a Danish context, the conditions required to provide ancillary services in Denmark are outlined, and a look into the potential future development of ancillary services in Denmark is previewed.

Chapter 3 sets the stage for the modelling work conducted in this thesis project. It starts with a brief overview of the associated experimental work that was completed during the same time period as the thesis project. This overview is followed by a description of the modelled distribution grid, the grid topology and a description of the main modelled components.

Chapter 4 describes and explains the main power system theory associated with the modelling work completed in this thesis. It provides a succinct description of the main power quality considerations that were focused on in the modelling component of this thesis project, as well as provides a description of the droop control implemented in the distribution grid model.

Chapter 5 contains the results of the modelled work completed for this thesis project.

Chapter 6 takes one of the main findings from the results of the simulation analysis and creates a simple economic analysis to determine a reasonable compensation level that could be provided to incentivize the integration of the control mechanism modelled in this thesis.

Chapter 7 summarizes the key findings of this thesis work, and outlines potential future work that could be considered.
ANCILLARY SERVICES

This chapter contains an overview of the key technology concepts in this thesis project. The literature review starts with ancillary services, and then moves to the distributed energy resources focused upon in this work.

The term ancillary services (AS) represents the set of services needed to ensure a reliable and stable power system. The need for various AS is dynamic throughout the year. The definition of AS, and what services are included in AS, varies from grid to grid. For example, the US Federal Energy Regulatory Commission (FERC) defines AS as [9]:

*Those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system. Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services.*

Whereas the European network of transmission system operators for electricity (ENTSO-E) defines AS in the following manner [14]:

*Ancillary services are Interconnected Operations Services identified as necessary to effect a transfer of electricity between purchasing and selling entities (transmission) and which a provider of transmission services must include in an open access transmission tariff.*

While the US National Renewable Energy Laboratory (NREL) defines AS as [15]:

*Services that help grid operators maintain balance on electric power systems. These include regulation and the contingency reserves: spinning, non-spinning, and, in some regions, supplemental operating.*

In general terms, AS encompass the necessary grid services to ensure the proper stability and security of supply in the power system.


2.1 Ancillary Services in Denmark

Energinet is the Danish transmission service operator (TSO). Energinet is a non-profit enterprise owned by the Danish Ministry of Energy, Utilities and Climate (Energi-, forsynings- og klimaministeriet, 2016) and is funded through a consumption tax on electricity and gas bills in Denmark [16]. Energinet is responsible for purchasing the correct amounts of ancillary services at all times in Denmark. Additionally, Energinet is a member company of ENTSO-E, and as such, defers to the defining of ancillary services to the ENTSOE-E Operation Handbook – Policy 1 [14].

The Danish electric power system is divided into two synchronous regions, also referred to as balance areas in the technical literature. The two balance areas are Western Denmark (‘DK1’) and Eastern Denmark (‘DK2’). DK1 is synchronized with the continental European grid whereas DK2 is synchronized with the interconnected Nordic synchronous system. There is a 400 kV, 600 MW Line Commutated Converter (LLC) HVDC interconnection between the islands of Funen (Fyn) and Zealand (Sjælland) called the Great Belt Power Link (Storebælt HVDC) that connects the two synchronous regions [17].

The specific definition of, and the set of services that encompass the term ancillary services in Denmark differs in DK1 and DK2. Ancillary services are defined according to the ENTSO-E Continental Europe (CE) Operation Handbook, the Nordic System Operation Agreement for DK1 and by Energinet.dk's regulations for grid connection for DK2, respectively [10].

Generally, in DK1 the following AS are purchased by Energinet [11]:

- Primary reserves
- secondary reserves, LFC
- Black-start capacity
- manual reserves
- Short-circuit power, reactive reserves and voltage control.

Generally, in DK2 the following AS are purchased by Energinet [11]:

- Frequency-controlled normal operation reserve (FNR)
- Frequency-controlled disturbance reserve (FDR)
- manual reserves
- Short-circuit power, reactive reserves and voltage control.

Both FNR and FDR are purchased in collaboration with Svenska Kraftnät, the Swedish TSO that is responsible for the part of the Swedish grid that is in the same synchronous region as DK2. Bids for all reserves in both DK1 and DK2 are for both upward and downward regulation reserves, except for frequency-controlled disturbance reserves, which are only upward regulation reserves.

On the Danish version of Energinet.dk’s Ancillary Services (Systemydelser in Danish) webpage, the Table 1 and Table 2 are provided. Combined, these two tables provide a succinct overview of the frequency based AS in Denmark, and for the purpose of this thesis, are particularly useful for understanding the specific technical description of
FNR and FDR for DK2 (Østdanmark, i.e. Eastern Denmark in the following two tables) subsequently conducted in this thesis.

**Table 1: Overview of reserve types in Denmark [18]**

<table>
<thead>
<tr>
<th>Funktion</th>
<th>ENTSO-E</th>
<th>Vestdanmark</th>
<th>Østdanmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frekvensstabilisering (Primær reserve)</td>
<td>Frequency Containment Reserves (FCR)</td>
<td>Primær reserve</td>
<td>Frekvensstyre (FNR) normal driftsreserve</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>Restoration</td>
<td>Reserves (FRR-A)</td>
</tr>
<tr>
<td>Balanceudligning (tertiair reserve)</td>
<td>Frequency</td>
<td>Restoration</td>
<td>Reserves (FRR-M)</td>
</tr>
<tr>
<td></td>
<td>Replacement</td>
<td>-</td>
<td>-</td>
</tr>
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</table>

**Table 2: Purchase of reserve capacity [18]**

<table>
<thead>
<tr>
<th>Funktion</th>
<th>Vestdanmark</th>
<th>Østdanmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNR</td>
<td></td>
<td></td>
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<tr>
<td>Frekvensstabilisering (Primær reserve)</td>
<td>Primær reserve</td>
<td>230 MW</td>
</tr>
<tr>
<td>Frekvensgenopretning (Sekundær reserve)</td>
<td>LFC</td>
<td>-</td>
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<tr>
<td>Balanceudligning (tertiair reserve)</td>
<td>Manuel reserve</td>
<td>Manuel reserve</td>
</tr>
<tr>
<td>+ 268 MW</td>
<td>+ 600 MW</td>
<td></td>
</tr>
</tbody>
</table>

1 Mængden kan variere årligt.

2 Yderligere 75 MW på Kontiskan, 50 MW på KONTEK og 18 MW på Storebælt

The two notes in the second table state that (1) the amount may vary annually and (2) an additional 75 MW are acquired from Kontiskan (a 285 kV HVDC interconnection between Jutland and Sweden), 50 MW on KONTEK (a 400 kV HVDC interconnection between Germany and Zealand) and 18 MW on the previously described “Great Belt”.

11
Ancillary Services

Elsewhere on Energinet.dk’s website, FNR and FDR are referred to as FCR-N and FCR-D [19], acronyms standing for frequency containment reserves – normal and frequency containment reserves – disturbance, respectively. Additionally, manual reserve is also denoted as both mFRR and FRR-M [20], both acronyms standing for frequency restoration reserve - manual. However, for the remainder of this thesis, the terms defined in [11] will be used.

As mentioned in section 1.5, DK2 constitutes the system in focus, and as such a detailed description of DK1 is outside the scope of this thesis. For a detailed description of ancillary services in DK1, the reader is referred to [11].

2.1.1 Ancillary Services in DK2

The following sub-sections detail the AS procured in DK2. The information provided in the following subsections on the specific AS in DK2 is taken solely from Energinet.dk’s current Danish ancillary services tender conditions regulation [11].

2.1.2 Frequency-controlled normal operation reserve (FNR)

The role of frequency-controlled normal operation reserve (FNR) is to compensate for minor frequency deviations between the equilibrium of electricity production and consumption, and restore the system frequency to its nominal frequency. FNR is the automatic regulation provided by production or consumption units which, by means of control equipment, responds to grid frequency deviations. It is purchased as a symmetrical product, meaning that the supplier is required to provide both upwards regulating power (during times the frequency is below its nominal level) and downward regulating power (during times where the frequency is above its nominal level).

ENTSO-E sets the need for FNR for the entire Nordic synchronous area. The Nordic synchronous area TSOs are jointly responsible for supplying FNR. The FNR requirement amount is updated annually in March and the update becomes effective in April. In 2015 the requirement was 600 MW for the entire Nordic synchronous area, of which Energinet was responsible to supply 23 MW to DK2. Energinet.dk purchases these reserves in a joint market with the Swedish TSO, Svenska Kraftnät, in the region SE4, through daily auctions. In contrast to DK2’s requirement of 23 MW, Svenska Kraftnät’s SE4 requirement was 230 MW.

The activated reserve must be supplied at a frequency deviation of up to ±0.1 Hz of the reference (nominal) frequency (i.e. 50 Hz). Deliveries must be made without a dead band, and must be supplied linearly at frequency deviations of between 0 and 0.1 Hz. Furthermore, the activated reserve must be supplied in 150 seconds, regardless of the size of the deviation and must be able to maintain the regulation constantly. The accuracy and sensitivity of frequency measurements must be better than ±0.01 Hz. The resolution supplier’s SCADA system must be faster than 1 second, and the signals must be stored for at least 1 week.

Each individual production or consumption unit supplying FNR must be connected through IT equipment to Energinet.dk’s Control Center in Erritsø. Online access to the following requirements must be provided to Energinet.dk’s Control Center:

- The status of the production/consumption unit, i.e. the circuit-breaker indication
Ancillary Services

- The ability to dis/connect the regulation function of the FNR
- The ability to provide upward regulation on the FNR unit
- The ability to provide downward regulation on the FNR unit
- Measurement data from the production or consumption unit, as well as the net production/consumption at the point of connection in MW

The provider of the FNR may combine the delivery of several production/consumption units with different technical properties. If the provider chooses to do this, the collective supplies must be able to meet the required response in the required response time. If the FNR provider is a balance responsible party (BRP) for both consumption and production (explained subsequently in section 2.2.1) and has balance responsibility for both consumption and production, they may make a delivery of both supplies from their consumption and production units simultaneously.

As previously mentioned, FNR is procured daily in collaboration with Svenska Kraftnät. It is done so in a two tiered approach where a portion of the reserve requirement is purchased two days before the day of operation (D-2) while the remainder is purchased the day before operation (D-1). Suppliers may submit bids in hourly bids or as block bids. For the D-2 auction, the supplier can submit block bids of up to six hours in duration, whereas in the D-1 auction the block bids can only be a maximum of three hours. The supplier picks which hour the block bid starts, but the block bid must end within the day of operation. All bids in connection with daily capacity auctions are submitted by market players to Energinet.dk through Ediel, which is the data communication standard used by players on the electricity market and Energinet.dk. D-2 bids may be changed until 15:00 two days before operation. D-1 bids may be changed until 19:00 the day before operation. After these two times the bids are binding on the bidder. Energinet.dk will then inform the player if their bid has been accepted or not at 16:00 two days before operation for the D-2 bids, and at 21:00 the day before the day of operation for D-1 bids. Upon notification, the player will also be told the average availability payment allocated to their bid on an hourly basis, corresponding to the price offered by the player (pay-as-bid).

Bids must state an hour-by-hour volume and a price for the day of operation. The volume must be the same for each hour if the supplier is making a block bid and the offer is made in number of MWs available. The price of the bid is stated in price per MW per hour. Minimum bids are 0.3 MW and must be stated in volumes of one decimal point, in whole DKK/MW or EUR/MW to two decimal points. Bids in DKK/MW are converted to EUR/MW before being forwarded to Svenska Kraftnät, using the latest official exchange rate from Nord Pool. Bids are sorted by price per MW and selected in an increasing manner such that the TSOs incur the minimal cost. Bids are accepted in their entirety or not at all. For equivalent bids where the TSO only needs a subset, the TSO is free to choose which bid to accept. If not enough bids are received, Energinet will send an email to all market players requesting more bids. Bids for upward and downward regulation are settled independently.

Energinet does not send signals for FNR to be activated during the day of operation. Rather, the FNR is activated based on the supplier’s own frequency measurements.
2.1.3 Frequency-controlled disturbance reserve (FDR)

*Frequency-controlled disturbance reserve* (FDR) must compensate for any sudden major loss of production. It is a fast reserve used for regulating the frequency following e.g. the outage of a major generation plant(s) or line(s) that causes a substantial drop in frequency. FDR is an automatic upward regulation reserve that is activated in the event that the frequency drops to under 49.9 Hz and remains active until balance has been restored or until sufficient manual reserves have been activated to replace it.

Like FNR, the volume of FDR required to be purchased by Energinet.dk is proportional to the size of DK relative to SE4 for Svenska Kraftnät. Energinet.dk’s share of FDR is determined by the largest dimensioning fault in DK2 and is fixed each Thursday for the upcoming week. Energinet.dk’s total share is approximately 150-180 MW, whereas Svenska Kraftnät’s share is approximately 410 MW. Some of the FDR is supplied from HVDC connections between Germany and Zealand, Jutland and Zealand and Jutland and Sweden. As such Energinet.dk’s actual required purchases often are reduced to the range between 25 and 55 MW.

The specific technical requirements for FDR are that it must be able to:

- Supply inverse-linear power at frequencies between 49.9 and 49.5 Hz
- Supply 50% of the response within 5 seconds
- Supply the remaining 50% of the response within the following 25 seconds.

The required accuracy of the measurements and the option to provide combined deliveries from several production units is the same for FDR as FNR. The data sharing procedure with Energinet.dk’s Control Centre is also identical to FNR, with the sole exception that as FDR is for upward regulation only, there is no rule in relation to downward regulation. The bidding procedure and the entire manner in which Energinet.dk and Svenska Kraftnät handles bids for FDR is identical to FNR.

2.1.4 Manual reserve

Energinet buys two types of manual reserves in DK1 and DK2, upward regulation power and downward regulation power. These two types are purchased on

Manual reserve is a manual upward and downward regulation reserve activated by Energinet’s Control Centre in Erritsø through the regulating power market. The role of the manual reserve is to relieve FNR and FDR and restore system balance.

The manual reserve must be fully supplied within 15 minutes of activation. These reserves are procured through daily auctions and are requested independently in DK1 and DK2 to meet demand on an hourly basis.

Each individual production or consumption unit providing manual reserve must be connected to Energinet.dk’s Control Center and provide access to the following parameters:

- Status reports on the in/out status of the production or consumption unit
- Measurements of the net production or consumption at the point of connection
- Measurements of the net production by BRPs.
Combined deliveries for manual reserves may not be made up of supplies from a mix of consumption and production units. This is a noticeable difference from FNR.

Bids in the manual reserve auctions must be made by 9:30 on the day before the day of operation. They can be amended up until this point, but after 9:30 become binding. The bids must state an hour-by-hour volume and a price for the following day of operation. Volume is stated the number of MWs. This represents the amount the bidder is offering to make available during the hour being bid upon. The minimum bid is 10 MW and the maximum bid is 50 MW. The currency regulations and procedure for making a bid is the same as bids in the FNR and FDR auctions. Energinet.dk notifies the players of the bids which have been accepted at 10:00 on the day before the day of operation and informs them of the availability payment allocated on an hourly basis.

In the event that the Great Belt Power Link is fully loaded from DK2 to DK1, Energinet.dk may require more manual reserves in DK1 than the ones purchased in the morning. During this situation, Energinet.dk will host an afternoon auction. The procedure for the afternoon auction is that all players are notified of the need for additional manual reserves by 14:30. An email is sent out to all players stating the requirement. The players then have until 15:00 to submit their bids. Energinet.dk thereby completed the auction and notified players of the results by 15:30 at the latest.

Bids in the manual reserve auction are accepted in their entirety or not at all. In the situation where accepting a bid greater than 25 MW would lead to excess fulfillment of the reserve requirement during a specific hour, Energinet.dk can disregard these bids. As in the case for FNR and FDR bids, Energinet.dk can freely choose between two or more of the exact same bid, and can request additional bids via an email to all players if the received number of bids is insufficient to cover the requirements. Both upward regulation and downward regulation accepted bids receive an availability payment corresponding to the price of the highest bid for upward/downward regulation accepted.

2.1.5 Short-circuit power, reactive power and voltage control

Short-circuit power, reactive reserves and voltage control are services that ensure that the power system is operated in a stable and safe manner. Currently, short-circuit power and reactive reserves are only supplied by the central power stations to Energinet.dk in Denmark, as they are connected to the main HV grid. Separate payment is not offered for the supplied short-circuit power and reactive power.

Energinet.dk, on a daily basis, just after the first operational schedules have been received “towards the end of the afternoon”, checks the load flow, short-circuit power, n-1 situations and reactive reserves for the power grid. If changes occur during the day of operation, another check of these four parameters must be completed.

Short-circuit power and reactive reserves currently can only be supplied by the central power stations in Denmark. The provided justification for this is that “they are connected to the main high-voltage grid”. The regulation also states that there is a need for three central power stations to always be in operation in DK2.
To ensure short-circuit power, reactive reserves and voltage control in the main HV grid, Energinet.dk can request the forced operation of power plants on different time scales. The time scales Energinet.dk may demand this are on:

- A monthly basis
- A weekly basis
- Very early on the previous day
- After the spot market closes, before the auctioning of frequency-controlled services
- Concurrently with the auctioning of frequency-controlled services
- After receiving the first operation schedule
- During the day of operation

If these measures are insufficient, special regulation and/or forced operation can occur, and this will entail Energinet.dk’s operator handling the situation by phone with the power system operator/balance operator.

Energinet.dk is responsible for ensuring that voltage control of the power plants is adjusted to ensure that reactive power is balanced in the entire system on Zealand for DK2 (as well as in DK1). At the 132 kV and 400 kV level, this is primarily accomplished via passive reactive components, which ensure that the power plants’ production and consumption of reactive power is within acceptable limits. If acceptable limits cannot be achieved with purely passive measures, Energinet.dk has the authority to order the supplier to change the reactive power production or consumption to achieve an acceptable level. In DK2 the ordering of reactive reserve/voltage control takes place by Energinet.dk calling the supplier by “the production telegraph” with the following initial order: the plant name and the requested reactive power level in Mvar with sign. If Energinet.dk would like an order to become effective immediately, the supplier must ensure this is so. This request of the amount of reactive power to be supplied can be any reactive power value within the plants’ capacity. Additionally, if needed, several orders can be placed in parallel at the same time at several power plants.

2.2 Danish market regulations and balance responsibility

Currently, the potentially most lucrative ancillary services, and those of which distributed EVs are highly technically suitable to provide services for, are bought and sold on the balancing market in Denmark. The balancing market is divided into two sub markets, the regulating power market and balancing power market. In order to participate in either of these markets in the balancing market, the player must assume balance responsibility and agree to become a BRP. On the regulating power market, Energinet.dk buys/sells (regulating) power to and from the market participants in the delivery hour based on the bids the players submit for upward and downward regulation to Energinet.dk prior to the hour of delivery. On the balancing power market, Energinet.dk buys/sells (balancing) power to and from the players in order to neutralize imbalances created by the market players. These payments are based on actual metered data, where the imbalances have been quantified. This is the most “real-time” market in Denmark, and its role is to be the last measure to ensure the proper balance of production and supply [21].
Regulations for the wholesale and retail electricity markets in Denmark consist of 12 independent regulations and their associated appendices. Regulations A-G focus primarily on the wholesale market, whereas regulations H1 and H2 provide regulations on the retail market. Regulations C1 through C3 detail the concept of balance responsibility and the role of a BRP [22]. A condition to become a BRP and subsequently be able to engage in the balancing market is that the BRP must assume balance responsibility. Balance responsibility encompasses the agreement that the BRP assumes financial liability to Energinet.dk for any imbalances that may occur in connection with the BRP’s production, consumption and trade of electricity. The exact specifications are defined in Energinet.dk’s “Regulation C2: Balancing Market”. Energinet.dk defines balance responsibility as [23]:

*Responsibility for variations between notification and actual consumption/production at a number of metering points.*

Only BRPs can provide AS in Denmark. In order to do so the business must sign an ‘Agreement on balance responsibility’ with Energinet.dk become a registered BRP [23]:

### 2.2.1 Balance responsible party (BRP)

BRPs must be assigned to all production, consumption and trading of electricity. Energinet.dk’s definition of a BRP is [23]:

“A player approved by and party to an agreement with Energinet.dk regarding assumption of balance responsibility.”

BRPs are split into three categories, of which the BRP may select to become a BRP for any combination of the three roles\(^2\). The three roles are “BRP for production”, “BRP for consumption” and “BRP for trade”.

A BRP for production is defined as [23]:

“A BRP that holds balance responsibility for production and related agreements on the physical trading of electricity.”

A BRP for production must be assigned to all electricity production. Electricity producers hold balance responsibility for the electricity produced at their own plants. If the producer does not want to have the balance responsibility, e.g. in the case of a small-scale producer, the producer is required to assign this responsibility to another. In the small-scale producer case, this is usually assigned to the buyer of their production, the ‘electricity supplier’. Production is calculated per metering point and only one BRP is allowed for each metering point [23].

A BRP for consumption is defined as [23]:

\(^2\) While there is no place in the regulations explicitly stating that a BRP can elect to not be a BRP for trade while remaining a BRP for consumption and/or production, this inherently is nonsensical as the BRP would have to mechanism to monetize its role of balancing production and/or consumption respectively. Therefore all BRPs are “at least” a BRP for trade, and several elect additional responsibility.
“A BRP holding balance responsibility for consumption, including grid losses, and related agreements on the physical trading of electricity.”

A BRP for trade is defined as [23]:

“A BRP exclusively holding balance responsibility for the physical trading of electricity (a trader).”

Table 3 shows all the currently registered BRPs in Denmark, as well as where and what BRP role they’re registered to. As of the submission date of this thesis project, there are 41 BRPs in Denmark. 24 are exclusively BRP for trade. Of the 17 BRPs with BRP for production and/or consumption, 16 are allowed to operate in DK2. Of these 16, 10 of the BRPs for have been granted rights for all three roles (i.e. production, consumption and trade), whereas 3 are solely BRPs for production while the last 3 are only BRPs for consumption [24].
### Table 3: BRPs in Denmark

<table>
<thead>
<tr>
<th>Player</th>
<th>Short name (DK1)</th>
<th>Short name (DK2)</th>
<th>BRP for Production</th>
<th>BRP for Consumption</th>
<th>BRP for Trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpiq AG</td>
<td>ALPIQ-W</td>
<td>ALPIQ-E</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>EGLNORD-W</td>
<td>EGLNORD-E</td>
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<td>x</td>
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</table>
2.3 Future Development of AS in DK

In the near future, the set of technologies that constitutes AS in Denmark will be revised. While it is unclear exactly how AS will change, there are two central documents that indicate the nature in which these services, as well as how they’re procured and compensated for, will evolve in the Danish context. These two documents are Energinet.dk’s ancillary services strategy 2015-2017 [25] and Energinet.dk’s Market Model 2.0 [26]. Both released in 2015, the former in early February, and the final version of the latter in late October, these two documents provide directional insights into how the AS landscape will change in the coming years. A synopsis of these two essential documents is subsequently conducted.

The specific explanation for the creation of a separate strategy for AS moving forwards in Denmark is provided in [25] and centers on how AS play a significant role in the development and operation of the power system and therefore are inextricably linked to Energinet.dk’s three commitments, as laid out in Energinet.dk’s overall strategy plan. These are to [25]:

1. Guarantee a high level of security of supply for electricity and gas – now and in the future
2. Take responsibility for an economically viable transition
3. Contribute to a healthy investment climate in the energy sector

Based on these three commitments, Energinet.dk has defined three principles in relation to their new AS strategy. The driving catalyst behind these three principles is to assist in the facilitation of procuring AS in an economically optimum manner, while acknowledging the significant changes that the energy system is currently undergoing. Chief among these changes in relation to the supply of AS, is the phasing out of central power stations coupled with the simultaneous continual growth in wind energy, international connections, demand response and growing numbers of more intelligent and controllable grid components [25]. The three principles of internationalization, competition, and transparency underpinning Energinet.dk’s AS commitments are emphasized in the following figure. Energinet.dk has defined 11 initiatives to support these three principles.

![Figure 3: Visual depiction of Energinet.dk’s guiding principles for their AS strategy [25]](image-url)
The long-term objective in focusing on internationalization is to ensure price competitiveness in procuring AS through increased competition, more liquid markets and increased system robustness. This focus is also in large part to ensure the maintenance of, and strengthening of, international trading in AS, particularly with neighboring and the Nordic TSOs as well as to be best prepared for evolving network code rules for a common European market. To support international market integration, Energinet.dk is considering that various characteristics in the current Danish market design could be abandoned. Provided examples of such future changes are the current minimum bid limits, and markets with high time resolution and short time frames [25].

The emphasis behind the transparency pillar in Energinet.dk’s AS strategy is to remove barriers to entry for future potential suppliers of an AS, irrespective of the technology behind the production of the service(s). Opening the market to less conventional suppliers increases competition through the increased number of players. The intent is to enable different technologies to participate on equal terms in providing AS. Of course, all suppliers must be able to ensure an adequate offering of their services.

To strengthen competition in the AS markets, several future initiatives will be implemented. The intent of these efforts is to increase the focus on the valuation of the technical services and properties required to properly operate the power system and to open the markets to new suppliers. Among these initiatives, Energinet.dk explicitly intends to explore the possibilities of creating new ways of valuing technical services and their associated properties in areas where there is currently no or limited competition. There is particular focus in relation to procuring AS that assist in maintaining power system stability, and completing such in a manner that reduces the economic costs associated with procuring these AS.

In valuing future services and their associated properties, the services will be categorized in terms of investment and operations. Energinet.dk will continue to invest in relevant grid components integral to the transmission grid, as long as the economic costs of ensuring the necessary properties in the system can be reduced. In certain operating situations, Energinet.dk may look to purchase a service that has analogous properties to specific grid components or those that could be offered from a power station. Energinet.dk will take potentially procuring these services into account when examining possibilities for optimizing the operating expenses across its own grid components and commercial suppliers. In this content, Energinet.dk intends to establish mechanisms to ensure that all the properties needed to ensure power system stability in all normal operating situations is covered by a combination of grid components and/or equivalent services purchased on market terms. Initiative 8 of Energinet.dk’s AS strategy defines Energinet.dk’s strategy in relation to the new valuation of services and properties that create value for the power system, but are not currently included in the current set of AS. The findings and recommendations from Market Model 2.0 will guide the analysis for determining the implementation of any new services in 2016, pending approval from the Danish Energy Regulatory Authority (Energitilsynet). This latter half (i.e. allowing new services to provide current, as well as potentially new AS) potentially opens interesting new possibilities for EVs and other aggregated DERs to participate in the Danish AS markets.

The three main focal areas of Energinet.dk’s Market Model 2.0 are capacity, demand-side flexibility and critical properties. Capacity focuses on ensuring a continually high level of security of supply. Flexibility focuses on changing and aligning market rules to
incentivize flexibility in all aspects of the future power system. “Critical properties” encompasses providing a framework for new technology and services to provide the ancillary services conventional power stations used to do.

Capacity is broken down into three concepts in Market Model 2.0. They are security of supply, strategic reserve and capacity market. Security of Supply consists of ‘system adequacy’, i.e. whether enough electricity is generated and/or imported to cover current needs and whether the electricity infrastructure can sufficiently deliver this electricity to customers; and ‘system security’, encompassing the system’s ability to handle failure(s). In order to maintain Denmark’s objective of having no more than 5 minutes of outages per year for the average customer in eastern Denmark Market Model 2.0 investigates the establishment of a strategic reserve or capacity market. The analyses completed in conjunction with Market Model 2.0 indicate that a strategic reserve would be the best way to address expected needs [26].

![Demand-side flexibility](image)

**Figure 4:** Market Model 2.0 vision for demand-side flexibility services by source [26]

Demand-side flexibility is the second concept emphasized in Market Model 2.0. Its aim is to provide significant contribution to counterbalance the expected deterioration in the future security of supply in Eastern Denmark. Analysis completed in conjunction with this report expects EVs and heat pumps alone to be able to contribute 700-900 MW by 2030. Market Model 2.0 identifies creating the role of the ‘third-party aggregator’ as a new role in the electricity market as critical to ensuring the provision of demand-side flexibility. Currently, there are extensive legislative barriers to the creations of an aggregator role, primarily among which includes the fact that the would-be aggregator would have to negotiate contracts with ~15 different companies acting as BRPs in order to control resources on behalf of their customers [26]. This, coupled with high running costs and the cost of metering individual customers, makes the current situation prohibitively difficult. Energinet.dk intends to lobby to change the existing legislation on an international level to promote a regulatory environment more conducive for demand-side flexibility. One of the other main initiatives to incentivize demand-side
flexibility is, in conjunction with neighboring countries, the removal of the current price cap of 3000 €/MWh to a level that more accurately reflects the real value of electricity to consumers.

In order to enhance market flexibility Market Model 2.0 advocates working in conjunction with the other Nordic TSOs towards enabling trading closer to the hour of operation to minimize forecasting errors by market participants and to change the market regulation requiring balance before the day of operation, as this principle works in contrast with the former. Thirdly, Market Model 2.0 advocates changing the imbalance settlement model from its current practice, where imbalances are settled on a two-price model for production units and a single-price model for consumption units, to a single-price model for both [26].

The majority of the 30 to 40 existing critical power system stability properties are supplied by power stations [26]. The power stations are obligated to provide these services, some of which they are compensated for, others they are not. Acknowledging this reality, coupled with the reality that progressively more power stations are being decommissioned, is the driving catalyst to define additional ancillary services based on the critical technical properties and functionalities required in the future power system, to what degree they will be needed, and how large an absence these services will be as more power stations go offline. Based on the future analysis associated with this future needs projection, proposals to isolate and procure these individual services in future markets will be explored. The timeline associated with these activities is show in the Marked Model 2.0 overview timeline in Figure 5.
### Ancillary Services

**Figure 5: Market Model 2.0 activities overview**

<table>
<thead>
<tr>
<th>Year</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Analysis of future needs, Legal analysis</td>
</tr>
<tr>
<td>2016</td>
<td>Recommendations on ways to procure new ancillary services, Follow-up on and implementation of any new ancillary services, Method approval of new ancillary services</td>
</tr>
<tr>
<td>2017</td>
<td>Follow-up and info to market participants</td>
</tr>
</tbody>
</table>

**ENSURING MARKET FLEXIBILITY**

<table>
<thead>
<tr>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reassessment of balance before day of operation rule</td>
</tr>
<tr>
<td>Adjustment of power imbalance settlement etc.</td>
</tr>
<tr>
<td>Follow-up and info to market participants</td>
</tr>
</tbody>
</table>

**ENSURING DEMAND-SIDE FLEXIBILITY**

<table>
<thead>
<tr>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigation of possible statistical methods for measuring consumption from homogeneous units</td>
</tr>
<tr>
<td>Adaptation of product design to demand-side flexibility</td>
</tr>
<tr>
<td>Preparation of standard terms and conditions for third-party aggregation</td>
</tr>
<tr>
<td>Assessment of more lenient requirements for consumption metering and, possibly, development of DataHub</td>
</tr>
<tr>
<td>Building of knowledge about demand side flexibility together with market participants, among other things to activate flexible consumption from buildings, industry and emergency power units</td>
</tr>
<tr>
<td>Follow-up, preparation and info to market participants</td>
</tr>
<tr>
<td>Implementation</td>
</tr>
</tbody>
</table>

**RAISING OF PRICE CAPS**

<table>
<thead>
<tr>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis of price cap to be proposed</td>
</tr>
<tr>
<td>Proposal to be discussed with the European TSOs</td>
</tr>
</tbody>
</table>

**ENSURING SUFFICIENT CAPACITY**

<table>
<thead>
<tr>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll-out of strategic reserve</td>
</tr>
<tr>
<td>Comparison of solutions from MMAs with DR/DG infrastructure</td>
</tr>
<tr>
<td>Evaluation of strategic reserve with heat production in light of the rolled-out strategic reserve in 2016</td>
</tr>
<tr>
<td>Approval and adaptation of guidelines, paving the way for possible roll-out</td>
</tr>
</tbody>
</table>
This chapter consists of two main components. The first details the background experimental work that served as the explanation behind the chosen control strategy for the power system modelling conducted in this thesis project. The second section is a detailed description of the modelled distribution network.

### 3.1 Nikola Microgrid Experiment - Power Quality Management

As described in section 1.2, this thesis work has been completed in collaboration with the Nikola Research Project. One of the current experiments WP 2 of the Nikola Research project has been engaged in during the time span of this thesis project was a power quality management microgrid experiment using SYSLAB PowerLabDK. The thesis author assisted the Nikola researchers with their work, and in doing so gained further insight into the value of the decentralized, autonomous control method applied in the control strategy tested at SYSLAB to a varying set of power system modelling simulation cases which constitute the main scientific contribution of this thesis project to the research community. These cases are reported upon in chapter 5.

#### 3.1.1 SYSLAB

The experimental validation work conducted by the author’s supervisors in concurrence with this thesis project was completed using SYSLAB PowerLabDK. SYSLAB PowerLabDK is DTU Risø campus’s flexible intelligent energy laboratory. The SYSLAB facility consists of a 400 V grid with flexible configuration, the ability to operate with a public grid connection, switch into autonomous/isolated operation, or be operated in various combinations. SYSLAB includes two wind turbines (10 kW and 11 kW), 3 photovoltaic (PV) plants (2x10 kW and 7 kW), a diesel generator set (48 kW / 60 kVA), three EV charging posts (2x50 kVA and 200 kVA EDISON bays), a 15 kW /120 kWh vanadium redox flow battery, a 75 kW dump load, three mobile 36 kW loads and a 104 kW back to back converter. SYSLAB also includes interconnections to the following buildings: DTU’s PowerFlexHouse facility, two domestic houses with controllable loads of 10 to 20 kW, and the Nordic Electric Vehicle Interoperability Centre (NEVIC) [27]. An overview of SYSLAB, including its configuration for during the aforementioned experiment, is provided in Figure 6.
3.1.2 Nikola Microgrid Experiment - Power Quality Management

Using SYSLAB’s equipment, a portion of a typical LV feeder was recreated. Three standard commercially available Nissan Leafs, 1 per phase, with single phase 16 A 230 V chargers and 24 kWh batteries were connected next to a variable “dump” load of 45 kWh, variable equally per phase up to 15 kWh. In addition, an onsite generating DER was incorporated into the experiment in the form of the 11 kW 2-blade Gaia wind turbine. To replicate a standard home charging setup, the EVs were connected next to the variable load. Voltage control was completed through modulating the current to change the active power set point for the EVs. This adjustment was made according to the locally measured phase voltage magnitude. The unidirectional charging EVs could have their charging rate remotely enabled and the current was modulated in 1 A steps from a maximum charging rate of 16 A down to the minimum of 6 A. This experimental analysis demonstrated that by intelligently controlling the EV charging current, power quality improvements could be realized in a LV network [28].

3.1.3 From SYSLAB experiment to system modelling

From this experimental research in Risø, where the charging of three EVs was intelligently controlled at one node at the end of a feeder with connected DERs, the question was posed as to how would this charging control impact a Danish distribution system? For obvious reasons, a full system study cannot be completed in real life using actual equipment and therefore answering this question necessitates the use of power system modelling software.

As will be subsequently elaborated, it is the same charging control configuration tested in this SYSLAB experiment that will be modelled and analyzed in a PowerFactory simulation of a section of Borup’s LV distribution grid.


3.2 Grid Topology of the Simulated Network

The simulated network is based on information from a network in the Danish town of Borup, in the Municipality of Køge, in east central Zealand (Sjælland). SEAS-NVE is a partner in the Nikola project at DTU, and has provided the detailed component and consumption data that is incorporated into the simulation. This level of detail makes the modelling work more representative of the real world conditions, and as such increases the relevance and accuracy of the results.

The simulated grid used is a modified version of that completed in [13], also completed under the Nikola research project. It is a residential three phase grid with hourly individual household consumption data provided for 1 of the 4 feeders connected to the substation. The data for the other 3 feeders is only provided in aggregate and is therefore modelled as such. The single-phase configuration of the modelled LV network is reprinted in Figure 7 below. All 43 households are modelled in the simulated network. Section A contains 17 houses located on the street called “Hørmarken” whereas section B represents 26 households on the street called “Græsmarken”. In the modelled scenarios with EVs, each household is modelled as having 1 EV. Households with rooftop PV installations are denoted in green, while those households without PV are in blue. Lastly, there is a street light at node 608 in Græsmarken which is in denoted in black [29].

![Figure 7: Single-phase diagram of the modelled Borup network [29]](image)

All the households in Hørmarken (section A) are connected to district heating. As such, these households have lower seasonal consumption profiles when heating is required when compared to the households in Græsmarken (section B), which are all equipped with their own individual heat pump. The heat pumps are not modelled into the system but account for the proportionally higher electricity consumption during the analyzed time period than their counterparts in Hørmarken.

The modelled LV feeder is connected to the medium voltage (MV) grid by an Alstrom-DCU 3631 H 400 kVA three-phase transformer with the nominal ratio of 10.5/0.42 kV [29]. The modelled transformer has a three-phase short circuit (SC) current power of 20 MVA, a short circuit voltage of 4%, the resistance of each winding is 0.005 p.u. and the leakage inductance of each winding is 0.02 p.u.. The LV wye side of the transformer is
Background experiment, Test Grid and System Modelling

directly grounded. The MV bus bar is also connected to the modelled external grid, which is setup to provide no voltage regulation [29]. The external grid is modelled with an acceleration time constant set to infinity, enabling “perfect” frequency regulation as the greater the time constant, the faster a generator reaches its steady state condition and the less time it takes to respond to a frequency deviation [30]. As such there is no additional frequency regulation provided to the simulations.

The grid topology represents that of a typical residential radial network. The detailed LV feeder is a radial feeder with two laterals. These three sections are physically laid and named in conjunction with the street names where the modelled households are located. The feeder consists of 14 nodes and 13 line segments with total line length of 681 meters.

A screenshot of the LV network schematic in PowerFactory is shown in Figure 8 below.

![Figure 8: The LV grid modelled in PowerFactory](image)

Node 613, shown in the bottom right corner of Figure 8 is shown in its expanded view in Figure 9 below. All the other household nodes (60x) in the network shown in Figure 8 are modelled in an analogous way to Figure 9. The other feeder loads, connected to bus 301, represent the aggregate load from three other connected feeders connected to this system for which only aggregated data was provided.
From left to right, the households are G20, G18, G15 and G13. The EVs at households G15 and 18 are connected to phase A, the EV at household G13 is connected to phase B and the EV at household G20 is connected to phase C.

3.2.1 Winter Case

The simulated grid is only analyzed under during the heaviest loaded week of the year. These conditions occur during the third week of January 2013, from January 13th to 19th. The main factor causing the additional seasonal stress in this system is the activation of the heat pumps in Græsmarken. Therefore if the system can handle full EV integration in the winter, when the system is most strained, it will be sufficient throughout the year.

3.2.2 Load modelling

Hourly household consumption data for was provided as input in the cases. These load measurements were provided by SEAS-NVE for the period of March 2012 to February 2013. From a measurements campaign conducted by the author’s supervisors, it was discovered that a heavy imbalance was present in the Borup grid under analysis. The height of this imbalance was approximately double the loading on phase A from phases B and C. As such the load modelling in PowerFactory has been modified to reflect this imbalance, i.e. phase A is loaded at 50% of the total demand profile in the system, where B and C equally consume 25%. The model was changed to reflect this real-world measurement by representing all the household loads as three phase loads and implementing a scaling factor on the input measurement data to reflect the measured imbalance.

Only active power values were provided by SEAS-NVE. Therefore reactive power levels were calculated under the assumption that an inductive power factor (p.f.) of 0.95 was present in the grid. This corresponds to the minimally acceptable level. As
mentioned in the system description, the houses in Hørmarken are connected to district heating, whereas the houses in Græsmarken are heated through individual heat pumps installed in each household. This distinction accounts for the large difference in electricity consumption throughout the winter. Furthermore, there were problems with the real data received at Hørmarken 2, and at Hørmarken 11 and 17 no data was provided, and were excluded from the simulations. While this is unfortunate as it slightly degrades the “real life” snapshot of the modelling, the comparative difference remains the same among the cases, and as such this does not impact the testing of the various controllers.

Figure 10 below shows the total hourly electricity consumption for Græsmarken and Hørmarken for the analyzed week. Table 4 on the following page shows the total energy consumption for the analyzed period by node and household.
Table 5 shows the daily and total electricity consumption for the other three feeders connected to the analyzed feeder.

![Græsmarken total household consumption](image)

![Hørmarken total household consumption](image)

**Figure 10:** Total household consumption data by neighborhood
Table 4: Total weekly consumption in Hørmarken and Græsmarken

<table>
<thead>
<tr>
<th>Location</th>
<th>kWh</th>
<th>Location</th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 602</td>
<td>535.63</td>
<td>Node 607</td>
<td>1797.02</td>
</tr>
<tr>
<td>Hørmarken 1</td>
<td>161.81</td>
<td>Græsmarken 17</td>
<td>379.16</td>
</tr>
<tr>
<td>Hørmarken 2</td>
<td>50.33</td>
<td>Græsmarken 19</td>
<td>356.69</td>
</tr>
<tr>
<td>Hørmarken 3</td>
<td>72.80</td>
<td>Græsmarken 21</td>
<td>315.49</td>
</tr>
<tr>
<td>Hørmarken 4</td>
<td>110.58</td>
<td>Græsmarken 22</td>
<td>361.66</td>
</tr>
<tr>
<td>Hørmarken 5</td>
<td>140.12</td>
<td>Græsmarken 24</td>
<td>384.01</td>
</tr>
<tr>
<td>Node 603</td>
<td>475.22</td>
<td>Node 608</td>
<td>1133.36</td>
</tr>
<tr>
<td>Hørmarken 6</td>
<td>154.85</td>
<td>Græsmarken 23</td>
<td>291.66</td>
</tr>
<tr>
<td>Hørmarken 7</td>
<td>154.52</td>
<td>Græsmarken 26</td>
<td>359.41</td>
</tr>
<tr>
<td>Hørmarken 8</td>
<td>71.09</td>
<td>Græsmarken 28</td>
<td>378.60</td>
</tr>
<tr>
<td>Hørmarken 9</td>
<td>94.75</td>
<td>Street light</td>
<td>103.69</td>
</tr>
<tr>
<td>Node 604</td>
<td>677.19</td>
<td>Node 609</td>
<td>1041.65</td>
</tr>
<tr>
<td>Hørmarken 10</td>
<td>146.72</td>
<td>Græsmarken 1</td>
<td>432.87</td>
</tr>
<tr>
<td>Hørmarken 11</td>
<td>0</td>
<td>Græsmarken 2</td>
<td>313.39</td>
</tr>
<tr>
<td>Hørmarken 12</td>
<td>158.67</td>
<td>Græsmarken 4</td>
<td>295.39</td>
</tr>
<tr>
<td>Hørmarken 13</td>
<td>72.53</td>
<td>Node 610</td>
<td>1708.09</td>
</tr>
<tr>
<td>Hørmarken 14</td>
<td>105.64</td>
<td>Græsmarken 3</td>
<td>573.49</td>
</tr>
<tr>
<td>Hørmarken 15</td>
<td>84.61</td>
<td>Græsmarken 5</td>
<td>363.79</td>
</tr>
<tr>
<td>Hørmarken 16</td>
<td>109.01</td>
<td>Græsmarken 6</td>
<td>302.98</td>
</tr>
<tr>
<td>Hørmarken 17</td>
<td>0</td>
<td>Græsmarken 8</td>
<td>467.84</td>
</tr>
<tr>
<td>Total</td>
<td>1688.04</td>
<td>Node 611</td>
<td>1294.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 10</td>
<td>527.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 12</td>
<td>389.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 7</td>
<td>377.56</td>
</tr>
<tr>
<td>Node 612</td>
<td>1873.41</td>
<td>Græsmarken 11</td>
<td>349.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 14</td>
<td>365.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 16</td>
<td>477.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 9</td>
<td>680.26</td>
</tr>
<tr>
<td>Node 613</td>
<td>1388.2</td>
<td>Græsmarken 13</td>
<td>343.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 15</td>
<td>479.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 18</td>
<td>208.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Græsmarken 20</td>
<td>357.45</td>
</tr>
<tr>
<td>Total</td>
<td>10236.28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5: Total household consumption of other three feeders

<table>
<thead>
<tr>
<th>Date of consumption</th>
<th>Energy consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/13/2013</td>
<td>1,920.3</td>
</tr>
<tr>
<td>1/14/2013</td>
<td>1,601.3</td>
</tr>
<tr>
<td>1/15/2013</td>
<td>1,649.8</td>
</tr>
<tr>
<td>1/16/2013</td>
<td>2,103.0</td>
</tr>
<tr>
<td>1/17/2013</td>
<td>2,034.3</td>
</tr>
<tr>
<td>1/18/2013</td>
<td>2,124.1</td>
</tr>
<tr>
<td>1/19/2013</td>
<td>1,833.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13,266.5</strong></td>
</tr>
</tbody>
</table>

For the neighborhood load modelling, Græsmarken constitutes 40.63% of the total consumption, Hørmarken constitutes 6.7% and the other feeder constitutes 52.66% of the load. This is visualized in Figure 11 below. There were also 3 other feeders connected to the system being analyzed. However, only aggregate data was provided for these three feeders. As such it was modelled in aggregated at bus 301 with the title “other feeder”. While it contributes approximately 50% of the total demand in the system, it is modelled without any EVs in all of the simulation cases.

![Figure 11: Load distribution over the analyzed week](image-url)
3.2.3 EV modelling

The EVs are connected to the modelled grid through single-phase converters. It has been assumed that the converters are connected in a rotation among the three phases as shown in Table 6 below. Hørmarken and Græsmarken are abbreviated H and G, respectively. The phase connections were completed in the following rotation to evenly distribute the EVs in the system.

For the EV modelling cases, each of the 43 households is modelled as owning an EV. The EVs in the Borup network are modelled as Peugeot iOns. The battery in the iOns’ is a 16.3 kWh lithium manganese oxide (LiMn$_2$O$_4$) battery. The charging profile used is equivalent to the worst case scenario in Denmark [31] – commonly referred to as a “dumb” charging profile. The profile is based on information obtained from the Test-an-EV program in Denmark, where real charging data from 184 EVs in 10 Danish cities was collected [31]. This profile is characterized by the simultaneous charging of all the EVs when the homeowners return to their homes in the evening, where charging starts at 18:00 and continues for a duration of 4 hours until 22:00. For the first hour the vehicle’s charging rate is 3 kW. For the following 2.5 hours, the EVs charge at their maximum rate of 3.7 kW. The last half hour represents a balancing of charge hour at 0.2 kW, corresponding to a daily charge consumption of 12.35 kWh. The maximum charging period coincides with peak household demand, causing the most strain on the system, hence the common term for this charging profile.

<table>
<thead>
<tr>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td>H01</td>
<td>H02</td>
<td>H03</td>
</tr>
<tr>
<td>H04</td>
<td>H05</td>
<td>H06</td>
</tr>
<tr>
<td>H07</td>
<td>H08</td>
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<td>H10</td>
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<td>H14</td>
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<td>H16</td>
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<td>H17</td>
<td>G01</td>
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<td>G14</td>
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<td>G21</td>
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<td>G23</td>
</tr>
<tr>
<td>G24</td>
<td>G26</td>
<td>G28</td>
</tr>
</tbody>
</table>

Table 6: Phase connection for the EVs

---

3 Sold in Europe by PSA Peugeot Citroen as the Peugeot iOn. The car is manufactured by Mitsubishi, which calls it the i-MiEV (an acronym for Mitsubishi innovative Electric Vehicle).
3.2.4 Cable modelling

Two different cables were used to connect the households to the modelled grid. The first is a three phase aluminium (Al) cross-linked polyethylene (PEX) cable with a cross-section area of 16 mm$^2$, whereas the second is a copper (Cu) PEX cable with a cross section area of 10 mm$^2$. The specifications of these two cables, as well as for the branch cables to the various nodes in the system are provided in Table 7. The neutral cable in the test grid is grounded on the transformer’s LV side.

<table>
<thead>
<tr>
<th>connection to nodes</th>
<th>Household to Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Al 4x150</td>
</tr>
<tr>
<td>Conductor Material</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Insulation Material</td>
<td>PEX</td>
</tr>
<tr>
<td>Rated current [A]</td>
<td>335</td>
</tr>
<tr>
<td>Rated voltage [V]</td>
<td>400</td>
</tr>
<tr>
<td>Phases</td>
<td>A-B-C-N</td>
</tr>
<tr>
<td>Cross-section [mm$^2$]</td>
<td>150</td>
</tr>
<tr>
<td>$R_1$ (20°C) [Ω/km]</td>
<td>0.27</td>
</tr>
<tr>
<td>$X_1$ (50 Hz) [Ω/km]</td>
<td>0.078</td>
</tr>
<tr>
<td>$R_0$ [Ω/km]</td>
<td>0.829</td>
</tr>
<tr>
<td>$X_0$ [Ω/km]</td>
<td>0.312</td>
</tr>
</tbody>
</table>

Based on testing the implemented simulation with the corresponding provided data sets, it was empirically determined that cable 301-601 was critical cable in the system. This makes sense, as it is the cable solely responsible for supplying both neighborhoods in the analyzed system. As such it will be the cable focused upon in the reporting of the results of the simulations in the Results chapter of this thesis.

3.2.5 Photovoltaic installations in the network

The modelled network consists of 27 PV installations. As previously mentioned all 26 households in Græsmarken have a PV installation installed as well as one household in Hørmarken (household H2). 24 of the installations have a peak power $P_{peak}=2.96$ kW and three installations were upgraded to $P_{peak}=4.07$ kW. The PV installations are connected through 3.6 and 5.4 kW single-phase inverters equipped with reactive power control (RPC), respectively. The phase connection of each individual installation is not known, and as such has been assigned sequentially to take into consideration that the overall production should approximately be the same on each phase. The PV production was measured on an hourly basis per household along with each household’s consumption data [29].

Based on the received measurement data, the PV production during this analyzed winter scenario is negligible. The PV units contribute only a minimal amount during mid-day, which does not coincide with the EV charging pattern initiated in this analysis. As such, it does not influence the critical periods being studied. Therefore PV production is not further addressed in these scenarios.
4 TIME-DOMAIN SIMULATION FOR STABILITY ANALYSIS

The analysis of power flows is an essential part of successful power system operation. Under normal, balanced three-phase steady state conditions the following conditions must be ensured to ensure successful power system operation [32]:

1. Generation supplies the demand plus losses
2. Bus voltage magnitudes remain within their limits
3. Generators operative within their specified real and reactive power limits
4. Power system equipment is supplied within their limits

The basic tool for ensuring these four properties is a power-flow (also referred to as a load flow in various literature) computer program. Solving a power flow problem means computing the voltage magnitude (|\(V\)|) and phase angle (\(\delta\)) for each bus in the power system. In doing so, the real (\(P\)) and reactive (\(Q\)) power flows, as well as losses, can be determined. Of these four variables (|\(V\)|, \(\delta\), \(P\) and \(Q\)) two are to are specified as input data while the other two are unknowns to be computed through an iterative process. The three main\(^4\) bus types are:

1. **Slack** or swing (V\(\delta\)) bus: There is only one slack bus. It is the reference bus where the voltage magnitude and phase angle are typically set to 1.0 and 0°, respectively, as input data and \(P\) and \(Q\) are then calculated.

2. **Load** (PQ) bus: \(P\) and \(Q\) are input data and the program calculates |\(V\)| and \(\delta\). Most buses in the power system are PQ buses [30].

3. **Voltage** controlled (PV) bus: \(P\) and |\(V\)| are input data and the program calculates \(Q\) and \(\delta\). PV busses are those with e.g. generator(s), switched shunt capacitors, or static var systems.

The program returns the active power, reactive power, voltage magnitude, and phase angle for every bus in the system under analysis. These parameters are calculated based on which are known in the system and this varies based on the type of bus in the system.

The primary iterative technique to solving power flow nonlinear algebraic equations is the Newton-Raphson method. It is the most robust power flow algorithm used in practice [33] and is the technique used by PowerFactory in the simulations in this thesis.

\(^4\) Q\(\delta\) (slack demand/tie) and CV (Controlled voltage magnitude) buses also exist [33], but are neglected here as they’re not used in the simulations in this thesis.
The primary benefits of the Newton-Raphson method are that it converges in many cases where other methods diverge, and the number of iterations required for convergence is independent of the dimension of the size of the matrix, whereas it increases for other methods [32]. For more details on the Newton-Raphson power flow technique, as well as the main other iterative methodologies, the reader is referred to chapter 6 in [33].

Power-flow calculations are used to analyze power systems under steady-state non-faulted conditions. It is analogous to “taking a picture” of the power system under consideration for a specified time frame. Loads follow a certain characteristic, and the calculated power values change accordingly.

The analyses completed in the subsequent cases in this thesis project consist of a multitude of power flows over a week long time period through the form of an unbalanced RMS simulation, which is a time-domain simulation used for stability analysis and the long-term analysis of electromagnetic transients. A power flow is calculated in intervals ranging from every half second to every sixty seconds of each week long case (604800 seconds), depending on if, and to what degree, any of the state variables change in the simulation. This long-term time-domain simulation allows for the analysis of dynamic behavior that is not captured in a simple power flow study, and provides further insights into how the various components in the system interact with each other over time and varying system conditions.

4.1 Modelling unbalances

In 1918, Charles LeGeyt Fortescue developed the method of symmetrical components. This is a powerful and widely used mathematical method for representing unbalanced poly-phase systems into corresponding sets of decoupled phasors. Fortescue defined a linear transformation from phase components to a new set of components called symmetrical components. By doing so, this simplifies the analysis of three-phase systems by representing an unbalanced set of phasors as three independent sets of phasors, through two balanced sets (called positive and negative sequence components) and a third set with identical phasors (zero sequence component). This greatly simplifies the computation, and the values can be converted back from the sequence domain to the time domain at the point of a fault to determine the phasors’ values, as desired.

Zero-, positive-, and negative-sequence components are commonly denoted through the subscripts 0, 1 and 2. Three voltage phasors can be expressed as the following symmetrical components:

\[
\vec{V}_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{a,0} \\ V_{b,0} \\ V_{c,0} \end{bmatrix} + \begin{bmatrix} V_{a,1} \\ V_{b,1} \\ V_{c,1} \end{bmatrix} + \begin{bmatrix} V_{a,2} \\ V_{b,2} \\ V_{c,2} \end{bmatrix}
\]  

(1)

Where \(V_a\), \(V_b\), and \(V_c\) are the set of arbitrary voltage phasors (which can either be balanced or unbalanced) and the three sets of sequence voltage phasors with their respective subscripts represent their corresponding sequence. From this baseline, the following defining criteria are imposed. That the positive sequence phasors are balanced, perfectly symmetrical, and in the positive sequence (i.e. ABC); that the negative sequence phasors are also balanced, perfectly symmetrical and in the opposite
sequence (ACB); and that the zero sequence phasors are identical (i.e. equal magnitudes with zero phase displacement). Figure 12 visualizes these relationships.

\[ V_{a0} V_{b0} V_{c0} = V_0 \]
\[ V_{a1} = V_1 \]
\[ V_{a2} = V_2 \]

(a) Zero-sequence components  (b) Positive-sequence components  (c) Negative-sequence components

**Figure 12**: Phase voltages and their corresponding three sets of sequence components [32]

In matrix notation, sequence components are defined by the transformation shown in equation 2:

\[
\vec{V}_{abc} = \begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha & \alpha^2 \\
\end{bmatrix} \begin{bmatrix}
V_0 \\
V_1 \\
V_2 \\
\end{bmatrix}
\]

Where the rotation operator, \( \alpha = 1\angle 120^\circ \). The inverse of the above transformation, provided in equation 3, provides the sequence phasor values directly:

\[
\begin{bmatrix}
V_0 \\
V_1 \\
V_2 \\
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha & \alpha^2 \\
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix}
\]

4.2 Modelling in PowerFactory

The intent of the conducted simulations is to study the simulated grid over the considered time period. As such an unbalanced root mean square (RMS) simulation is completed. This simulation function uses a steady-state, three-phase representation of the passive electrical network and therefore can be used to compute unbalanced network conditions [8].

The following unbalanced simulation cases were conducted with the integration step sizes for electromechanical transients set to 0.5 seconds, and with a maximum step size of 60 seconds for the Step Sizes parameters. The step size adaptation parameters were left at their default values.

These simulations use load measurement files to define the system loads’ power profiles. The load profiles in the measurement files are assigned to the appropriate loads through the implementation of a composite frame for each load type and the composite models link the profiles’ to specific loads in the PowerFactory model. The composite frame dictates the control procedure used for each of the loads in that composite frame.
The composite frame used in the modelling varies depending on the control implemented in the case and will be subsequently described in each case.

By default, PowerFactory uses a constant impedance load model when defining loads in the system. The electric vehicles are modelled as constant current loads, and as such the reference power equation must be manipulated to reflect this. This is accounted for in the power reference block in each composite frame.

### 4.3 Key Power Quality parameters

In this thesis power quality is defined in accordance with the definition provided in EN 61000-4-30:2015 Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods, namely that it is the [34]:

“characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters”

There are many important reasons to monitor power quality. The main underlying reason is economic, and this is particularly true if critical loads are being adversely affected by electromagnetic phenomena. Negative effects can range from direct damage of equipment, disruption of supply, increased rates of degradation, inadvertent switching of protection equipment leading to shutdown, equipment malfunction, negative and even detrimental events to end-users, etc. It is of primary importance to ensure that the power quality is satisfactory in the power system. It would be far too encompassing to detail every power quality parameter for each of the analyzed cases. As such, the following subset of power quality parameters was chosen to be focused upon in the modelled cases in this thesis.

#### 4.3.1 Cable 301-601 Profile

The energy is supplied to the modelled distribution grid from the external grid, through the transformer and first along cable 301-601. The varying power consumption profiles for the analyzed cases will be shown in their respective cable 301-601 profile sections in each case. Furthermore the cable loading is reported for each case to monitor if the EV charging behavior introduced congestion along this cable.

#### 4.3.2 Voltage Profile

A grid’s voltage profile is one of the main parameters in assessing power quality. Proper voltage levels are necessary for reliability and stability.

The nominal phase to neutral voltage is 230 V in Denmark. According to the European Standard, EN 50160 Voltage Characteristics in Public Distribution Systems, the LV supply voltage must be within ±10% of the nominal voltage value for 95% of the week, measured in 10 minute RMS values, and can never go below 0.85 p.u. [35, 36]. The voltage profile for each case will be report against this metric.

More specifically, section 4.2.2.1 the Requirements of the Supply voltage variations section of EN 50160:2010 for continuous phenomena, states the following [36]:

```
Under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed ±10% of the nominal voltage $U_n$.

In cases of electricity supplies in networks not interconnected with transmission systems or for special remote network users, voltage variations should not exceed +10% / -15% of $U_n$. Network users should be informed of the conditions.

Furthermore, three notes are provided as addendums to these stated requirements [36]. Most notably, in note one, the following is stated:

...If following a complaint, measurements carried out by the network operator according to 4.2.2.2 [the defined test method] indicate that the magnitude of the supply voltage departs beyond the limits given in 4.2.2.2 causing negative consequences for the network user, the network operator should take remedial action in collaboration with the network user(s) depending on a risk assessment. Temporarily, for the time needed to solve the problem, voltage variations should be within the range of +10% / -15% of $U_n$, unless otherwise agreed with the network users.

The specific phrasing for the test method for verifying the normal operating conditions consists of the following two clauses [36]:

- During each period of one week 95% of the 10 min mean RMS values of the supply voltage shall be within the range of $U_n \pm 10\%$; and
- All 10 min mean RMS values of the supply voltage shall be within $U_n + 10\% / -15\%$;

It is against these testing criteria that the analyzed cases will be measured to determine whether or not the voltage profile is acceptable. The implications associated with section 4.2.2.1 of EN 50160:2010 and its associated note 1 will be expanded upon in the discussion section of this thesis.

In order to determine if the voltage limits have been exceeded, phase-neutral voltage measurements are completed at each node in the simulated grid for each simulation scenario. The critical node in the system is node 613. This was expected due to the network configuration, as this is the node at the end of the feeder and as such experiences the cumulative impact of the additional voltage drops by the households at each node closer to the PCC (i.e. nodes 601, 606, 609, 610, 611, and 612). The impact of the various control systems on the system and node 613’s voltage will be shown in the Voltage Profile section of each case.
4.3.3 Voltage Unbalance

The term voltage unbalance (also called voltage imbalance\(^5\) in the literature), expressed in a percentage, represents the ratio between the difference between the negative and positive sequence voltage magnitudes. This same concept is called the voltage unbalance factor (VUF) elsewhere in Power System literature, e.g. in IEC’s glossary [37]. While the two terms refer to the same underlying physical phenomena, voltage unbalance will be the term used throughout the remainder of this text. The percent voltage unbalance is defined on page 15 of IEEE standard 1159-2009 Recommended Practice for Monitoring Electric Power Quality [38] by the following equation:

\[
\% \text{Unbalance} = \text{VUF} = \frac{|V_{\text{negative}}|}{|V_{\text{positive}}|} \times 100\% \tag{4}
\]

Standard 1159 states that “typically, the voltage imbalance of a three-phase service is less than 3%” [38] whereas EN 50160’s guidelines are that the voltage unbalance must be \(\leq 2\%\). Equation 4 represents the preferred, recommended practice to determine the voltage imbalance according to standard 1159 because it directly represents the phenomena without approximation [38]. This will be the method used to determine the VUF for the cases in the results chapter of this thesis.

However many measurements are collected from simple meters that only collect RMS values [38]. Since the imbalance is computed using a ratio of sequence components, the value of those components is not required. The following equations, using only phase-to-phase RMS magnitude measurements can be used to determine this same ratio [38]:

\[
\% \text{Unbalance} = \text{VUF} = \sqrt{\frac{1-\sqrt{3}-6\beta}{1+\sqrt{3}-6\beta}} \times 100\% \tag{5}
\]

where

\[
\beta = \frac{|V_{AB}|^4 + |V_{BC}|^4 + |V_{CA}|^4}{(|V_{AB}|^2 + |V_{BC}|^2 + |V_{CA}|^2)^2} \tag{6}
\]

However, this method only provides results analogous to the “true unbalance” method (equation 1) if the following conditions are met; if the harmonic content is low, phase-to-phase measurement are used, and the zero sequence components is zero. In contrast, equation 1 is always valid, regardless if using phase-to-neutral or phase-to-phase measurements [38].

\[\]

\(5\) Imbalance is the term used in IEEE standard 1159-2009 and imbalance is the proper word choice, although unbalance is also ubiquitous in the literature. Imbalance is a noun describing a state being out of equilibrium, whereas unbalance is a transitive verb describing the state where someone or something loses balance. www.merriam-webster.com/dictionary/imbalance and www.merriam-webster.com/dictionary/unbalance. However, IEEE std 1159 also recognizes that imbalance is called unbalance, and in the terms and definitions section of EN 50160:2010 voltage unbalance is defined as the “condition in a polyphasor system in which the r.m.s. values of the line-to-line voltages (fundamental component), or the phase angles between consecutive line voltages, are not all equal”.

---

41
4.4 Droop Control

4.4.1 Droop control theory

Droop control, also known as “proportional only” control and “speed/load” control [39], is a proportional control strategy that allows for parallel operation which in turn allows load sharing.

In order to explain the theory behind droop control, first an understanding of how power is transferred between active sources should be established. The complex power $\bar{S}$ where the line represents phasor notation, $r$ and $s$ represent the receiving and sending ends, respectively and $\theta$ and $\delta$ represent power factor angle and load angle\(^6\), respectively) at the receiving end is characterized by the following equations:

\[
\bar{S}_r = P_R + jQ_R = \bar{V}_R\bar{I}^* = \bar{V}_R \left[ \frac{\bar{V}_S - \bar{V}_R}{Z} \right]^* = V_R \left[ \frac{V_S - V_Re^{j\delta}}{Ze^{-j\theta}} \right]^*
\]

Then using Euler’s identity to expand the apparent power from its phasor to rectangular expression, leads to the following equation:

\[
= \frac{V_S}{Z}e^{j\theta} - \frac{V_S V_R}{Z}e^{j\theta + \delta}
\]

(7)

Which when represented in terms of active and reactive power becomes:

\[
P = \frac{V_S^2}{Z} \cos\theta - \frac{V_S V_R}{Z} \cos(\theta + \delta)
\]

(9)

\[
Q = \frac{V_S^2}{Z} \sin\theta - \frac{V_S V_R}{Z} \sin(\theta + \delta)
\]

(10)

Wherein defining the line impedance $\bar{Z} = R + jX$ the equations are rewritten as:

\[
P = \frac{V_S}{R^2 + X^2} \left[ R (V_S - V_R \cos\delta) + V_R X \sin\delta \right]
\]

(11)

\[
Q = \frac{V_S}{R^2 + X^2} \left[ X (V_S - V_R \cos\delta) - R V_R \sin\delta \right]
\]

(12)

As transmission lines are modelled at being predominantly inductive [30], the resistance is commonly neglected. This reduces the equations to:

\[
P = \frac{V_S V_R}{X} \sin\delta
\]

(13)

\[
Q = \frac{V_S^2 - V_S V_R \cos\delta}{X}
\]

(14)

Furthermore, if the load angle is small, then the small angle approximation can be used (i.e. $\sin\delta=\delta$ and $\cos\delta=1$) [40]. This enables the following further simplification. Rewriting the equations gives:

\[\text{Also called the power angle. It represents the phase difference between the voltages at the two locations.}\]
And these two equations show how the load angle heavily depends on the real power and the voltage difference depends on the reactive power. In other words, the active power transfer depends mainly on the angle by which the sending end voltage leads the receiving end voltage and reactive power transfer is primarily dependent upon voltage magnitudes and is transmitted from the side with a high magnitude to the side with a lower magnitude [30]. Based on this knowledge two typical equations are defined by applying a linear approximation for Q/V and P/f controls [41]:

\[ f - f_0 = -k_p (P - P_0) \]  

\[ V_s - V_{s0} = -k_q (Q - Q_0) \]

Where \( f_0 \) and \( V_{s0} \) are the nominal frequency and voltage, \( P_0 \) and \( Q_0 \) are the temporary set points for the real and reactive power of the machine under consideration, and, \( k_p \) and \( k_q \) are the droop coefficients of the active and reactive power\(^7\).

Rearranging equations 19 and 20 above provides the droop coefficients:

\[ k_p = \frac{\Delta f}{\Delta P} \]  

\[ k_q = \frac{\Delta V}{\Delta Q} \]

Where \( \Delta f, \Delta V, \Delta P \) and \( \Delta Q \) represent the change in frequency, voltage, active power and reactive power from their nominal set points. The lower the machine’s droop value, the more that machine proportionally contributes to the system. Conversely the higher the droop value, the less it participates in load following. For example, for a machine with a P/f droop controller with a droop of 4%, a 4% change in frequency corresponds to a 100% change in active power output. In other words, a machine with a 4% droop

\(^7\) R is used instead of K to symbolize the droop is various texts, e.g in [29].
reaches its nominal active power output at 104% of the machine’s rated speed. In the ideal case, as shown in Figure 13 above, the droop is linear. However, it is only linear in the ideal case. In reality, a machine’s droop characteristic may exhibit incremental regulation, depending on the unit output [30].

4.4.2 Droop controller modelling

As previously mentioned, the implemented droop control is the same as those implemented in the experimental setup in [28]. The following droop control is implemented using the current control mode (CCM). The EVs charging rate is set at its maximum when the measured system voltage is above 0.95 p.u. resulting in nominal power consumption (3.7 kW). The minimum charging rate is set to 6 A and corresponds to when the local voltage measurements reach 0.9 p.u. and 0.925 p.u for the standard and steep droop controllers, respectively. Within these two thresholds, the current is controlled in 10 current steps of 1 A, equally distributed between the aforementioned minimum and maximum voltage set points. These set points are shown in Table 8 and figures 14 and 15 for the standard droop and the steep droop profiles used in the control cases of the simulation work in this thesis. The 1 A step granularity was chosen in alignment with [28].

Table 8: Active Power Droop Controller set points

<table>
<thead>
<tr>
<th></th>
<th>Standard Droop</th>
<th>Steep Droop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V p.u.</td>
<td>V</td>
</tr>
<tr>
<td>6</td>
<td>0.9</td>
<td>207</td>
</tr>
<tr>
<td>7</td>
<td>0.905</td>
<td>208.15</td>
</tr>
<tr>
<td>8</td>
<td>0.91</td>
<td>209.3</td>
</tr>
<tr>
<td>9</td>
<td>0.915</td>
<td>210.45</td>
</tr>
<tr>
<td>10</td>
<td>0.92</td>
<td>211.6</td>
</tr>
<tr>
<td>11</td>
<td>0.925</td>
<td>212.75</td>
</tr>
<tr>
<td>12</td>
<td>0.93</td>
<td>213.9</td>
</tr>
<tr>
<td>13</td>
<td>0.935</td>
<td>215.05</td>
</tr>
<tr>
<td>14</td>
<td>0.94</td>
<td>216.2</td>
</tr>
<tr>
<td>15</td>
<td>0.945</td>
<td>217.35</td>
</tr>
<tr>
<td>16</td>
<td>0.95</td>
<td>218.5</td>
</tr>
<tr>
<td>16</td>
<td>1.1</td>
<td>253</td>
</tr>
</tbody>
</table>
The droop coefficients for the two active power only control cases was determined by first defining the nominal power as the available range of regulating power afforded to the EVs, instead of the maximum EV charging power (i.e. 2.3 kW instead of 3.7 kW), as this is the control range allotted in this modelling work and the associated experimental work. With this nominal power value, the following droop coefficients are determined:

\[
\text{Standard droop coefficient } (k_1) = \frac{\Delta V}{\Delta P} = \frac{0.05 \text{ p.u.}}{1 \text{ p.u.}} = \frac{11.5 \text{ V}}{2.3 \text{ kW}} = 5\%
\]

\[
\text{Steep droop coefficient } (k_2) = \frac{\Delta V}{\Delta P} = \frac{0.025 \text{ p.u.}}{1 \text{ p.u.}} = \frac{5.75 \text{ V}}{2.3 \text{ kW}} = 2.5\%
\]

![Figure 14: Theoretical standard droop (k₁=5%) and steep droop (k₂=2.5%) profiles](image)

However, due to the fact that the charging is regulated in 1 A steps, the actual active power droop EV charging profiles follow the plots shown in **Figure 15**. Implementing the realistic standard droop profile in case 4 created too many large oscillations. Therefore, the ideal standard droop characteristic was implemented instead, as shown in the blue trace in **Figure 14** as well as the black trace in **Figure 15**. While this changed the charging set points, it still kept the charging rates within a close enough range to be comparable.
Figure 15: Actual droop profiles

The standard active power droop control set points were used in cases 2 and 4, while the steep droop profile was used in case 3.

For case 4, when both active and reactive power control is implemented, the following reactive power matrix, shown in Figure 16, was used for the reactive power control portion. The standard active power droop setting was used in case 4.

Figure 16: Reactive power droop profile in Case 4

The reactive power control matrix increments in 0.001 p.u. voltage measurements. From the voltage range of $V = 0.9$ to $0.95$ p.u. and in active power steps of 0.2 p.u., it supplies
the maximum amount of capacitive reactive power in 0.1 p.u. steps (with a maximum of $Q = 0.5$ p.u. at $p = 1.0$ p.u.) is supplied. From $V = 0.95$ to $0.975$ p.u., the reactive power output steps progressively decrease at increments of $Q = 0.0025$ p.u. per step per 0.001 V p.u. step while increasing per step by $Q = 0.0025$ p.u. per increase in $P = 0.2$ p.u. step, as visualized by the transition to the steeper slope. From $V = 0.975$ to $1.025$ p.u. there is a dead band where no reactive power is supplied or absorbed. Above $V = 1.025$ p.u., the reactive power control follows the same pattern described above but now absorbs reactive power by the same increments for the same ranges; i.e. increments in 0.0025 p.u. steps for the first range of 0.025 V p.u. until $V = 1.05$ p.u., wherein the amount of inductive reactive power absorbed increases to its maximum based on active power measurements. This reactive power control has the same characteristic, but with the opposite capacitive and inductive injection and absorption profile as the PV inverters installed in the system, as the PV is modelled as a generator in the system, whereas the EVs are modelled as loads.

The overarching control architecture for the EV charging, as elucidated in [28], is shown in Figure 17 below.

![Figure 17: EV charging architecture: power and communication flow](image-url)
4.4.3 Composite Frame for the EVs

The droop controller is implemented in the EV composite frame, as shown in Figure 18 and Figure 19. The composite frame connects the various slots and associated inputs and outputs to manipulate the EV’s load profile to ensure that EV charging is modulated properly during varying grid conditions. An overview of the controller’s composite frame is shown in Figure 18 for cases 2 & 3 and in Figure 19 for case 4. A sequential description of the slots included in the two frames is provided.

In the Vmeas slots the phase to neutral voltage is measured for all three phases in p.u. These three measurements are created during the simulation and their corresponding output signals (named ua, ub, and uc in the frame, respectively) are sent to the voltage Selector slot.

The Selector slot determines which voltage to select based on the three aforementioned signals being individually multiplied by a flag parameter (titled flagA, flagB and flagC) which corresponds to the specific DSL slot that has assigned to the specific composite model of the specific EV analyzed through the frame. For example, the EV connected to the household named Græsmarken01, titled EV_G01, is connected to phase B. As such, its voltage selector slot corresponds to an EV connected to phase B, is named accordingly, and provides the Selector slot with the information 0,1,0 corresponding to the listed flag order above. Thereby the measured voltages on phase A and C are zeroed out and only the voltage for phase B (the phase the EV is connected to) is output to the next slot, the Delay slot.

The Delay slot delays the signal from being sent onwards to the Droop slot to simulate a more realistic control process. The delay is set to 1 second.

After the delay, the voltage signal is sent to the Droop slot where the voltage is used to determine the current reference set point for the EV’s charging rate. The Droop slot returns a current reference value that is rounded to the closest whole integer by first creating a linear approximation using the measured voltage value and then rounding this value to its closest whole digit to find the appropriate corresponding current value. As denoted in Table 8, 1 A steps are implemented for cases 2 & 3, to simulate more realistic conditions that identically matched the associated experimental work.
Once the current reference value is determined, it is sent to the **Power reference** slot where, in conjunction with the measured voltage value, the active power reference value ($P_{\text{ref}}$) is determined.

Next, the power reference value is input along with the EV measurement file to determine the external power value using the active Power Selector (**P_Selector**) slot. The EV measurement file is a file that tells the desired weekly charging schedule of the EV into the simulation. The **P_Selector** slot performs a select function to ensure that the desired power draw is not greater than the system can permit at this point. It does show by ensuring that the requested charge level (the input active power value ($P_{\text{file}}$) from the EV measurement file) does not exceed the value just calculated in the power reference slot. If this is the case, the output of the P_Selector slot, the external active power ($P_{\text{ext}}$) is set equal to $P_{\text{file}}$, otherwise $P_{\text{ext}}$ is capped to the maximum permissible charging level determined by a lower voltage, i.e. $P_{\text{ext}}$ is set to equal $P_{\text{ref}}$. Lastly, the $P_{\text{ext}}$ is then used to set the active power load value using the **EV load** slot. The EV’s load is updated accordingly in the simulation.

![Figure 19: EV Composite Frame for Case 4](image)

For case 4, with both active and reactive power control, at the same time the voltage signal is sent to the **droop** slot for the active power regulation, this voltage signal is also sent to the reactive power (Q) controller slot where in conjunction with $P_{\text{ext}}$, the reactive power is modulated according to the control profile shown in **Figure 16**. This provides the appropriate reactive power set point for the EV supply equipment (EVSE). In order to do so, first the $P_{\text{ext}}$ value is converted to a per unit value. This allows it to be directly used along with the voltage signal (which is also in p.u.) to determine the associated p.u. Q value using the sapprox2 function in PowerFactory, which returns the spline approximation of a two-dimension array based on the provided Q matrix. The Q matrix is a 7x202 matrix denoting the Q values from 0 to 0.5 p.u. in 0.1 p.u. increments, voltage values from 0.9 to 1.1 V p.u. in 0.001 p.u. increments and active power values from 0 to 1 P p.u. in 0.2 p.u. increments. The correspondingly selected Q p.u. value is then converted to $Q_{\text{ext}}$ by multiplying it by the actual nominal power value.
4.4.4 Droop controller testing

In order to ensure that the designed droop controller was properly implemented into the simulated grid, a simple test grid case was built in PowerFactory. In this simple case, a two bus system with three loads was created. The first bus was represented as a slack bus. The three loads, representing three EVs, were connected one per phase to the second bus, and a ramp load event was initiated where the active power was gradually increased through a proportional load step to create gradual changes throughout the entire range of the controller. The three “EV” loads were set to the same unbalance as in the modelled grid of the Borup network being analyzed. The load was gradually increased to ensure that the voltage dropped to below the minimum set point as defined in section 4.4.2. This validation process is show for phase A in Figure 20 below.

**Figure 20:** Validating that the controller works properly in PowerFactory

Figure 20 shows the charging set point mechanism based on the local voltage measurements for seven charging periods. In the top plot, the black trace, $P_{in}$ corresponds to the EVs requested charging level, the red trace, $P_{ref}$ corresponds to the maximum permissible charge rate based on the local voltage measurements, and $P_{ext}$ the blue trace, corresponds to the actual charging level for the EV. In the second plot, the current reference value $I_{ref}$ is shown.

As the load ramp event increases, the local voltage value drops proportionally. Accordingly, the actual active power charging level is curtailed to the corresponding highest permissible level. For the last three charging period requests, this corresponds to the minimum charge rate, as the local voltage value has dropped to values $\leq 0.9$ p.u and the EVSE is charging the EV at 6 A. The oscillation in the fourth charging event (Wednesday) occurs due to the implemented resolution time step. A finer resolution eliminates the oscillations here.
5 RESULTS

This chapter reports the results of the PowerFactory simulation of the portion of the Danish distribution grid in the town of Borup under analysis. The results are divided into the five simulated cases, the first two being uncontrolled reference cases, without and then with the inclusion of EVs; whereas the latter three are defined by their respective droop control. For each case a plot of the power profile across the critical cable in the system cable 301-601 is presented, as is this cable’s loading profile. Then the voltage profile for phase A in the critical feeder in the system is presented, along with a table outlining the low voltage range and frequency of occurrence in the case. This is followed by a plot depicting the line-to-ground phase voltages at bus 613, the most problematic bus in the system. Lastly, the voltage unbalance factor is reported for each case. All the plotted simulation result data has been aggregated into 10 minute averaged values to align with the measurement criteria set forth in EN 50160, as described in section 4.3.2.

5.1 Case 0: No EVs in Borup

This initial case is used as a benchmark for the system. In it, none of the modelled houses have EVs and as such only the standard household load profiles are considered. These values provide a baseline point of reference for the latter cases considered.
5.1.1 Cable 301-601 Profile

Figure 21 below shows the apparent power (S), active power (P) and reactive power (Q) for cable 301-601 for the week under analysis. Cable 301-601, as shown in Figure 8, represents the cable connecting both the neighborhoods of Græsmarken and Hørmarken to bus 301, which is the connection point to the other three feeders in the system and the transformer to the external grid. As such, it carries the full current of both neighborhoods under analysis, and experiences the most stress in this analyzed system. The cable’s loading profile is shown below in Figure 21. The apparent power is the relevant power to monitor in terms of cable loading. The reactive power is plotted for comparison purposes, and in particular to show the relative difference with the first four cases in comparison with case 4. The maximum S over the cable in case 0 is 50.047 kVA.

![Power Profile Over Cable 301-601](image)

**Figure 21** Case 0: Power profile over cable 301-601

The power profile remains within the cable’s limits at all times, and as can be seen in Figure 22, the maximum cable loading does not exceed 66.34% of the cable’s rated current (335 A).

![Current Loading Profile Along Cable 301-601](image)

**Figure 22** Case 0: Current loading profile along cable 301-601
5.1.2 Voltage Profile

Figure 23 below plots the Phase A voltage profiles for buses 609-613. This represents the most problematic path considered, as bus 613 is the furthest from the point of common coupling (PCC). As such it experiences the largest voltage drops, and will be the bus focused on for further investigation and analysis. The plot is read from right to left, where the week begins on Sunday and then proceeds sequentially through the weekdays ending on Saturday. The maximum voltage deviations occur on Wednesday evening peak load during the second hour of EV charging. The total number of periods below 0.9 V p.u. in case 0 for all buses in the analyzed system was 254.

As shown below in Table 9, even before the EVs are introduced into the system, the minimum voltage limits are violated. To reiterate, EN 50160 states that during lower voltages, the voltage may not drop below 0.85 p.u. at any time and is only allowed to drop between 0.9 to 0.85 p.u. for a maximum of 5% of the 10 minute average voltage samples for a week (1008 total samples). Buses 611, 612 and 613 exceed this latter constraint by 11.9%, 44.8% and 72.6%, respectively.

Table 9 Case 0: Phase A voltages along the critical feeder

<table>
<thead>
<tr>
<th>Bus</th>
<th>( V_{\text{max}} )</th>
<th>( V_{\text{min}} )</th>
<th>( V_{\text{average}} )</th>
<th># samples below 0.9</th>
<th>% below 0.9</th>
<th># below 0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>609</td>
<td>220.76</td>
<td>206.61</td>
<td>214.49</td>
<td>5</td>
<td>0.50%</td>
<td>0</td>
</tr>
<tr>
<td>610</td>
<td>220.05</td>
<td>204.99</td>
<td>213.36</td>
<td>38</td>
<td>3.77%</td>
<td>0</td>
</tr>
<tr>
<td>611</td>
<td>219.55</td>
<td>203.81</td>
<td>212.52</td>
<td>51</td>
<td>5.06%</td>
<td>0</td>
</tr>
<tr>
<td>612</td>
<td>219.23</td>
<td>202.95</td>
<td>211.94</td>
<td>73</td>
<td>7.24%</td>
<td>0</td>
</tr>
<tr>
<td>613</td>
<td>219.09</td>
<td>202.50</td>
<td>211.69</td>
<td>87</td>
<td>8.63%</td>
<td>0</td>
</tr>
</tbody>
</table>
5.1.2.1 Voltage Profile at bus 613

Figure 24 below shows the voltage profile of bus 613 for case 0. This plot highlights extent to which phase A is impacted under case 0. The red trace $V_{\text{min}}$ is set to 207 V (0.9 p.u.) as a visual reference point.

Figure 24 Case 0: Node 613 phase voltages over the week

The voltage profile for phase A in node 613 is under the minimum permissible voltage (207 V) for 87 of the 10 minute average periods during the week (1008 periods), corresponding to 8.63% of the periods. This corresponds to exceeding the minimum acceptable voltage for 72.6% more than the permissible amount of time under EN 50160, as a maximum of 50 10 minute averaged violations (5%) is allowed in the standard.
5.1.3 Voltage Unbalance Factor

The average VUF for the case 0, reported in 10 minute averaged intervals, was 1.06, with a peak value of 1.66 and a minimum value of 0.63. These values are always within their limitations, and as such are acceptable. Figure 25 below shows the VUF for the entire week in this scenario.

![Figure 25 Case 0: Voltage Unbalance Factor](image-url)
5.2 Case 1: Uncontrolled Charging with 100% EV penetration

Case 1 represents the uncontrolled charging case with 100% EV penetration. This case is primarily used to highlight the worst-case-scenario of the cumulative impact of EVs in the grid under a “dumb” charging scenario with full penetration in a Danish distribution grid. The unacceptable added stress the system experienced under this scenario is what a DSO or EV aggregator would seek to minimize in a more intelligent charging scenario. It is against this case that the subsequent three droop control charging cases will be compared.

5.2.1 Cable 301-601 Profile

Figure 26 below shows the apparent power (S), active power (P) and reactive power (Q) for cable 301-601 for case 1. The magnitude of the cumulative additional load from the added 43 EVs into the system is clearly shown below in Figure 26 when compared to Figure 21. The maximum S demand is increased by 86.7% from just over 50 kVA in case 0 to 93.47 kVA here in case 1.

![Figure 26 Case 1: Power profile over cable 301-601](image_url)
Cable 301-601’s current loading profile for the week is shown in Figure 27. As can be clearly seen, during every EV charging period, the loading limit is exceeded for this cable, with a peak load occurring on Wednesday at 124.38% of the cable’s rated current.

![Figure 27 Case 1: Cable 301-601 loading profile](image)

If this degree of cable loading was to occur daily for multiple weeks every winter, this situation would presumably represent an unacceptably high level of loading. Consistent overloading, as well as severe overloading is to be avoided, as this inevitably leads to overheating temperatures, which in turn shorten the lifetime of the cable. Reducing cable lifetime can significantly increase operating costs [42]. This also has significant security of supply concerns for these two neighborhoods. However, other factors, if proportionally more pronounced, may mitigate the otherwise potentially alarming level of overloading on this cable. Two important factors in this consideration are how analogous are these loading levels to those during the rest of the winter. If they’re very analogous this raises the concern, whereas if this peak week is much higher than the rest of the winter then it becomes less problematic. Secondly, the cable’s specifications play a role in how permissible over currents are, and for what duration extended over loading scenarios are permissible, and to what magnitude. If analogous to [43], then the cable can tolerate 133% loading for up to 1 hour. If so, this would indicate that the 3.5 hour EV charging window represents far too long an allowance to be considered prudent management of this asset.
5.2.2 Voltage Profile

Figure 28 below shows the phase A voltage profiles for buses 609-613. As previously mentioned, this represents the most problematic path considered, as bus 613 is the furthest from the PCC.

Figure 28 Case 1: Phase A bus voltages along critical feeder

The total number of periods below 0.9 V p.u. (207 V) in case 1 for all buses in the analyzed system was 1263, which is an increase by 1009 measurements from case 0, corresponding to an overall increase of 497%. This is visualized in the severity of the drops during the EV charging periods in Figure 28, highlighted by the dark blue regions in the bottom of the plot. As can be seen, the most adversely affected day in the system is Wednesday evening. As an aside, the Z axis has a correspondingly lower minimum level to accommodate the severity of these voltage drops.
The effect of the impact of the additional cumulative load from the 42 EVs along this feeder is highlighted in Table 10 below. The impact of the EVs is pronounced, as the latter half of Table 10 denotes. The number of 10 minute averaged voltage samples that drop below the minimum threshold of 0.9 p.u. is doubled at node 613 from case 0, and the rates are increased along the earlier buses in this feeder. Most pronounced is that there are now measurements that drop below 0.85 p.u., which represents an unacceptably low voltage measurement in any quantity. This happens for 9 periods at bus 612, and 19 times at bus 613.

**Table 10** Case 1: Phase A voltages along the critical feeder

<table>
<thead>
<tr>
<th>Bus</th>
<th>609</th>
<th>610</th>
<th>611</th>
<th>612</th>
<th>613</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{max}}$</td>
<td>220.76</td>
<td>220.05</td>
<td>219.55</td>
<td>219.23</td>
<td>219.09</td>
</tr>
<tr>
<td>$V_{\text{min}}$</td>
<td>199.31</td>
<td>197.10</td>
<td>195.52</td>
<td>194.47</td>
<td>193.77</td>
</tr>
<tr>
<td>$V_{\text{average}}$</td>
<td>213.41</td>
<td>212.19</td>
<td>211.29</td>
<td>210.68</td>
<td>210.39</td>
</tr>
<tr>
<td># samples below 0.9</td>
<td>147</td>
<td>152</td>
<td>161</td>
<td>171</td>
<td>174</td>
</tr>
<tr>
<td># increase from Case 0</td>
<td><strong>142</strong></td>
<td><strong>114</strong></td>
<td><strong>110</strong></td>
<td><strong>98</strong></td>
<td><strong>87</strong></td>
</tr>
<tr>
<td>% increase from Case 0</td>
<td>2940%</td>
<td>400%</td>
<td>316%</td>
<td>234%</td>
<td>200%</td>
</tr>
<tr>
<td>% below 0.9</td>
<td>14.58%</td>
<td>15.08%</td>
<td>15.97%</td>
<td>16.96%</td>
<td>17.26%</td>
</tr>
<tr>
<td># below 0.85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>19</td>
</tr>
</tbody>
</table>
5.2.2.1 Voltage Profile at bus 613

The impact of the cumulative addition of the uncontrolled EVs in case 1 at bus 613, by each phase, is shown in Figure 29 below. This impact is particularly pronounced when taken in comparison to Figure 24. The peak load is magnified by the cumulative impact of all the EVs charging. The impact is most problematic in phase A, where the 10 minute averaged voltage has an average value of 0.91 p.u. and a minimum value of 0.84 p.u. This clearly demonstrates the need to mitigate the combined impact of a high penetration uncontrolled charging scenario.

![Figure 29 Case 1: Bus 613 phase voltages](image)

The voltage profile for phase A in node 613 is under the minimum voltage (207 V) for 174 of the 10 minute average periods during the week (1008 periods), corresponding to 17.26% of the periods and exactly double that in case 0. This corresponds to exceeding the minimum acceptable voltage for 245% more than the permissible amount of time under EN 50160. Furthermore, for 19 periods, the voltage drops below 0.85 p.u., representing voltage levels never permissible.
5.2.3 Voltage Unbalance Factor

The average VUF for case 1, averaged into 10 minute averaged intervals, was 1.06, with a peak value of 1.75 and a minimum value of 0.62. These values are always within their limitations, and as such are acceptable. Figure 30 below shows the VUF for the entire week in case 0. Unsurprisingly, these numbers and this figure are only marginally different from those reported in case 0, as the EVs were connected in a balanced rotation when incorporated into the system.

![Figure 30 Case 1: Voltage Unbalance Factor](image-url)
5.3 Case 2: EVs with standard Active Power droop control

The intent of this control mechanism is to demonstrate how a simple autonomous, distributed control can facilitate the penetration of increased percentages of EVs into the analyzed distribution system. The benefits of such a solution is that it provides voltage support and can assist in providing an alternative to deferring distribution upgrades, which is a costly measure conducted by the DSO. By doing so, this would enable a higher penetration of EVs into the existing power system. Case 2 is an extension of the experimental work discussed in section 3.1, applied to the modelled system under consideration.

5.3.1 Cable 301-601 Profile

Figure 31 below shows the apparent power (S), active power (P) and reactive power (Q) for cable 301-601 for case 2. The maximum S over cable 301-601 in case 2 is 75.45 kVA, representing an apparent power curtailment over the cable of 18.02 kVA, which is a 19.3% reduction from case 1.

![Figure 31 Case 2: Power profile over cable 301-601](image-url)
Cable 301-601’s current loading profile for case 2 is shown below in Figure 32. As can be seen, especially in comparison to Figure 27, the loading profile has been curtailed markedly. This shows that the droop controller is functioning properly, and at these set points, can ensure that the most critical cable in the system is not overloaded. The maximum loading is 100.31% on Wednesday. This small, short term overloading is considered acceptable, as it only occurs briefly on the most loaded day of the most loaded week in the system.

![Figure 32 Case 2: Cable 301-601 loading profile](image-url)
5.3.2 Voltage Profile

Figure 33 below shows the case 2 phase A voltage profiles for buses 609-613. As previously mentioned, this represents the most problematic path considered, where bus 613 is the furthest node from the PCC. As such it experiences the largest voltage drops, and is of the most concern. The total number of periods below 0.9 V p.u. in case 2 for all buses in the analyzed system was 599, which is an increase of 345 low voltage measurements from case 0, corresponding to an overall increase of 236%, but at the same time represents 664 fewer violations than in case 1, the uncontrolled case, showing how the basic droop control prevents 52.57% of the low voltage violations that would otherwise occur in the system.

![Voltage Profile Graph]

**Figure 33** Case 2: Phase A bus voltages along critical feeder

Table 11 provides a snapshot of how the standard droop control curtails the EV charging, enabling the voltage to recovery to better rates relative to case 1. However, the magnitude and duration of the voltage drop at various points in the system is still unacceptably large, as defined in EN 50160 (i.e. >50 samples below 0.9 V p.u. for the week), for buses 610 through 613, as reported in the fourth row of this table.

**Table 11** Case 2: Phase A voltages along the critical feeder

<table>
<thead>
<tr>
<th>Bus</th>
<th>609</th>
<th>610</th>
<th>611</th>
<th>612</th>
<th>613</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{max}}$</td>
<td>220.33</td>
<td>219.62</td>
<td>219.13</td>
<td>218.81</td>
<td>218.67</td>
</tr>
<tr>
<td>$V_{\text{min}}$</td>
<td>203.69</td>
<td>201.98</td>
<td>200.70</td>
<td>199.87</td>
<td>199.48</td>
</tr>
<tr>
<td>$V_{\text{average}}$</td>
<td>213.68</td>
<td>212.56</td>
<td>211.73</td>
<td>211.16</td>
<td>210.90</td>
</tr>
<tr>
<td># samples below 0.9</td>
<td>41</td>
<td>65</td>
<td>114</td>
<td>146</td>
<td>164</td>
</tr>
<tr>
<td>---------------------</td>
<td>----</td>
<td>----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td># improved from Case 1</td>
<td>106</td>
<td>87</td>
<td>47</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>% below 0.9</td>
<td>4.07</td>
<td>6.45</td>
<td>11.31</td>
<td>14.48</td>
<td>16.27</td>
</tr>
<tr>
<td># below 0.85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.3.2.1 Voltage Profile at bus 613

The impact of case 2 at bus 613 for each phase is shown in Figure 34 below. Phase A experiences an average voltage value of 0.917 p.u., a minimum value of 0.867 p.u and a maximum voltage of 0.951 p.u.

![Figure 34 Case 2: Bus 613 phase voltages](image)

The voltage profile for phase A in node 613 is under the minimum voltage (207 V) for 164 of the 10 minute average periods during the week (1008 periods), corresponding to 16.27% of the periods. This corresponds to exceeding the minimum acceptable voltage for 225% more than the permissible amount of time. However, the voltage never drops below 0.85 p.u., an improvement over case 1.

5.3.3 Voltage Unbalance Factor

The VUF for the case 2, reported in 10 minute averaged intervals, was 0.99, with a peak value of 1.57 and a minimum value of 0.63. These values are always within their limitations, and as such are acceptable. Figure 35 below shows the VUF for the entire week in case 2.
Figure 35 Case 2: Voltage Unbalance Factor
5.4 Case 3: EVs with steep Active Power droop control

In case 3, the slope of the droop is doubled from case 2, the normal droop controller. The following results show the impact of using this steeper droop with a shorter voltage range on the system.

5.4.1 Cable 301-601 Profile

Figure 36 below shows the apparent power (S), active power (P) and reactive power (Q) for cable 301-601 for case 3. The maximum S over cable 301-601 in case 3 is 76.67 kVA, representing an apparent power curtailment over the cable of 21.8 kVA, which is a 23.3% reduction from case 1.

![Figure 36 Case 3: Power profile over cable 301-601](image)

The slightly higher rate of power curtailment in case 3 relative to case 2 was expected due to the more refined set points in this controller.
Cable 301-601’s current loading profile for case 3 is shown below in Figure 37. As can be seen, especially in comparison to Figure 27 in case 1, the loading profile has been curtailed markedly and more so than in Figure 32 in case 2. This shows that the droop controller is functioning properly, and at these set points, can ensure that the most critical cable in the system is not overloaded. The maximum loading is 95.35% on Wednesday.

Figure 37 Case 3: Cable 301-601 loading profile
5.4.2 Voltage Profile

Figure 38 below shows the case 3 Phase A voltage profiles for buses 609-613. As previously mentioned, this represents the most problematic path considered, where bus 613 is the furthest node from the PCC. As such it experiences the largest voltage drops, and is of the most concern. The total number of periods below 0.9 V p.u. in case 3 for all buses in the analyzed system was 600, which is an increase of 346 low voltage measurements from case 0, corresponding to an overall increase of 236%, but at the same time represents 663 fewer violations than in case 1, the uncontrolled EV charging case, showing how the basic steep droop control prevents 52.49% of the low voltage violations that would otherwise occur in the system.

![Voltage Profile Diagram]

**Figure 38** Case 3: Phase A bus voltages along critical feeder
Table 12 provides a snapshot of how the steep droop controller curtails the EV charging. However, the magnitude and duration of the voltage drop at various points in the system is still unacceptably large, as defined in EN 50160, for buses 610 through 613, as reported in the fourth row, as the maximum permissible number of samples between 0.85-0.9 V p.u. (195.5 – 207 V_LN) for the week is 50 according to EN 50160.

<table>
<thead>
<tr>
<th>Bus</th>
<th>609</th>
<th>610</th>
<th>611</th>
<th>612</th>
<th>613</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{max}</td>
<td>220.33</td>
<td>219.62</td>
<td>219.13</td>
<td>218.81</td>
<td>218.67</td>
</tr>
<tr>
<td>V_{min}</td>
<td>204.02</td>
<td>202.31</td>
<td>201.02</td>
<td>200.17</td>
<td>199.78</td>
</tr>
<tr>
<td>V_{average}</td>
<td>213.70</td>
<td>212.57</td>
<td>211.72</td>
<td>211.15</td>
<td>210.88</td>
</tr>
<tr>
<td># samples below 0.9</td>
<td>38</td>
<td>66</td>
<td>120</td>
<td>153</td>
<td>165</td>
</tr>
<tr>
<td># improved from Case 1</td>
<td>109</td>
<td>86</td>
<td>41</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>% below 0.85</td>
<td>3.77</td>
<td>6.55</td>
<td>11.90</td>
<td>15.18</td>
<td>16.37</td>
</tr>
<tr>
<td># below 0.85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.4.2.1 Voltage Profile at bus 613

The impact of case 3 at bus 613 for each phase is shown in Figure 39 below. Phase A experiences an average voltage value of 0.917 p.u., a minimum value of 0.867 p.u and a maximum voltage of 0.951 p.u.

The voltage profile for phase A in node 613 is under the minimum voltage (207 V) for 165 of the 10 minute average periods during the week (1008 periods), corresponding to 16.37% of the periods. This corresponds to exceeding the minimum acceptable voltage for 227% more than the permissible amount of time under EN 50160. Here again, the voltage never drops below 0.85 p.u.
5.4.3 Voltage Unbalance Factor

The average VUF for Case 3, reported in 10 minute averaged intervals, was 1.02, with a peak value of 1.60 and a minimum value of 0.63. These values are always within their limitations, and as such are acceptable. Figure 40 below shows the VUF for the entire week in Case 3.

![Figure 40 Case 3: Voltage Unbalance Factor](image-url)
5.5 Case 4: EVs with Active and Reactive Power droop control

The droop controller used in Case 4 is markedly different from the previous two cases, as now it is modelled to provide reactive power control locally during over or under voltage situations, providing a further level of local voltage support in addition to the active power droop controller implemented in cases 3 and 4. As the analyzed week represents the most heavily loaded time period in the system, these conditions correspond to the reactive power portion of the controller providing capacitive reactive power to increase the local voltage levels. Case 4 goes past the experimental work discussed in section 3.1 and considers the following scenario with a more encompassing control mechanism.

5.5.1 Cable 301-601 Profile

Figure 41 below shows the Apparent Power (S), Active Power (P) and Reactive Power (Q) for cable 301-601 for Case 4. The maximum S over cable 301-601 in Case 4 is 76.12 kVA, representing a net apparent power curtailment over the cable of 17.35 kVA, representing a 18.56% reduction from Case 1.

![Figure 41 Case 4: Power profile over cable 301-601](image)

A notable difference in this case is how the reactive power in the system changes during the EV charging periods, shown in the blue Q trace. The level of reactive power support provided changes the p.f. angles at each bus where the EVs are present to leading, from lagging as they are in every other time period in the system. This indicates that the EVs are providing a level of reactive power compensation that exceeds their local voltage requirements, as the level of compensation provided goes beyond unity p.f. and leads to the net exporting reactive power to attempt to improve the voltage levels elsewhere in the system, i.e. exporting reactive power for the “other feeders” at bus 301. This is visualized in Figure 41, not only directly in the Q trace during the EV charging periods, but also in the P trace as it overlaps the S trace, whereas in the previous four cases, it follows the specified inductive p.f. of 0.95. The maximum Q exported is 4.84 kvar during Friday’s EV charging period.
Cable 301-601’s current loading profile for case 4 is shown below in Figure 42. The loading profile is higher than in case 3 and most analogous to case 2. The maximum loading is 100.78% briefly during the peak load on Wednesday. The cable loading profile is only exceeded for two 10 minute averaged periods, periods 551 and 552, and only by 0.45% and 0.35% each, respectively. This is considered acceptable under the same rationale provided in case 2. That is, that since this week is the most heavily loaded one in the system, and this overloading is so brief, that it does not warrant further action or concern.

![Figure 42 Case 4: cable 301-601 loading profile](image-url)
5.5.2 Voltage Profile

Figure 43 below shows the case 4 voltage profiles for phase A of buses 609-613. As previously mentioned, this represents the most problematic path considered, where bus 613 is the furthest node from the PCC.

![Voltage Profile Diagram]

Figure 43 Case 4: Phase A bus voltages along the critical feeder

The combined P & Q control implemented in this case notably improves but voltages across the entire profile, as Figure 43 demonstrates. The total number of periods below 0.9 V p.u. in Case 4 for all buses in the analyzed system was 367, which is an increase of 113 low voltage measurements from case 0, corresponding to an overall increase of 145%, but at the same time represents 896 fewer violations than in case 1, the uncontrolled EV charging case, showing how the combined active and reactive power droop control solution prevents 70.94% of the low voltage violations that would otherwise occur in the system.
Table 12 provides an overview of how the combined standard P and Q droop control curtails the EV charging. However, the magnitude and duration of the voltage drop at various points in the system is still unacceptably high for buses 611 through 613, as reported in the fourth row of this table.

Table 13 Case 4: Phase A voltages along the critical feeder

<table>
<thead>
<tr>
<th>Bus</th>
<th>609</th>
<th>610</th>
<th>611</th>
<th>612</th>
<th>613</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{max}</td>
<td>220.33</td>
<td>219.62</td>
<td>219.13</td>
<td>218.81</td>
<td>218.67</td>
</tr>
<tr>
<td>V_{min}</td>
<td>204.87</td>
<td>203.29</td>
<td>201.99</td>
<td>201.18</td>
<td>200.81</td>
</tr>
<tr>
<td>V_{average}</td>
<td>213.87</td>
<td>212.78</td>
<td>211.94</td>
<td>211.39</td>
<td>211.14</td>
</tr>
<tr>
<td># samples below 0.9</td>
<td>14</td>
<td>35</td>
<td>79</td>
<td>103</td>
<td>116</td>
</tr>
<tr>
<td>% below 0.9</td>
<td>1.39</td>
<td>3.47</td>
<td>7.84</td>
<td>10.22</td>
<td>11.51</td>
</tr>
<tr>
<td># below 0.85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.5.2.1 Voltage Profile at bus 613

Figure 44 below shows the voltage profile of bus 613 in case 4. While there are numerous intervals when the voltage drops below the acceptable limits in phase A, as clearly shown by the red horizontal trace at 207 V (0.9 p.u.)

![Voltage Profile at bus 613](image)

The voltage profile for phase A in node 613 is under the minimum voltage (207 V) for 116 of the 10 minute average periods during the week (1008 periods), corresponding to 11.51% of the periods. This corresponds to exceeding the minimum acceptable voltage for 130% more than the permissible amount of time under EN 50160. The lowest voltage during a 10 minute averaged period was 200.81 V (0.873 p.u.). However, there are marked improvements over case 1, as highlighted in the bolded row in Table 13.
5.5.3 Voltage Unbalance Factor

The average VUF for Case 4, reported in 10 minute averaged intervals, was 0.974, with a peak value of 1.55 and a minimum value of 0.57. These values are always within their limitations, and as such are acceptable. Figure 45 below shows the VUF for the entire week in Case 4.

![Figure 45 Case 4: Voltage Unbalance Factor](image-url)
5.6 Results Summary

The power quality and congestion management considerations are partially and fully mitigated in the control cases, respectively. A summary to the extent to which the focused power quality considerations are partially resolved, as well as a summary as to the mitigation of cable overloading is henceforth conducted.

It is important to note that these problems are seasonal in nature. As load levels decrease in in the other seasons of the year, coupled with an increased PV penetration in the system under consideration, the magnitude and volume of low voltage violations will decrease and may be potentially eliminated entirely through reduced demand and the PV inverters being used to provide local voltage control.

5.6.1 Cable 301-601

In each of the control cases, the implemented droop control strategy was successful in preventing the overloading of the most critical cable in the analyzed system, cable 301-601. Case 4 was able to do with while supplying the most active power to the loads downstream of cable 301-601, and as such provides the highest level of service to the EV owners while ensuring that the cable’s constraints are not violated.

5.6.2 Voltage profile

Case 0 represents the simulated grid before the introduction of EVs. Case 1, the uncontrolled charging case, introduces just under a factor of 5 increase in the number of low voltage violations in comparison to the no EV case, case 0. This increases the number of low voltage violations in the entire system from 254 to 1235.

Cases 2 through 4, the control cases, show both the actual number of low voltage violations realized in each case in their row “below 0.9 p.u.” as well as the per bus violation reductions from case 1 achieved through the specific droop control implemented. This latter set of information is shown in cases 2-4’s improvement row. The improvement total is expressed as the percent improvement of the respective case to case 1.

Table 14: Overview of low voltage violations by bus

<table>
<thead>
<tr>
<th>Voltage measurements</th>
<th>Bus 602</th>
<th>603</th>
<th>604</th>
<th>606</th>
<th>607</th>
<th>608</th>
<th>609</th>
<th>610</th>
<th>611</th>
<th>612</th>
<th>613</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 0</td>
<td>below 0.9 p.u.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>38</td>
<td>51</td>
<td>73</td>
<td>87</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>below .85 p.u.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 1</td>
<td>below 0.9 p.u.</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>135</td>
<td>142</td>
<td>145</td>
<td>147</td>
<td>152</td>
<td>161</td>
<td>171</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td>below .85 p.u.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>19</td>
<td>28</td>
</tr>
<tr>
<td>Case 2</td>
<td>below 0.9 p.u.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>29</td>
<td>35</td>
<td>41</td>
<td>65</td>
<td>114</td>
<td>147</td>
<td>165</td>
</tr>
<tr>
<td>Improvement</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>132</td>
<td>113</td>
<td>110</td>
<td>106</td>
<td>87</td>
<td>47</td>
<td>33</td>
<td>28</td>
<td>210.85%</td>
</tr>
<tr>
<td>Case 3</td>
<td>below 0.9 p.u.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>26</td>
<td>30</td>
<td>38</td>
<td>66</td>
<td>120</td>
<td>153</td>
<td>165</td>
</tr>
<tr>
<td>Improvement</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>133</td>
<td>116</td>
<td>115</td>
<td>109</td>
<td>86</td>
<td>41</td>
<td>27</td>
<td>28</td>
<td>210.50%</td>
</tr>
<tr>
<td>Case 4</td>
<td>below 0.9 p.u.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>10</td>
<td>14</td>
<td>35</td>
<td>79</td>
<td>103</td>
<td>116</td>
</tr>
<tr>
<td>Improvement</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>134</td>
<td>133</td>
<td>135</td>
<td>133</td>
<td>117</td>
<td>82</td>
<td>77</td>
<td>77</td>
<td>344.14%</td>
</tr>
</tbody>
</table>
5.6.2.1 Voltage Profile at bus 613

Figure 46 provides the bus 613 voltage profile for each analyzed case. This comparison visualizes the contrasting magnitude to which the different EV charging scenarios have on the furthest bus from the PCC in the analyzed system.

Figure 46 highlights the relative difference between the uncontrolled and controlled cases. The difference between case 4 and the other cases is particularly pronounced during Thursday’s charging period, where the black trace goes notably above the minimum permissible voltage, whereas cases 2 and 3 remain just below the limit.

Figure 47 and Figure 48 provide a zoomed in view of the Sunday and Wednesday EV charging periods, respectively. Sunday experiences some of the most mild load demands during the analyzed week, whereas Wednesday represents the day with the highest demand in the entire year.

Figure 47: Bus 613 voltage profile, zoomed in to Sunday’s charging period
5.6.2.2 Voltage oscillations

During the process of implementing the droop controllers, oscillations appeared in the simulations. The oscillations varied in magnitude and duration among the three control cases, but were present in all of them. There are several methodologies to remedy the oscillations introduced by voltage based droop controllers [44], however going into the details of such modifications is outside the scope of this thesis.

These oscillations were the result of the controller switching between the set points as the induced load changes from the control cause a correspondingly large enough local voltage deviation to cause the controller to switch set points every time the new one measurement is made. As such, they were most pronounced in case 3, which had the most refined steps in its droop controller. However, when averaging the voltage measurements into 10 minute average values to make them directly comparable to the requirements set forth in 50160, these oscillations were masked. As severe deviations reduce customer security [45], the fact that they are filtered out when measuring the voltage levels for the purposes of fulfilling the standard’s requirements leaves customers potentially at risk to an unacceptable degree. A further investigation of these voltage oscillations was not pursued in the interest of time and prioritizing other aspects of the thesis, coupled with the thesis supervisors’ informing the author that these oscillations can be readily mitigated through the introduction of either an integral or derivative component to the droop controller, incorporating a type of memory functionality to prevent the rapid changes in the controllers’ set points.
The oscillations are shown for the three control cases, where the first subplot shows the average phase voltages in the 10 minute average intervals, whereas the second subplot shows the actual measurements with a 0.5 second resolution during the oscillations.

Figure 49: Case 2 phase voltages at bus 613, 10 minute average value vs measured values

The sharp sudden spikes observed in the second subplot in Figure 49 are the result of the rounding function implemented to ensure the 1 A steps in the controller.
Figure 50: Case 3 phase voltages at bus 613, 10 minute average value vs measured values

The oscillations are most pronounced in case 3, in phases’ b and c during the EV charging periods, as the large current and therefore power steps in the controller’s set point coupled with the small voltage difference between set points results in large voltage deviations during the curtailed voltage range. Since EVs connected to phase A are set to their minimum charging level for the majority of the charging periods, the oscillations are less pronounced in phase A.

Figure 51: Case 4 phase voltages at bus 613, 10 minute average value vs measured values
5.6.3 VUF

The VUF for each simulated case was always within the limitations. This is primarily due to the balanced connection of EVs in the system coupled with the fact that the household loads were not so imbalanced to begin with to lead to a violation, although the observed imbalance from the household load led to the modelling of an imbalance with a doubling of the load on phase A relative to B and C. Although the VUF is not a problem in these simulations, it could become one if there was not a measure to ensure a more even distribution on the phases, e.g. through a phase shift control on the EVSE or via ensuring that during installation that the electrician providing the installation had some certification or knowledge of the importance of alternating the connections, although this presumes a level of coordination with the DSO that is most probably nonexistent. However, it would be highly prudent to avoid a replication of the observed problem with the installation of the heat pumps in Hørmarken; i.e. that in the heat pump installation guide it said to connect to phase A, so all the heat pumps in the neighborhood were connected to phase A, further exacerbating the imbalance.
Given the evolving framework on ancillary services (AS) outlined in section 2.3, it is highly plausible that a more expansive AS market becomes established in Denmark, either through the modification of existing markets, and/or the creation of new market(s). As such the following simplified economic considerations are taken in the hypothetical future scenario in which the value of voltage regulation is internalized in the future Danish AS marketplace. In order to arrive at a reasonable service payment, a number of assumptions have to be taken. While this additional economic case is inherently speculative, and provides only an initial rough estimate of what could potentially be a reasonable service payment, it does outline a plausible application of the information reported upon in the previous chapter on an alternative method to remedy the unacceptable voltage drops that would accompany large scale “dumb” charging in a Danish distribution grid.

In order to arrive at this economic estimate, first a general quantification of the existing solution is outlined. Based on the price assumptions associated with this business-as-usual solution, this information is subdivided based on the voltage violation information obtained from the simulation work, and a working estimate is generated as to how much EVs should be compensated to assist and alleviating the low voltage problems that occur during large scale charging at high load times.

6.1 Current DSO solution to solve the low voltage problem

Under existing Danish legislation, if a customer complains to a DSO about power quality issues, and if upon subsequent testing the problem is substantiated, the DSO is required to take the appropriate remedial action. In the case of a complaint associated with too frequent low voltage deviations, the testing methodology is identical to that described in section 4.3.2 by the standard EN 50160. In order to solve this problem the DSO may choose one of many solutions to improve the voltage in their system. While the exact solution is subject to change depending on the exact nature of the problem being solved, and other solution methodologies are at the DSO’s disposal, for the low voltages associated with high load periods observed in the modelled simulation work, it is reasonable to assume that the DSO would install a shunt capacitor bank on the secondary side of the substation’s transformer to provide the appropriate amount of capacitive reactive power when required. It is this baseline case that will be considered to determine a price profile for what could be a reasonable amount to compensate an EV aggregator to remedy the low voltage violations in a future alternative scenario where a
market participant would be compensated for providing this grid service instead of the DSO being required to purchase an additional asset.

### 6.2 Cost and compensation estimation

A shunt capacitor bank was added to the PowerFactory simulation of case 1 described in chapter 5. Its maximum level was varied in an iterative process until an acceptable size was found to remedy the low voltages experienced in the grid during the unregulated EV charging. This size of this required shunt capacitor bank was determined to be 200 kvar. An approximate estimate for the cost for a capacitor bank was determined to be 0.1 €/var, which at the writing of this thesis corresponds to ~ 0.746 DKK/var. This corresponds to 149,200 DKK for the 200 kvar capacitor bank, before considering any additional costs such as installation costs or O&M. The lifetime of this capacitor bank was estimated to be 10 years. Taking a simplified approach for estimation and discussion purposes, i.e. excluding any particular economic analysis to account for the discounted rate of future compensation/payments, this corresponds to an annual cost of the investment for the capacitor bank of 14,920 DKK/year or 286.92 DKK/week.

**Table 15: Cost assumptions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. size of C bank</td>
<td>200 kvar</td>
</tr>
<tr>
<td>cost per var</td>
<td>0.10 €</td>
</tr>
<tr>
<td>corresponding to</td>
<td>DKK 0.75</td>
</tr>
<tr>
<td>cost of C bank</td>
<td>20,000 €</td>
</tr>
<tr>
<td>corresponding to</td>
<td>DKK 149,200</td>
</tr>
<tr>
<td>annual cost</td>
<td>DKK 14,920</td>
</tr>
<tr>
<td>weekly cost</td>
<td>DKK 286.92</td>
</tr>
</tbody>
</table>

From this, a quantification of the total number of violations by case in the system was taken into account.

**Table 16: Number of voltage violations in the system by bus and case**

<table>
<thead>
<tr>
<th>Number of Voltage Measurements</th>
<th>Bus</th>
<th>Total Violations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>602</td>
<td>603</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Case 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>below 0.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>below .85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>below 0.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>below .85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>below 0.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>below .85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>below 0.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>below .85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>below 0.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>below .85</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

84
Then the number of low voltage violations that was reduced for each of the EV charging strategies was determined.

### Table 17: Number of low voltage violations reduced by case

<table>
<thead>
<tr>
<th>Case</th>
<th># V violations</th>
<th>Violations reduced</th>
<th>Reduced by (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1263</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 2</td>
<td>599</td>
<td>664</td>
<td>52.57</td>
</tr>
<tr>
<td>Case 3</td>
<td>600</td>
<td>663</td>
<td>52.49</td>
</tr>
<tr>
<td>Case 4</td>
<td>367</td>
<td>896</td>
<td>70.94</td>
</tr>
</tbody>
</table>

Now assuming that the value of providing this service is linear and equivalent regardless of how the low voltage abatement is provided, this enables the quantification of the benefit provided by the EV droop control options in cases 2-4. The corresponding level of equivalent compensation to procuring the appropriate shunt capacitor bank is therefore determined by dividing the annual cost of the capacitor bank out proportionally to the number of violations created in the unmitigated case, case 1. This percentage reduced by calculation in column four of Table 17 is thereby multiplied with the weekly and annual cost estimates for the shunt capacitor bank to quantify the value the corresponding control cases provide the system. These monetary calculations are provided in Table 18.

### Table 18: Corresponding proportional EV compensation in DKK

<table>
<thead>
<tr>
<th>Case</th>
<th>per week</th>
<th>per year</th>
<th>Weekly per EV</th>
<th>Annually per EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2</td>
<td>150.84</td>
<td>7843.93</td>
<td>3.51</td>
<td>182.42</td>
</tr>
<tr>
<td>Case 3</td>
<td>150.62</td>
<td>7832.11</td>
<td>3.50</td>
<td>182.14</td>
</tr>
<tr>
<td>Case 4</td>
<td>203.55</td>
<td>10584.58</td>
<td>4.73</td>
<td>246.15</td>
</tr>
</tbody>
</table>

Taken in isolation, while these numbers are far away from indicating a viable business, they do indicate that the value of the service of voltage support is not negligible, and if considered as one secondary revenue stream available to an EV aggregator, opening the AS market to allow EVs to provide this modest service, would make the role of a third-party aggregator more viable than it would be otherwise.
7 CONCLUSION

This thesis presented achieved two overarching objectives. First, it provided a synopsis on the current state of, and the potential near future progression of, ancillary services in Denmark. Secondly, it investigated a potential future application of providing increased flexibility in the future power system through a set of simple, autonomous droop controllers that provided voltage control through power curtailment based on local voltage measurements, and in the latter case, also provided reactive power compensation. It was demonstrated that using such a simple controller could provide moderate to high levels of voltage support to partially solve some of the power quality issues introduced from large scale uncoordinated EV integration, and alleviate congestion on the most stressed cable in the system.

The set of essential grid services that encompasses the term ancillary services in a Danish context is evolving. In alignment with Energinet.dk’s strategy to increase the competition, internationalization and transparency of the Danish ancillary services markets and with the strategy detailed Energinet.dk’s Market Model 2.0, the future Danish ancillary services marketplace may be one more conducive to providing new grid services. Modulating EVs’ charging through modulating their current may be a useful strategy to further ensure flexibility in electricity consumption and assist in the integration of higher numbers of EVs into the power system.

The conducted simulation work validated and reinforced [28]. It showed how in case 1, uncontrolled EV charging can adversely impact the power quality of distribution grid. This is particularly so in unbalanced networks, and most pronounced at the end of the feeder. The simulation work quantified the improvement that can be obtained in cases 2 through 4, demonstrating how a simple, decentralized autonomous droop controller can remediate a large percentage of the introduced added stress in the unbalanced analyzed system that would otherwise be present from current typical EV charging behavior. The active power only droop controllers were able to mitigate 52.5% of the low voltage violations experienced in the system by the increased cumulative load imposed by a 100% EV penetration scenario, while the active and reactive power droop controller enabled a 70.9% reduction in the number of low voltage violations.

However, even with these improvements, the low voltage minimum threshold requirements as set forth in the standard EN 50160 were exceeded at multiple buses in each case. At bus 613, the bus that experiences the most low voltage deviations in the system, this lower bound was exceeded by 225%, 227%, and 130% of its permissible amount in cases 2, 3 and 4 respectively. Further action would be required to remediate this unacceptable situation.

Due to implemented pattern for simulating the connection of EVs into the analyzed system, the VUF did not exceed its limitation in any of the modelled cases.
The incorporation of these droop controllers enables the integration of more EVs into a distribution grid than would otherwise be permissible, and in doing so potentially provides one option to prolong capacity upgrade deferral in the form of grid reinforcements. However, the implemented controller needs further refinement to ensure that it does not introduce any problems in the power system, such as the voltage oscillations observed in case 3. Furthermore, as none of the control cases fully solved all the LV problems in the simulated grid, additional remedial action would be required in order to safely realize the modelled level of EV penetration in a Danish distribution system.

7.1 Future work

During the completion of this thesis, the following topics were identified as potential extensions of the completed work:

- A further investigation into how effective the implemented strategy would be in a distribution grid that was balanced at the representational level for Denmark? The simulated grid’s phase balance of 50/25/25% was based on grid measurements obtained by SEAS-NVE. How would the results change if the simulated grid was balanced to the average rates for a Danish distribution grid?

- Further testing of the simulated grid with the integration a more intelligent controller to include memory functionality to eliminate the observed voltage oscillations.

- An investigation into the impact on the VUF if an analogous protocol for EVSE installation was implemented as to the heat pump installation procedure in Græsmarken (i.e. if the installation manual instructed the EVSE to be connected to phase A) and the associated calculations into what degree of EV penetration could be tolerated before remedial action would be required on part of the DSO.

- An additional set of simulations incorporating the European trend for more stringent distribution grid voltage requirements, e.g. such as a permissible voltage band of only ±4% as proposed in Germany [42] or the outright elimination of the 5% 0.85-0.9 p.u. low voltage allowance as proposed in [45], which calls for the voltage minimum to always be 0.9 p.u.

- An investigation of the control strategy implemented in case 4 with the active and reactive power control decoupled, potentially in an analogous way to [46], to provide additional voltage support in an “extended case 4” enabling further reductions in the amount of low voltage violations.

- A more detailed economic investigation, potentially including compensation for the provision of multiple services. Among other types of compensation, this could include determining analogous compensation levels for EV participation in a distribution grid capacity market, potentially as described in [47].
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