Master's thesis

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

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Leveraging residential battery energy storage systems for voltage support in remote distribution grids with high penetration of renewables

Master's thesis in Energy and Environmental Engineering
Supervisor: Jayaprakash Rajasekharan
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Abstract

The high penetration of renewable energy resources (RES) in the distribution grid causes new operational challenges for the distribution system operator. Over-voltage is especially an issue that constitutes the major limitation to the increase in RES penetration and integration. One solution to cope with this technical challenge is to utilize the active power support from battery energy storage systems (BESS). Due to market structure and regulation, the implementation of BESS in the power system is restricted to network customers.

In this thesis, a distributed control method for residential BESS coupled with photovoltaic systems was proposed. The objective was to utilize customer-owned BESS to solve the over-voltage issues caused by high wind and solar penetration without significantly affecting the BESS owners' profits. This was achieved by taking most of the operational decisions locally, where a local controller optimally schedules the charging and discharging of the BESS. Voltage control was accomplished by remotely controlling the BESSs with a central controller. The central controller was activated only during critical periods, determined based on a prediction of the network. A voltage sensitivity method was used to select the BESS with the greatest effect on the system to participate in the voltage regulation.

The performance of the proposed method was validated through a case study conducted at Utsira island in Norway. The island experiences large voltage variations due to a combination of variable production from two wind turbines, load variations, a weak grid, and an underdimensioned submarine cable. The results showed that utilization of residential BESS could successfully solve both over-and under-voltage issues with the proposed method.

Utilization of customer-owned BESS for voltage support is only possible with a commercially viable business model. A proper business model will not only motivate the customer to invest in a BESS, but both the customer and the distribution system operator will get benefits if the operation of the BESS is properly controlled. The system operator reduces their need for grid reinforcement, and the customer can decrease their electricity bill by increasing their self-consumption or by responding to price variations. Different business models for operational cost-sharing are proposed in this master's thesis.

Sammendrag

Den høye penetrasjonen av fornybare energiressurser i distribusjonsnettet medfører nye operasjonelle utfordringer for nettselskapene. Overspenning er spesielt et problem som utgjør den største begrensningen for integrering av fornybare energiressurser i distribusjonsnettet. En løsning for å håndtere denne tekniske utfordringen kan være å bruke aktiv effektstøtte fra batterisystemer. På grunn av markedsstruktur og regulering er implementeringen av batterisystemer i kraftsystemet begrenset til nettkunder.

I denne oppgaven er det foreslått en kontrollmetode for batterisystemer i boliger kombinert med solcelleanlegg. Målet er å bruke kundeeid batterisystemer til å løse overspenningsproblemer forårsaket av høy vind- og solinntrengning uten at dette i vesentlig grad vil påvirke kundenes økonomiske fortjeneste. Dette var oppnådd ved å ta de fleste operasjonelle beslutningene lokalt, der en lokal kontroller bestemte en optimal opp- og utlading av batterisystemet. Spenningskontroll ble utført ved å fjernstyre batterisystemene med en sentral kontroller. Den sentrale kontrolleren ble kun aktivert under kritiske perioder, bestemt ut ifra en prognose av nettet. En spenningsfølsomhetsmetode var brukt til å velge batterisystemet med størst påvirkning på systemet til å delta i spenningsreguleringen.

Den foreslåtte metoden ble validert gjennom en case-studie utført på øya Utsira i Norge. Øya opplever store spenningsvariasjoner grunnet en kombinasjon av variabel produksjon fra to vindturbiner, lastvariasjoner, et svakt nett og en underdimensjonert sjøkabel. Resultatene viste at ved bruk av den foreslåtte metoden kunne kundeeide batterisystemer løse både over- og underspenninger.

Bruk av kundeeid batterisystemer for spenningsstøtte er kun mulig med en kommersiell forretningsmodell. En bærekraftig forretningsmodell vil ikke bare motivere kunden til å investere i et batterisystem, men kan gi både kunden og nettselskapet nytte av investeringen hvis batterisystemet kontrolleres riktig. Nettselskapet reduserer behovet for nettforsterkning, og kunden kan redusere strømregningen ved å øke selvforbruket eller ved å respondere på prisvariasjoner. Ulike forretningsmodeller for operasjonell kostnadsdeling er foreslått i denne masteroppgaven.

Preface

This master's thesis was completed during the semester of 2021 and marks the final part of the Master of Science degree in Energy and Environmental Engineering. The thesis was written at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU) in collaboration with Haugaland Kraft Nett.

First and foremost, I would like to thank my supervisor, Jayaprakash Rajasekharan, for proofreading, valuable guidance, and productive discussions during this period. Your engagement within the topic has had a contagious effect. I would also like to thank Haugaland Kraft Nett for being a great collaboration partner, especially Odd Håland Øksnevad and Kristian Finborud Hansen.

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Abbreviations

AMS	–	Advanced Metering System
BESS	–	Battery Energy Storage System
CPP	–	Critical-Peak Pricing
DER	–	Distributed Energy Resource
DG	–	Distributed Generation
DoD	–	Depth of Discharge
DSO	–	Distribution System Operator
EMS	–	Energy Management System
ESS	–	Energy Storage System
HAN	–	Home Area Network
HV	–	High Voltage
HVAC	–	Heating, Ventilation and Air-Conditioning
LV	–	Low Voltage
PCC	–	Point of Common Coupling
PTR	–	Peak-Time Rabates
PV	–	Photovoltaic
RES	–	Renewable Energy Resource
RTP	–	Real-Time Pricing
SoC	–	State of Charge
TOU	–	Time-Of-Use Pricing
VRES	–	Variable Renewable Energy Resources

Chapter 1

Introduction

1.1 Background

Global energy consumption is growing due to an increasing population and rising welfare, in addition to new technology developments. However, the energy demand must be covered with climate-friendly solutions to reduce global greenhouse gas emissions. This is also supported by the Road Map 2050 designed by the European Union, which has set a target of an energy system without CO_2 emissions from the power sector [1]. In order to reach this target, traditional energy resources have to be replaced by renewable energy sources (RES) such as wind and solar.

Contrary to traditional energy resources, wind and solar plants are often decentralized and connected to the local distribution network. The advantage of installing generation to the local distribution network is that it is closer to the consumer, thus reducing the need for power transmission. This can especially be advantageous for remote areas such as islands, which are often connected to the national grid through long and underdimensioned cables. Despite the environmental advantages and sustainability of RES, their integration with the grid results in a more complex operation. RES strongly depends on local weather and climate conditions, where the stochastic characteristics of the non-dispatchable resources can affect the reliability and stability of the power system [2]. The most common technical challenge due to the high penetration of RES into the distribution grid is over-voltage issues during high production times. Over-voltage occurs as a result of reverse power flow and overloading of system components [3].

Over-voltage issues can be solved with network reinforcement. In Norway, these investments are financed through network tariffs, which the consumer pays. Since the network is only congested for a few hours due to either high production or load demand, network reinforcement is considered expensive and inefficient. A better solution would be to adjust the demand for electricity to better match generation from wind and solar energy. This can be achieved by increasing the demand-side flexibility in the distribution grid.

Demand-side flexibility can be defined as a part of the demand that could be reduced, increased, or shifted to meet a demand in the power grid [4]. Voltage support through demand-side flexibility can be achieved by allowing the system operator to control, or by providing price signals to various flexible resources. Flexible resources of electricity demand include *electric distributed generations*, energy storage systems, electric vehicles, heating, ventilation, and air-conditioning (HVAC), and heat pumps. Both the system operator and the customer can benefit from the concept of demand-side flexibility. The system operator can postpone or prevent necessary grid investments, which further lead to lower network tariffs for customers. The customer will also have their electricity costs reduced due to the smarter use of electricity.

1.2 Motivation

There has been a growing interest in battery energy storage systems (BESS) in the residential sector, especially in remote areas with increasing energy demand. Residential BESSs are often combined with photovoltaic (PV) systems, where the storage system is used to increase the customer's self-consumption and thus reduce the electricity bill. Although the battery prices have fallen significantly in recent years, the price is still relatively high [5]. Therefore, it can be questioned whether an investment can be profitable in terms of payback time.

To increase the profitability of the BESS, the customer can offer ancillary services to the distribution system operator, such as voltage control. The more services that can be stacked, the higher the revenue for the customer. Numerous studies have been conducted on BESS utilization for voltage support in the distribution grid. A droop control strategy was proposed in [6] to regulate the energy storage systems (ESS) for voltage support. However, due to limited communication between the systems, the optimal operation of the overall system cannot be guaranteed. Therefore, several papers focus on the coordination of the multiple ESSs in the distributed grid. A coordinated control algorithm was proposed in [7] for mitigating voltage and frequency deviation, where a central controller determined the charging and discharging of the BESSs. However, the state of charge (SoC) controller can be explored further to utilize the BESSs efficiently. In [8], a local controller was implemented to regulate the SoC of each ESS within its limits, while a distributed control regulated the feeder voltages by using a consensus algorithm. The delimiter with this strategy is the two-way communication between the controllers. Further, a voltage sensitivity-based control scheme was presented in [9] to mitigate voltage unbalance issues and improve the voltage profile while supporting the increasing number of PV systems.

Most papers consider only voltage issues caused by either high penetration of solar or wind production. However, in [10], a control strategy for improving the voltage profile, fluctuations, and imbalance of a distribution network with high penetration of rooftop PV-wind turbine hybrid generation systems was presented. The control scheme included both a local and a central control method. However, the controllers aim to control the voltage profile and disregard the customers' operational preferences. Disregarding the customer's operational preferences may reduce the participation interest and disincentivize customer engagement in providing ancillary services. As the operational preferences of the BESS for the customer's benefit may deviate from the operational preferences of the BESS for voltage support, it is vital to find a control strategy that increases the overall benefit for both the customer and the system operator.

1.3 Scope of Work

This thesis investigates the potential for utilizing demand-side flexibility for voltage support, where utilization of residential battery energy storage systems will be of main interest. In order to achieve an efficient operation of multiple residential storage systems, a new control strategy had to be designed. The control strategy aims to mitigate voltage issues and, at the same time, allows the customer to operate the battery storage system based on their preferences. The research focused on the operational challenges in the distributed grid caused by the high penetration of RES and how different voltage regulation techniques can solve these challenges. Different control strategies for coordinating multiple battery storage systems for mitigating voltage issues will be investigated. This thesis will therefore include the following:

- **Identify challenges** - Identify and describe challenges with high penetration of renewable energy resources in the distribution grid.
- **Voltage regulation techniques** - Present and describe voltage regulation techniques with the focus on how battery energy storage systems can be utilized for voltage support.
- **Demand-side flexibility** - Describe how customers can provide services to the distribution system operator.
- **Grid modeling** - Model a distribution grid for investigation of flexible opportunities in the distribution grid.

1.4 Contribution

The main contributions of this master's thesis are summarized below.

- A control method that utilizes residential BESSs to benefit both the customer and the distributed system operator was proposed. The proposed control method is based on a distributed control concept consisting of a central controller and local controllers. The charging and discharging of the BESS is mostly determined by the local controller, where the BESS is controlled to minimize the customer's electricity bill. During periods with voltage violations, referred to as critical periods, the central controller adjusts the active power setting of the BESSs to regulate the voltage within its limits. A voltage sensitivity-based control method is used to determine which BESS should participate in the voltage regulation.
- The proposed model was validated through a simulation case study of the distribution grid at Utsira island. Analysis and simulations showed that the control method was able to completely mitigate over-voltage issues cause by high penetration of both wind and solar production. Furthermore, the control strategy was also able to resolve under-voltage problems due to high load and low production in the network.
- Different business models for commercially viable utilization of residential BESS for voltage support was proposed, divided into cost-sharing models and price mechanism models.

1.5 Thesis Outline

This report consists of six chapters with the following content:

- Chapter 2 - Theoretical background:
  Presents relevant theory necessary to understand this master's thesis. The theoretical background addresses challenges in the distribution grid caused by high penetration of renewables, voltage regulation techniques, demand-side flexibility, and control strategies for residential battery energy storage systems. Previous research, terminology, and concepts used in this thesis will be presented in this chapter.
- Chapter 3 - Case study: Utsira island
  System description of Utsira's distribution grid and the voltage situation experienced at the island.
- Chapter 4 - Methodology
  Describes the modeling process of the distribution grid at Utsira, the proposed distributed control strategy and the different scenarios investigated in this thesis. A description of data collection will also be presented in this chapter.
- Chapter 5 - Results and discussion
  Presents the results of the two scenarios simulated in this thesis; over-and under-voltage scenario. The scenarios include results from several simulations where three parameters have been changed. The three parameters are battery capacity, the active power rate allocated to the system operator, and the percentage of the battery capacity allocated to the system operator. Based on the results, an evaluation of the control strategy will be provided. Further, different business models will be presented and discussed. At the end of this chapter, further work will be given.
- Chapter 6 - Conclusion
  Summarize the findings and concludes the thesis.

Chapter 2

Theoretical Background

This chapter addresses some theoretical background that is necessary to understand this master's thesis. First, the challenges with the increasing penetration of renewable energy resources in the distribution grid and measures to solve these challenges will be presented, focusing on voltage issues. As battery energy storage systems have shown great performance for voltage support in the distribution grid, important battery storage characteristics will be presented, in addition to residential battery storage options. Further, as this thesis investigates the role of flexibility in the distribution grid, the concept of demand-side flexibility will be described. Moreover, different strategies from the literature for controlling battery storage systems to solve voltage problems will be presented. Finally, the theory about power flow analysis will be provided.

2.1 The Distribution Grid

In recent years, the power system is gradually transforming from a centralized to a decentralized system. This is mainly due to the increase of *distributed energy resources* (DER), which is small-scale power generation units located in the distribution network. Due to these connections, the distribution system is changed to an active system with power flows to and from the consumers.[11] However, the distribution grid was never designed for this transition. The distribution grid is often characterized by long and weak radial lines stretching over large areas with multiple nodes. In addition, the capacity of the equipment often decreases with the voltage level. Integration of multiple distributed generations will lead to several operational challenges, such as voltage violations, overloading problems, high line losses, and other power quality aspects [12].

The Norwegian power system can be divided into three parts: transmission, regional, and distribution network. The transmission and regional network have a voltage level at 300-420 kV and 33-132 kV, respectively. The distribution network is divided into a high voltage (HV) distribution network, 11-22 kV, and a low voltage (LV) distribution network, 0.23-0.40 kV.[13] Traditionally, a few large power plants have been connected to the transmission network, where the voltage has been stepped down to the regional and the distributed network, as illustrated in Figure 2.1.1.

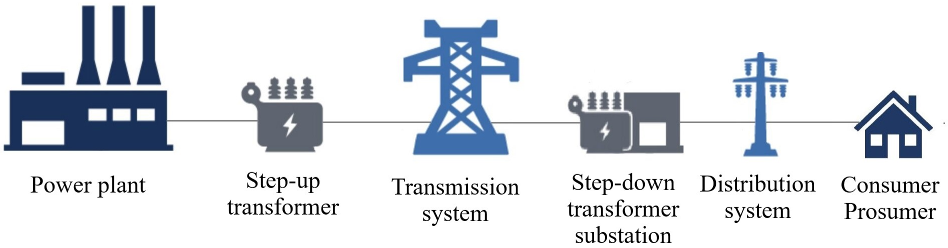


Figure 2.1.1: *Structure of the Norwegian power system. The voltage is stepped-up from the power plant to the transmission system, and conversely stepped-down to the distribution system. The figure is inspired by [14].*

This section describes the challenges caused by the increasing penetration of renewable energy resources in the distribution grid. Furthermore, as the distribution system operator, the owner of the distribution grid, has an obligation to maintain the system within certain bounds, laws and regulations will be presented, in addition to voltage regulation techniques.

2.1.1 Challenges with High Wind and Solar Penetration

High penetration of variable renewable energy resources (VRES), such as wind and solar, leads to various technical challenges in the distribution network. This section addresses the most critical challenges, focusing on voltage issues.

Voltage Fluctuation

Voltage quality can be affected by the intermittency of solar and wind production. The wind speed and sun irradiance vary from moment to moment, where the power production follows the same pattern. As consumption and production always must be balanced, variation in power production causes voltage fluctuation.[3] A consequence of voltage fluctuations and flicker may be the destruction of electrical appliances connected to the grid [15].

Voltage Rise

Voltage rise is one of the most usual negative effects with high penetration of VRES in the distribution network. A voltage rise can occur at the load bus if the output power of a distributed generation unit is greater than the demand. The occurrence can be explained by considering a radial system as illustrated in Figure 2.1.2.

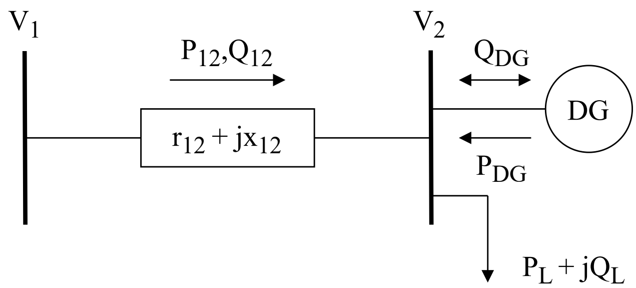


Figure 2.1.2: *Part of a distribution system with a distributed generation and a load connected to bus 2. The arrows indicate the direction of the power flow.*

When considering a system with no distributed generation units, the power flow between bus 1 and 2 (P_{12} and Q_{12}) is equal to the load demand at bus 2 (P_L and Q_{jL}). The voltage drop in per unit at bus 2 is given approximately by Equation 2.1.1, where r_{12} and x_{12} are the resistance and reactance of the line between bus 1 and 2, respectively.[16]

$$V_1 - V_2 = P_{12}r_{12} + Q_{12}x_{12} \tag{2.1.1}$$

The direction of the power flow can be reversed if a distributed generation unit is placed at bus 2. In this case, the voltage drop along the feeder is given by Equation 2.1.2, where P_{DG} and Q_{DG} are active and reactive power of the distributed generation unit.

$$V_1 - V_2 = (P_L - P_{DG})r_{12} + (Q_L \pm Q_{DG})x_{12} \tag{2.1.2}$$

Based on Equation 2.1.2, when the active power of the distributed generation increases above the load demand, the voltage at bus 2 may be greater than the voltage at bus 1. This means that the injected power from the distributed generation unit can cause voltage problems. It can further be observed from the equation that the magnitude of voltage rise is determined by two main terms, namely $(P_L - P_{DG})r_{12}$ and $(Q_L \pm Q_{DG})x_{12}$. The dominant term implicates the most suitable method for reducing the voltage rise. The resistance and reactance depend on the characteristics of the system and are constant values. If the x/r ratio is high, reactive power control can be an effective method to limit over-voltage. On the contrary, a low ratio indicates that active power control is a more effective solution. In the low voltage distribution network is often the x/r ratio low.[16]

Voltage Imbalance

An inverter is needed to connect a PV system to the distribution grid. In Norway, IT network has been dominant in the distribution system for households. This is not the case in the rest of Europe, which primarily uses 400 V TN networks. As a consequence, electric equipment for the 230 V IT network is somehow limited. This limitation also accounts for PV inverters, where only single-phase inverters are available for smaller PV plants.[17]

Connecting a PV system by means of a single-phase inverter can cause voltage imbalance. The imbalance can further raise the voltage compared to a symmetrical system. Therefore, the distribution system operator should aim to distribute the PV systems between the three phases. According to the regulation of supply, the degree of asymmetry should not exceed 2%. In a study conducted by SINTEF, asymmetry is restrictive with low solar penetration, while the voltage violation is restrictive with high penetration [17]. For larger PV systems, systems above 20 A, a three-phase inverter should be used to distribute the production between the three phases.

Overloading of Cables and Transformer

Overloading of cables and transformers is another challenge with increased VRES in the distribution grid. Connection of VRES can cause the current in the network to change direction, which can lead to violation of the loading levels of network elements, often referred to as thermal rating. The thermal rating is defined as the amount of electric current a transmission line or transformer can conduct without being damaged due to overheating or cause violation of other power quality issues [18]. A situation that leads to the highest risk of overloading is with minimum load demand and maximum generation [19]. However, it should be mentioned that VRES connected to the distribution network can also minimize the stress on system elements if the local production generates during peak load periods.

2.1.2 Network Strength

Network strength is a measure of network stability and is measured based on the short-circuit performance at a node [20]. Based on the short-circuit performance, the network can be considered as weak or strong. Short circuit performance less than 1.1 kA is considered a weak network and is usually characterized by a high impedance. Due to the high impedance, the voltage at that node will be more affected by changes in demand or production. A considerable amount of the distribution networks in Norway is reported with a short circuit performance lower value 1.1 kA.[21]

Converter-connected production and consumption unit decreases the short-circuit performance. Low short-circuit performance in the network leads to more complicated voltage regulation. In addition, the protection in consumption and production facilities can be affected, where in a worst-case scenario, no faults are detected.[22]

2.1.3 Laws and Regulation

The regulatory authority for energy regulates the distribution system operator to ensure that the power is transferred within a delivery quality and that the grid is utilized and expanded in a safe and socially rational manner [23]. This section describes regulations that apply to prosumers and distribution system operators relevant for this thesis.

Prosumers

A *prosumer* is defined as an end-user that both produces and consumes power behind the connection point. The energy produced by the prosumer is mainly for own consumption. However, during periods when production is higher than demand, surplus power is injected into the grid. The injected power at the connection point should under no circumstances exceed 100 kW. Prosumers cannot sell the power directly to other customers but to an energy supplier willing to buy the power. Prosumer is allowed to utilize the existing capacity of their circuit-breaker for injection and withdrawal. If the injected power causes a requirement to upgrade the grid, the distribution system operator cannot require an investment contribution from the prosumer as long as the customer has not changed the size of their circuit-breaker. Furthermore, as the regulation is today, a prosumer is exempt from paying a tariff for injection.[24]

Norwegian Power Quality Regulations

To ensure that all electric power users in Norway get a satisfactory delivery quality regardless of where they live, NVE (Norges Vassdrags og Energidirekorat) has developed a regulation on delivery quality in the power system. Delivery quality is important for obtaining good function of electric equipment and appliances, where reduced quality can lead to casualty, malfunctions, and financial loss for everyone connected to the power system.[25]

The distribution system operator is responsible for monitoring the quality within its supply area, and requirements are set for how the system operator should handle the application for delivery quality from the customer. Voltage quality is especially important for the analysis in this report. Key regulation concerning voltage quality are [25]:

- **Slow variation in voltage magnitude** - In the low voltage distribution network, slow voltage variation should be within a range of ± 10% of nominal voltage, measured as the average over one minute in the point of common connection. In the high voltage network, 11 kV and 22 kV, a maximum of 5% stationary voltage drop is permitted when transmitting power.
- **Over-voltages, under-voltages and voltage changes of low duration** - The number of occurrences of deviations exceeding 3% of the stationary voltage or 5% above the maximum allowed voltage should not exceed 24 within a 24-hour period.
- **Voltage asymmetry** - The degree of voltage asymmetry should not exceed 2% on average over a period of 10 minutes at the connection point.

Network Tariff

A customer must pay for the connection and utilization of the grid, in addition to the electricity. This is referred to as network tariff. Network tariff gives the distribution system operator income to cover the costs of transporting electricity, given efficient operation, development and utilization of the grid [26]. To prevent the system operator from setting an unreasonable high network tariff, NVE determines an annual individual income limit for each system operator. The system operator can set a tariff based on the income limit, defined as permitted income divided by expected energy consumption. The network tariff consists of three segments[26]:

- **Energy segment** - reflects the costs of power transmission losses. The power losses can be significant if the capacity limit in the grid is almost reached. The energy segment depends on the amount of energy the customer consumes or injects into the grid. For most customers, the energy segment is constant throughout the year.
- **Fixed segment** - a defined amount per year equal for all customers within the same network company. The fixed segment reflects the cost of measurements, collection of meter data, and invoicing.
- **Power segment** - applies to industrial customers with a yearly consumption above 100,000 kWh. The power segment provides a reasonable return on network investments and is calculated based on the end user's power consumption for a defined period.

As the tariff is structured today, 90% of the costs are fixed costs that are not affected by the customer's use of the grid. The rest of the costs are directly related to the transmission of electricity.[27] Electrification and production in the distribution grid can create a risk for extensive network development and thus increase the tariff more than necessary. To prevent this, NVE has suggested a proposal for changes in how distribution system operators should design the network tariff.

The customer's power consumption and availability have the greatest impact on the costs in the network, not the energy consumption. Power consumption is the amount of electricity used at the same time, where the network must be dimensioned to transmit as much power as the customers use at any given time. Availability means that there is power in the sock when needed, with a quality that does not damage electrical appliances. With the new model proposed by NVE, the tariff structure aims to simulate efficient use of the network.[27]

Important changes relevant for this thesis are that the energy segment can be set higher than the marginal loss and can vary over the day. NVE also states that the energy segment should amount to a maximum of 50% of the network company's income for each customer group. With the new model, the system operator can change the energy segment based on the *Time-of-Use* principle.[27]

2.1.4 Voltage Regulation Techniques

The integration of variable renewable energy resources (VRES) into the grid causes operational challenges for the distribution system operator (DSO). For VRES to be integrated into the distribution grid with benefits, appropriate voltage regulation techniques must be used. Numerous approaches have been proposed in the literature to mitigate voltage issues, where the techniques can broadly be classified into four categories:

- Grid reinforcement
- On-Load Tap Changer Transformer
- Reactive power control
- Active power control

Grid reinforcement

A straightforward way to solve the voltage problem in the distribution grid is grid reinforcement. Examples of grid reinforcement can be replacing overhead lines with cables, increasing the cables' cross-section, or upgrading transformers [28, 29]. A larger cross-section decreases the grid impedance, thus reducing the voltage drop in the power lines. This decrease can also be shown by Equation 2.1.2 given in the previous subsection.

The distribution line capability can be constrained by three factors: thermal limits, voltage limits, and stability limits. The thermal limit restricts the current-carrying capability for shorter power lines, while for longer lines, the capability to transmit power is restricted by voltage limits. Stability limits usually determine the capability for extra long lines.[18] As described in [28], the majority of cable replacements in cities and towns are often due to voltage violations rather than capacity constraints. Therefore, a significant portion of upgrading costs could be avoided using voltage regulations or seasonal tap changing of the transformers. However, it will be more difficult to avoid grid reinforcement due to violations of thermal limits. In a study conducted in [29], the hosting capability was increased by 50-90% by upgrading a few critical lines and the transformer. Grid reinforcement for solving voltage and congestion issues due to the high penetration of VRES is a cost-intensive and inefficient solution as the network is only fully utilized a few hours of the day. Therefore, the solution makes it difficult to justify the expenses.

On-Load Tap Changer Transformer

On-load tap changers (OLTC) is another method of regulating voltage. OLTC is an autotransformer with the ability to change the turn ratio of the transformer under loaded conditions. This device can be beneficial in a network that both experiences under-and over-voltage issues on the same day. However, in a distribution network with multiple distributed generation units, the regulation of the voltage will be more complicated, and the action of OLTC may be more frequent due to the variability of VRES. Frequent use of OLTC decreases the lifespan, thus increases the maintenance costs [30]. By combining OLTC with either active [31] or reactive [32] power control, effective voltage control can be achieved.

Reactive Power Control

Reactive power support from converter interfaced renewable energy resources (e.g., PV) or flexible loads (e.g., electric vehicles and battery energy storage systems) is another method of solving voltage problems. Power electronic converter can affect the steady-state voltage by absorbing reactive power during over-voltage issues or injecting reactive power during under-voltage issues. The reactive power capability is limited by the rated apparent power of the converter and the instantaneous active power generated.

As PV panels produce electricity using the photovoltaic effect, the panels have no reactive power support. However, the inverter used for DC/AC conversion can provide a significant amount of reactive power. A disadvantage is that an operation of a PV inverter with a nonunity power factor will reduce the active power injection. There are no grid codes that specify that PV systems must provide reactive power support. However, this may change with the increasing level of PV systems in the grid.[33] A droop function derived from the standard Q(V) is the most commonly used control method for reactive power compensation, where either a constant or variable droop-based method can be selected [34, 35, 36]. A constant droop-based method utilizes same droop coefficient for all systems, where a variable droop-based method uses different droop coefficient for different systems. The calculation of the coefficient for a variable droop-based method is based on a voltage sensitivity matrix.[37]

Utilizing the reactive power capability from a battery unit converter is possible with the same methods as the PV system [36]. As mentioned earlier, the x/r ratio is usually high in the low voltage distribution network. Therefore, a high amount of reactive power is required to solve the voltage problems. In a study given in [38], the network losses increased by 52% due to the reactive power control. Therefore, active power control is a more efficient solution for voltage control in grids with a high x/r ratio.

Active Power Control

Active power control can be achieved by curtailing power produced from RES, controlling the active power settings of battery storage units, or controlling flexible loads (e.g., electric vehicles, HVAC, heat pumps). The active power is absorbed from the grid if over-voltage issues are detected, where the opposite is done during under-voltage issues.

Power curtailment is when the active power from a PV system is fully or partially curtailed. Like reactive power control, the droop-based method is commonly used to regulate active power for voltage support [39, 38]. The droop-based control regulates the active power following a linear droop function, resulting in a slow voltage change. Another control method, referred to as sensitivity-based control, trims active power based on a sensitivity matrix where the voltage levels are maintained closer to the threshold limits. Both of the methods were tested in [40], where they both effectively mitigated voltage issues. However, the sensitivity-based control gave a more improved voltage profile than linear droop control.

The major disadvantage of active power curtailment is that the revenue reduces if this intervention continues to be deployed. In some cases, the PV owner may also be dependent on maximizing the output from the installation to cover the installation and maintenance costs. In order to maximize the overall regional profit, Reference [41] proposed a shared operation of energy storage systems and curtailment allocation based on a sensitivity matrix. The results indicated that the entire region's economic benefit could be greatly improved, both due to arbitrage to utility and the reduction of losses caused by the curtailment.

The most commonly used solution for active power control is to integrate energy storage systems with PV systems. In this way, the energy storage system can store excess power from the distributed generation to control the power flow between the generation system and the grid, thereby increasing the voltage stability. Control of flexible loads can be utilized similarly to energy storage systems, where the load can be shifted during peak hours. For example, a control scheme was proposed in [42] where electric vehicles were used to provide voltage support in a microgrid. The charging and discharging of electric vehicles were controlled in a way to cater to the microgrid's and electric vehicle's needs simultaneously. Further, HVAC systems were demonstrated in [43] to have enormous potential to reduce power losses and increase the minimum voltage magnitude. However, control of flexible load may affect the customers' time and comfort, where an energy storage system has the advantage that it allows the customer to carry out their daily activities as usual.

2.2 Battery Energy Storage System

Battery energy storage system (BESS) is the most widely used energy storage system and is usually used for active and reactive power support for renewable energy resources in distribution networks [44, 45]. The deployment of BESS in the power system has increased over the last decades [5]. This is both due to the multiple functions the BESS can perform and the gradually falling price of the BESS. Among other things, BESS is characterized by rapid response, high commercialization potential, and modularization [46]. Due to its flexible charging and discharging characteristics, BESS has shown great performance in regulating voltage in the power system with high penetration of intermittent renewable energy resources [47, 48] .

In many countries, including Norway, market structure and regulations hinder the distribution system operators from owning a storage system. This restricts the implementation of battery storage systems for voltage support to network customers [49]. Therefore, some residential BESS options on the market will also be provided in this section. However, first, important parameters and how the operation of the battery can affect the battery lifetime will be presented.

2.2.1 Important Characteristics

Several parameters are important for the performance of a battery storage system. The parameters important for this thesis are [50]:

- **Power rating [kW]** - Amount of energy per time unit that can be transferred into or out of the storage system.
- **Energy rating [kWh]** - Amount of energy that can be stored in the battery.
- **Energy efficiency [%]** - Storage system round-trip efficiency and reflects the amount of energy that is possible to draw from the storage unit versus what is put into it.
- **State of charge (SoC)** - Amount of stored energy relative to its capacity.
- **Depth of Discharge (DoD)** - Amount of capacity utilized from the fully charged battery.

The battery capacity fades due to several factors, such as operating conditions, charging and discharging rate, and operation window. The rate of degradation also depends on battery technology. Battery lifetime can be measured in both cycle and calendar life. *Cycle life* is the number of charge and discharge cycles that a battery storage system can complete before losing its performance. A parameter that has a significant impact on the cycle life of Li-ion batteries is the DoD.[51] Furthermore, a full charge or a maximum SoC at the end of charging can prolong the lifetime of the battery storage system. *Calendar life* is the expected life in years and is dependent on the SoC and operation conditions, such as temperature. It is common to define the end of life when the storage capacity has faded to 70-80% of its initial capacity.[52] Typical efficiency, lifetime, and storage costs for different battery technologies are summarized in Table 2.2.1.

Table 2.2.1: *Energy efficiency, lifetime and storage costs for different battery technologies.[46]*

Battery technology	**Energy efficiency** [%]	**Lifetime/Cycles**	**Storage costs** $[USD/kWh]$
Lithium-ion	90-94	1,000-10,000	1,200-4,000
Lead-Acid	75-85	500-1,200	300-600
Sodium-Sulfur	75-86	2,500-4,000	1,000-3,000

2.2.2 Residential Battery Storage Options

BESS is considered an effective way to increase the customer's self-consumption, as the simultaneity of solar power and demand is limited. Several companies offer lithium-ion batteries to store excess PV generation. Table 2.2.2 provides a list of residential battery storage options on the market. From the table, it can be observed that the capacity varies from 4.2 to 17.1 kWh. It should be mentioned that the price for each package varies as it depends on what the package includes, such as inverter, installation cost, and software. The installation cost for the residential BESS is relatively high in terms of payback time. The customer can provide grid support to the distribution system operator to increase the profitability of installing a BESS and can be achieved through demand-side management programs.

Table 2.2.2: *Residential battery storage options on the market.[53]*

Name	Capacity $[kWh]$	Power rating $[kW]$	Price $[USD/kWh]$	Warranty $years$
Tesla Powerwall 2	13.5	5	578	10
LG CHEM RESU10H	9.8	5	536	10
Pika Energy Harbor 3	10.1	10	1,336	10
Sonnon Eco Specs	5-15 (steps of 2.5)	2.5-3.3	1,675-2,500	10
Panasonic	5.7/11.4/17.1	4.8	1,114-2,229	10
Nissan XStorage	4.2/9.6	3.6-6	881-1,041	5-10
Enphase Encharge	10.08	3.84	1057	10

2.3 Demand-Side Flexibility

Demand-side flexibility is the consumers' capability to adjust their consumption to meet a demand in the power grid [54]. Traditionally, demand-side flexibility has been limited to larger industrial customers. Due to cheaper and smarter communication and control technologies, smaller customers, such as households, can offer adjustment of consumption to solve problems in the grid.[22] Although the amount of flexibility each customer can provide is relatively small, an aggregation of multiple flexible resources can have an enormous effect.

Flexible resources located with the customer can be controllable loads (e.g. electrical vehicles, HVAC, heat pumps), distributed generations, and storage systems. The flexible resources are often characterized by four attributes, as illustrated in Figure 2.3.1: (a) direction, (b) rate of change, (c) starting time and its trigger, and (d) duration. Other attributes can also be location, controllability, delivering time, and predictably.[11]

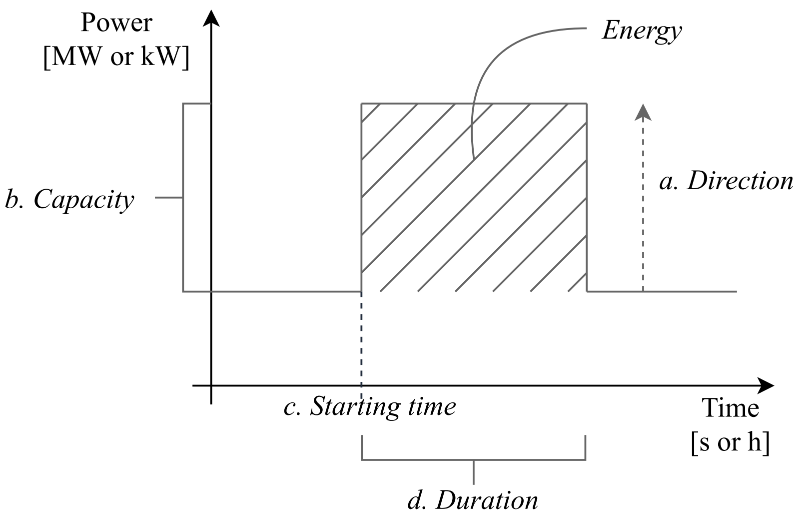


Figure 2.3.1: *Characterization of flexibility attributes. Flexible resources are often characterized into four attributes: (a) direction, (b) capacity, (c) starting time, and (d) duration. Other attributes can also be location, controllability, delivering time, and predictably. Inspired by [11].*

2.3.1 Types of Demand Response

The traditional demand profile can be modified in different ways with demand-side management depending upon the market and type of flexibility needed. Types of adjusted load shapes are illustrated in Figure 2.3.5-2.3.3. Demand response where the intention is to reduce consumption during peak times can be categorized as peak clipping. On the other hand, where the intention is to increase consumption, demand response types can be categorized as valley filling or flexible load. An increase in consumption can be desired during times with high penetration of renewable energy. Load shifting is a demand response type between the two proposed techniques, where loads are moved from peak hours to off-peak hours.[55]

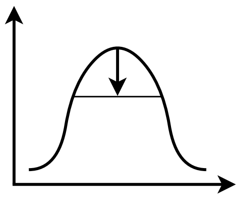


Figure 2.3.2: *Peak clipping.*

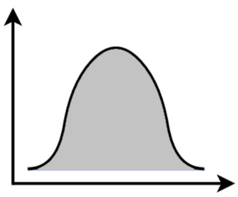


Figure 2.3.3: *Flexible load.*

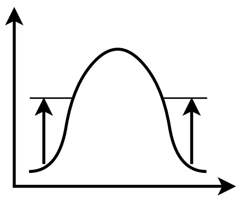


Figure 2.3.4: *Valley filling.*

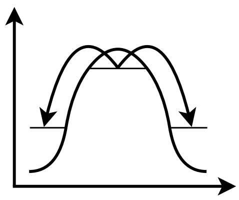


Figure 2.3.5: *Load shifting.*

2.3.2 Activation of Demand Response

There are different ways to activate demand response in the power system. Broadly speaking, it can be divided into price-based and controllable methods [56].

Price-based Method

In a price-based method, the customer adjusts their consumption in response to changes in the electricity price. The most common pricing structures include real-time pricing (RTP), time-of-use pricing (TOU), critical-peak pricing (CPP), and peak-time rebates (PTR).[57] RTP is an hourly rate depending on the day-ahead market, while TOU prices can be adjusted for different time blocks within a period. With CPP, the system operator can adjust the price at short notice to incentivize a load change. These three price methods require no information on the customers' baseline consumption and give the user more freedom. In contrast, PRT requires a baseline as the customer receives a penalty or payment for specific load adjustments.[56]

Controllable Method

A controllable method for demand response is applied in order to maintain the reliability of the power supply. Direct control is where a central actor, such as the system operator, electricity supplier, or aggregator, has direct access to the load and can regulate it when needed.[55] Contrary to the price-based method, the controllable methods are usually contractual and impose obligations for providing flexibility. As a result, flexibility can be provided in time and place for the central actor. Therefore, this method is more suitable for services that require a precise location of action, such as voltage control and congestion management.[56]

A flexiblility market is a possible market tool to utilize flexible load with the controllable method. A *flexibility market* can be defined as a flexibility trading platform to trade flexibility in geographically limited areas, such as small cities, towns, neighborhoods, and communities [11]. The most advanced initiatives in terms of implementation of a flexibility marketplace are NODES (nodesmarket.com), Piclo Flex (picloflex.com), Enera (projekt-enera.de) and GOPACS (gopacs.eu). The trading platform NODES has been tested in Norway through the pilot project, NorFlex, with great success. The pilot project aims to test different technological solutions by utilizing a flexibility market. The project is intended to finish by 2021.[58]

The price for flexibility is not well established. This is related to that the distribution system operator has little or no practical experience of utilizing flexibility. Without effective competition, there is a risk that the system operator will pay "too much" for the flexible service. In a study about promoting acceptance of direct load control in the United States, incentives from system operators were reviewed. Incentives anywhere from $25 to $100 per year, $5 to $20 per month, or 2 cents to $1 per kWh were given.[59] This indicates that there is no standardized price for flexibility, where several factors impact the pricing. The study highlights especially different social groups and levels of control as factors that must be considered when setting incentives. Giving the participants some level of control may increase the acceptance rates to participate in demand response programs.

In the literature, several models have been used to determine the price for flexibility where the interaction between the different participants and their behaviors are mathematically modeled. The models can be categorized into centralized optimization models from the viewpoint of one participant, auction theory-based models, game theory-based models, and simulation models. Smaller subgroups can be found within each category. More information about each category and its subgroups can be found in [11].

Incentives should only be used if external causes or other market failures make this tool a more socio-economic alternative. In order to be cost-efficient, the incentive should be limited to time, proportionate, and target a specific objective. Assess how flexibility generates value and how the created value is shared between the different parties is essential to determine the amount of incentive.[60]

2.3.3 Communication and Control System

Price signals alone will most likely be inadequate to take full advantage of the demand-side flexibility. The financial profit is assumed to be insufficient for the individual customer to find it worth changing their behavior. However, combining advanced communication and control strategies with price signals may have great importance.

Integration of communication infrastructure is an essential part of the development towards smart grids, as it facilitates control of network elements and sophisticated real-time monitoring. In addition, communication infrastructure may increase the reliability and quality of supply and ensure optimal utilization of network elements.[61]

The installation of advanced smart meters in Norway allows communication with external parties. The advanced smart meters record the hourly energy consumption and send the information directly to the distribution system operator. In addition, the smart meters have the ability to record events that occur in the grid, such as interruptions and earth faults, and other parameters, such as current and voltage. Every smart meter is equipped with a physical output, called the Home Area Network (HAN) port. With this port, the customer can get information about their consumption and further control their consumption with communication and control systems.[62] The HAN port makes it also easier for the customer to provide grid support to the distribution system operator.

2.4 Control Strategy

This thesis focuses on how a residential battery energy storage system (BESS) can provide services to the distribution system operator (DSO). The operational preferences for the customer and the DSO can cause conflicts. For example, the customer wants to charge the BESS to minimize costs, while the DSO may want the customer to discharge due to low voltages in the network. This situation can occur in periods of low demand and high production, in addition to low electricity prices. An example is during nights with high wind production. In order to operate the BESS in a way that benefits both the system owner and the DSO, a proper control strategy must be developed. Utilizing ESS for grid services has been heavily studied in the literature, where three control strategies can be identified [63]:

- **Centralized control** - charging and discharging control of the BESSs are determined by a central controller, where the control actions are based on measurements from all subsystems. This means that the central controller knows the state of the network and voltages at every node at every given time. Therefore, reliable and fast communication infrastructure is required, where the control system is highly dependent on the performance of the central controller.
- **Decentralized control** - the subsystems are controlled independently and without information from other subsystems. A decentralized control strategy is often a cheaper solution since there is no need for investment in communication infrastructure. However, the drawback is that an optimal operation of the systems cannot be guaranteed. In addition, the simultaneous response of the local controllers can cause operational conflicts and negative interactions, which can further cause instability in the system.
- **Distributed control** - a compromise between decentralized and centralized control, where the control method has combined the desirable feature of these two to deliver the best results. In this method, the central controller is only activated when it is needed. Therefore, only moderate communication and automation control systems are required.

A centralized control strategy is often used in remote areas where there is no available power system or a power system of low quality or consistency. Therefore, a central controller is required to maintain the stability of the grid. As the BESSs are only operated to maintain the stability of the grid and disregard the systems owners' operational preferences, this control strategy is not relevant for this master's thesis. Further in this section, decentralized and distributed control strategies will only be considered.

2.4.1 Decentralized Control

The main objective of a residential storage system is to maximize the economic benefit for the customer. This can either be done by increasing the customer's self-consumption or reducing the electricity bill by responding to electricity prices.

The two most common control method in the literature for residential BESSs coupled with PV systems is rule-based control [64] and optimization-based control [65, 66]. In a rule-based control method, charging/discharging power is decided based on certain rules, where the objective can be to store surplus power from the PV system and use it later to supply the local load when there is no production. In an optimization-based control, the charging/discharging schedule is decided based on an optimization algorithm, where the objective function is locally decided. The scheduling is often calculated based on a selected horizon length, for example, 24 hours. Therefore, an optimization-based control will be more dependent on predicted values than a rule-based control, which makes decisions based on real-time measurements.

Over-voltage issues in the distribution grid usually occur as a result of high penetration of solar production. The given control methods indirectly support the grid by charging the BESS when there is surplus power, thus preventing over-voltage issues. However, the BESS may be fully charged before solar noon. As the customers do not have information about the network, a constraint that considers when it is preferred to charge can be implemented into the optimization problem. This has been done in [67] and was achieved by setting a limit on the amount of power that can be injected into the grid during a critical period. The allowable power injection is either set to zero or a feasible limit that considers the battery's power rating and capacity.

A decentralized control can also be implemented to solve the voltage problems in the distribution grid directly [36, 63, 68]. However, in these strategies, the BESSs are installed with the sole purpose of contributing to voltage support. The disadvantage with this control strategy is the lack of coordination between the systems. The lack of coordination reduces the ability to operate all system resources optimally. In addition, without any communication between the systems, there is impossible to support other nodes in the system that are distressed by over-voltage or other grid issues. Therefore, a decentralized control strategy cannot ensure that grid is operated within its limits.

2.4.2 Distributed Control

A distributed control strategy consist of both a central controller and multiple local controllers, where the central controller is only activated when needed. This section presents some distribution control strategies from the literature.

Several researchers focus on the coordination of multiple BESSs. The distributed control strategy in [69] used a weighted consensus control algorithm for fair charging/discharging of BESSs, where the total required power among the BESSs was allocated proportionally to the battery capacity. A local droop-based controller calculated the required power. Further, a dynamic consensus control algorithm was also included to consider the SoC of the BESSs. The advantage of this control strategy is the limited communication links among the systems, which may be decisive in some networks.

A central controller will solve the voltage issues in the grid more efficiently, as the controller has access to measurements from all subsystems. With the roll-out of smart meters and the increasing availability of smart grid technologies, a central controller can be a realistic option in the near future. In order to select the most appropriate BESS to participate in the voltage regulation, several articles have used a voltage sensitivity matrix [30, 70, 71]. A SoC control was performed in all three strategies to identify if the preferable BESSs were available. However, there is no guarantee that there is battery capacity available in the network to respond to voltage problems at all times. Therefore, in [72], the BESS owner gave the DSO permission to control the power settings of the BESSs during hours of high PV penetration, in addition to a share of the battery capacity. The required power for voltage regulation was shared between the systems in proportion to rated power and energy capacity to utilize the multiple BESSs better.

A common delimiter is that the control strategies do not consider the overall benefit for the DSO and customers. Better coordination between the parties is essential to increase demand-side management participation and effectively solve the voltage issues. An energy management system (EMS) was used in [73, 74] to schedule the operation of the BESS for maximizing the economic benefits for its owner. If the scheduling could not support the grid to maintain the voltage within its thresholds, the central controller utilized the reactive power capability of the battery units' converters for voltage support. However, as the x/r ratio is low in the distribution network, active power is more effective in voltage regulation. Therefore, the central controller in [75] first adjusts the active power set points before utilizing the reactive power capability of the converters. As the central controller only adjusts the active power among the three phases, the charging and discharging schedule, determined by the local controller, was not affected.

Most of the strategies consider a BESS owned by the customer, where it is assumed that they get financial incentives from the DSO to participate in the voltage regulation. In [76], the DSO has invested in the storage system and therefore has the main priority of using the BESS to mitigate network problems. The customer can use the remaining capacity to maximize PV production and thus reduce energy costs. The SoC was constrained within 20-90% of the battery capacity to prolong the lifetime. The proposed concept was adopted in a smart grid demonstration project SoLa Bristol, where the results showed that the concept could provide an attractive solution to realize the dual conflict.

Table 2.4.1 provides a summary of the distributed control strategies presented in this section. The table includes the method used, control parameter, and main findings. Under method, it was desirable to elucidate which controllers and control method was used, rule-based or optimization. The proposed control strategy in this thesis is included in the last entry ($[MT]$).

Table 2.4.1: *A summary of the distributed control strategies.*

Ref	Summary	Method	Control parameter	Main findings
[69]	Distributed control of BESS for voltage regulation in distribution networks with high PV penetration.	Rule-based. Local droop-based control and a distributed control scheme based on two consensus algorithms.	Active power	Keeps the voltage in the network within the allowed limits. The power sharing among the batteries are fairly allocated based on the SoC and installed capacity.
[30]	Coordinated control of ESS for voltage regulation in distribution networks.	Rule-based and voltage sensitivity matrix.	Active power	Able to divide the battery units into voltage regulation areas for effective voltage regulation.

[70]	Voltage/frequency deviations control via BESS considering SoC.	Rule-base, SoC control, voltage sensitivity matrix.	Active power	Total number of charging and discharging cycles was reduced compared to a non coordinated control algorithm.
[71]	Coordination of multiple energy storage units in LV distribution networks.	Rule-based, local controller, central controller, voltage sensitivity matrix.	Active + reactive power	Able to solve real-time voltage problems that could not be solved independently by a local controller. The control scheme used the BESSs evenly.
[72]	Centralized control of ESS for voltage support in LV distribution networks.	Optimization problem, voltage sensitivity matrix. DSO had full control over the power settings during a critical period.	Active + reactive power	Single-phase BESS is more effective than three-phase BESS when used for voltage support in an unbalanced network.
[73]	Techno-economic optimum control of residential BESS.	Optimization problem. Local controller: energy management system. Central controller: reactive power control.	Active + reactive power	A competitive feed-in tariff can be used to reduce the risks of under-voltage issues.
[74]	Economical and efficient voltage management using residential BESS in a distribution network with high PV penetration.	Optimization problem.	Active + reactive power	Has the potential to reduce the total subsidy cost in a network with high PV penetration. The duration of voltage violations where reduced.
[75]	Distributed control scheme for residential BESS coupled with PV systems.	Optimization problem. Local controller: energy management system. Central controller: active and reactive control.	Active + reactive power	Able to solve the over-voltage issues without affecting the charging/discharging schedule of the battery.
[76]	Flexible operation of shared ESS at households to facilitate PV penetration.	Charging envelopes and optimization problem.	Active power	Energy cost savings up to 34% could be realized with the proposed charging envelopes. System peak demand reduction increased from 12% to 22%.
$[MT]$	Leveraging residential BESS for voltage support in remote distribution grids with high penetration of renewables.	Local controller: energy management system. Central controller: rule-based. Voltage sensitivity matrix.	Active power	Completely mitigate voltage issues caused by both wind and solar production. Reduce the total amount of required power for voltage support. Includes the customers' the operational preferences.

2.5 Simulation of the Power System

In order to investigate the performance of the control strategy presented in this master's thesis, it was necessary to model a distribution grid. In this thesis, the distribution grid at Utsira was modeled. Simulation of the power system can be performed by using a simulation software tool. There are many different simulation software tools available in the market. Some software tools are commercially available, while others are largely linked to research environments and are developed there. However, all of the simulation software tools are based on the fundamental study of *power flow analysis*. This section will briefly describe the theory behind power flow analysis. Further, it will also contain a section on how a sensitivity matrix, extracted from the power flow analysis, can be used to select the most appropriate BESS for voltage regulation.

2.5.1 Power Flow Analysis

Power flow analysis is widely used in power system operation and planning, where the objective is to determine the steady-state operation characteristics for a given load, generation, and network condition. Voltage magnitude and phase angle of each bus, overloading of power system elements, and the weakest point of the network are information that can be extracted from a power flow analysis.[77]

Necessary input parameters to perform a power flow analysis are bus data, line data, and generator/load data. There are four variables associated with each bus: voltage magnitude ($|V|$), phase angle (δ), active power (P), and reactive power (Q). At each bus, two of four variables are defined, while the remaining two are unknown. The known variables depend on the bus type. The bus types are provided in Table 2.5.1. Most buses in a study are classified as PQ bus, while buses with generation are classified as PV bus. There is only one slack bus in the system, where the main task of this bus is to balance generation, load, and losses and serve as the reference for all other bus voltage angles.[77]

Table 2.5.1: *Types of buses in a power flow analysis.*

Bus types	Known variables	Unknown variables
Slack Bus (Reference Bus)	$\lvert V_i\rvert, \delta_i$	P_i, Q_i
PQ Bus (Load Bus)	P_i, Q_i	$\lvert V_i\rvert, \delta_i$
PV Bus (Generator Bus)	$P_i, \lvert V_i\rvert$	Q_i, δ_i

The unknown variables are found using static load flow equations, given in Equation 2.5.1 and 2.5.2, where i, j denote the bus numbers and P, Q, U, δ, Y, and θ denote, respectively, the active power flow, reactive power flow, phasor bus voltage, voltage angle, line admittance, and impedance angle. The equations are deduced from Kirchhoff's current law. As the equations are non-linear algebraic equations, the equations can be solved using iterative numerical techniques, such as Newton-Raphson and Gauss-Seidel.[77]

$$P_i = |V_i| \sum_{k=1}^{N} |V_j||Y_{ij}|cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.5.1}$$

$$Q_i = |V_i| \sum_{k=1}^{N} |V_j||Y_{ij}|sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.5.2}$$

The power flow study assumes a three-phase steady-state condition. This makes it possible to assume that all voltages and currents in the system are balances, and a per-phase representation of the power system can be used. Further, a per-unit system is often used for simplification.[77]

2.5.2 Voltage Sensitivity Matrix

The most appropriate battery energy storage system to react to a voltage disturbance can be determined using a voltage sensitivity matrix. The voltage sensitivity matrix provides information about the influence of changing load and generation parameters (P and Q) on the system voltage.[16] The sensitivity matrix can be obtained from the two load flow equations (Eq. 2.5.1 and 2.5.2). For each iteration, a Jacobin matrix is obtained and multiplied by a vector of incremental unknown bus voltages and angles until the convergence criterion is satisfied.[70]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{2.5.3}$$

The sensitivity matrix is the inverse of the Jacobin matrix, given by Equation 2.5.4, where $[\frac{\partial V}{\partial P}]$ is the voltage-active sensitivity matrix, and $[\frac{\partial V}{\partial Q}]$ is the voltage-reactive power sensitivity matrix.

$$S = J^{-1} = \begin{bmatrix} \frac{\partial \delta}{\partial P} & \frac{\partial \delta}{\partial Q} \\ \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{bmatrix} \tag{2.5.4}$$

Each of the coefficients in the voltage sensitivity matrix indicates the amount of voltage change caused by active and reactive power changes. Therefore, the node with the highest sensitivity coefficient has the greatest effect on voltage regulation. The voltage change of node i can be calculated by the active and reactive power change of node j, and are given by Equation 2.5.5.

$$\Delta V_i = \left[\frac{\partial V_i}{\partial P_j}\right] \Delta P_j + \left[\frac{\partial V_i}{\partial Q_j}\right] \Delta Q_j \tag{2.5.5}$$

Chapter 3

Case Study: Utsira Island

This master's thesis was performed as a case study where the aim was to design a control strategy for residential battery energy storage systems for voltage support in a distribution network with high penetration of renewable energy resources. This thesis was carried out in collaboration with Haugaland Kraft Nett, where data from Utsira island was used to validate the performance of the control strategy. Utsira island has become a test facility for developing new technology with associated business models. The aim is to make smart energy services and flexibility profitable for energy users, distribution system operators, and electricity suppliers [78]. This section will give a brief description of Utsira and relevant components. Part of this chapter is reused from the specialization project [79].

3.1 Overview

Utsira is an island located in the North Sea outside Karmøy. Two wind turbines are installed at the island to supply the population, in addition to a submarine cable. A map section of Utsira is given in Figure 3.1.1, where the wind turbines can be found northeast of the island.

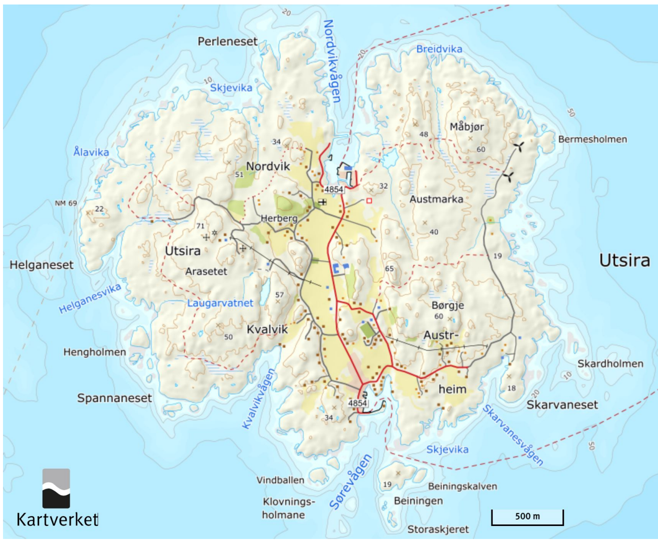


Figure 3.1.1: *Map section of Utsira extracted from norgeskart.no. Two wind turbines are installed northeast of the island.*

With a combination of variable wind production, load variation, a generally weak grid, and an underdimensioned submarine cable, the island experiences large voltage variations. As the situation is today, the voltage variations are at the limit of what can be defended according to the quality of supply. As grid reinforcement is associated with high investment costs, it is desirable to investigate other measures to mitigate voltage issues. Communication and control systems, local production, and energy storage systems can reduce the need for power transmission between the island and the mainland. As a result, grid reinforcement may be postponed or avoided.

3.2 Distribution Grid

Utsira is supplied from Stava substation located at Karmøy, approximately 7 km from the submarine cable. At Stava substation is the voltage transformed from 60 kV to 22 kV. Several substations are connected to the grid between Stava and the submarine cable, where some of the voltage variations at Utsira are due to the voltage drop along this stretch. However, the largest contribution to voltage variations is the 17 km submarine cable that connects Utsira to the mainland. The cable has a small cross-section, and due to a significant voltage drop during normal load variations, the cable is not dimensioned for power transmissions of more than 1 MW. With appropriate voltage regulation measures, this limit can be extended.

Until recently, the HV distribution grid at Utsira consisted of two voltage levels, 11 and 22 kV. This has been changed, and the entire grid now has a voltage level of 22 kV. Further, the grid consists of 11 transformers, where two of them are connected to the wind turbines. One of the substations, SS61020, was selected to be modeled in this thesis with the associated network. The specific substation was selected in consultation with Haugaland Kraft Nett and was selected due to low short-circuit performance at several customers. A simplified single-line diagram of the LV distribution grid is illustrated in Figure 3.2.1. The LV distribution grid is connected to the upper grid by means of a three-winding transformer, where only the 230 V network was modeled.

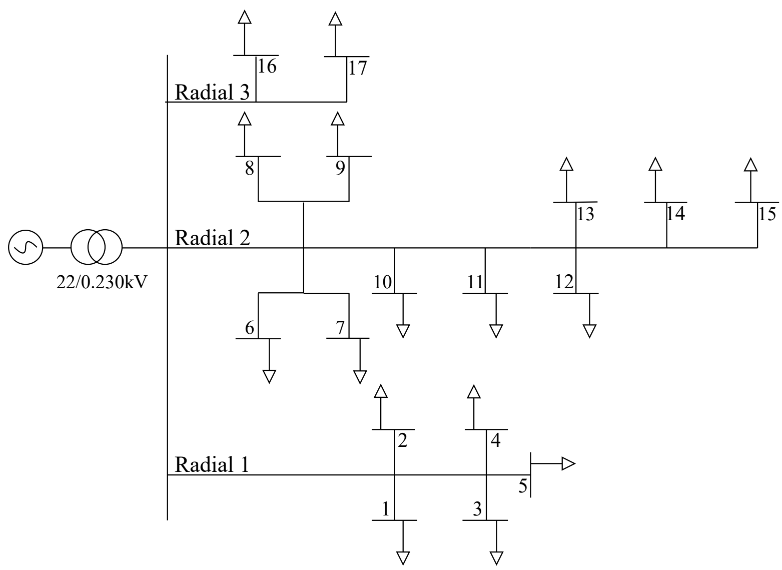


Figure 3.2.1: *Simplified single-line diagram of the LV distribution grid. The LV distribution grid is connected to the upper grid by means of a three-winding transformer.*

3.3 Wind Turbines

The installed capacity of the two wind turbines is enough to supply the whole population. The wind turbines are of the type E-40 from the German manufacturer Enercon GmbH, where the main parameters of the wind turbines are presented in Table 3.3.1. The wind turbines were installed in 2004 as a part of a project established by Hydro. Today, the wind turbines are owned by Solvind.[80]

Table 3.3.1: *Specifications of the wind turbines at Utsira.[81]*

Specification	**Enercon E-40/6.44**
Hub height	46 m
Rotor diameter	44 m
Generator rated power	600 kW
Generator rated voltage	440 V
Cut-in wind speed	2.5 m/s
Rated wind speed	12 m/s

The wind turbine generators are synchronous, and they are directly connected to the HV distribution grid by means of two three-phase transformers. Although the wind turbines can collectively produce up to 1.2 MW, the production is limited to a total of 1 MW. The limitation is required due to the voltage situation at Utsira. The control and SCADA system associated with the wind turbines are old, and the reactive power regulation is limited. As the control system works today, the turbines are not regulated according to a voltage reference but according to a constant power factor set to 1, which can be changed between 0.95 inductive and 0.95 capacitive. If the voltage exceeds an upper or lower limit, the turbines are automatically disconnected.

The average monthly production of the two wind turbines is illustrated in Figure 3.3.1. Production from wind turbine 1 was equal to zero in several of the months. This incident may be due to maintenance. Apart from the limited production from wind turbine 1 in the first part of the year, the average monthly production was approximately equal in September, October, and November.

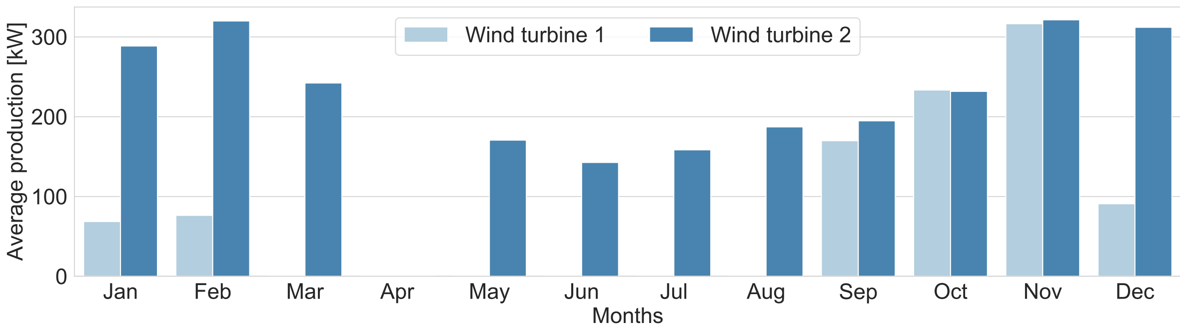


Figure 3.3.1: *Average monthly production of the two wind turbines at Utsira.*

3.4 Loads

The customers connected to the grid at Utsira are mainly households and cottages, but larger installations, such as a school, industrial buildings, and shops, are also connected to the grid. The smaller customer group consists of both single- and three-phase customers. There are no densely populated areas where the customers are geographically spread across the island. There are currently 193 inhabitants distributed over around 97 households and 35 cottages [82]. Due to the number of cottages, the island experiences a seasonal increase in energy demand. A fast-charging electric ferry is also planned to be connected to the island.

The LV distribution grid modeled in this master's thesis consist of 17 customers: four cottages, one small industrial building, and twelve households. The total hourly load consumption of the customers connected to the LV distribution grid is illustrated in Figure 3.4.1 for the period January to November 2020. The average hourly load consumption for this substation was 21.5 kW.

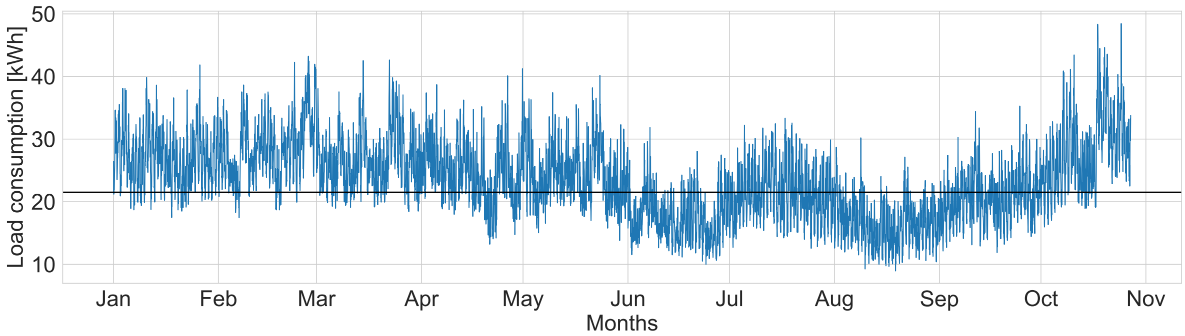


Figure 3.4.1: *The aggregated load consumption for substation 61020 in the period January to November 2020. The average hourly load consumption during this period was 21.5 kW.*

3.5 Photovoltaic systems

Today, there are no installed PV systems in the distribution grid at Utsira. However, the existing submarine cable does not have the capacity to supply electricity to the future power-intensive industry on the island. In order to prevent expensive grid reinforcement, more production must be installed on the island. The desire is to cover the electricity demand with renewable energy resources.

Rooftop PV panels will be installed at several customers at Utsira as a part of the ongoing pilot project. The location of these panels has not been determined at this point. As the island experiences large voltage variations due to wind production, the production from the PV panels will amplify the voltage variations. Therefore, some PV systems will be installed with a battery storage system to control the power flow [83].

Chapter 4

Methodology

This section provides information about the modeling process of the distribution grid at Utsira and the two controllers designed in this thesis. Further, a description of the different scenarios and the system settings used in the simulations will be given. Finally, the process of collecting data will be presented.

4.1 Modeling of the Distribution Grid at Utsira

This section describes the modeling process of the distribution grid at Utsira. First the simulation software will be presented, followed by a description of the modeling process. At the end of this section, some assumptions and limitations will be given, in addition to a verification of the model.

4.1.1 Simulation Software: Pandapower

Pandapower was selected as simulation software to simulate the static operation characteristics of the distribution grid at Utsira. Pandapower is a library within Python and consists of the packages *Pandas* and *Pypower*. Pandapower is an open-source tool for convenient modeling, analysis, and optimization of electric power systems developed with the University of Kassel and Fraunhofer Insitute for Energy Economics and Energy System Technology (IEE) [84]. The program can simulate both static and quasi-static analysis, where the power flow calculation is solved based on the Newton-Raphson method.

Network Modeling

To model the electric grid, Pandapower uses an element-based model. This model differs from the commonly used approach bus-branch model. The bus-branch model is an accurate mathematical representation of the network and defines the network as a collection of buses defined by generic branches (Section 2.5.1). The bus-branch model approach has several advantages, such as power flow equations can be directly derived from the model, and parameters are not bound to specific models.[84] However, this approach may be cumbersome and error-prone, especially for more extensive networks. Due to little experience with network modeling, an element-based approach seemed like the best alternative.

An element-based model uses separate models for each element in the network, such as lines, transformer, load, and generation. This model gives the possibility to define the network with nameplate parameters, such as impedance and length for lines, or rated apparent power for transformer. Further, Pandapower is based on a tabular data structure, which means that a table represents each element type, including all parameters. The results are also presented in the same way.[84]

Table 4.1.1 presents relevant elements that are used in the simulation and input parameters necessary to perform a power flow calculation. A three-winding transformer was also used in the simulation. The input parameters for the three-winding transformer are almost the same as for the transformer.

Table 4.1.1: *Relevant elements used in the modeling process and necessary input parameters for executing a power flow calculation.*

Element	Input parameter
External grid	Voltage set point [p.u] Angle set point [degree]
Bus	Rated voltage of the bus [kV]
Line and Cable	Resistance of the line [Ω/km] Inductance of the line [Ω/km] Capacitance of the line [nF/km] Length of the line [km] Maximal thermal current [kA]
Transformer	Rated apparent power [MVA] Rate voltage at high voltage bus [kV] Rated voltage at low voltage bus [kV] Short circuit voltage [$\%$] Real component of short-circuit voltage [$\%$] Iron losses [kW] Open loop losses in [$\%$] Transformer phase shift angle
Static generator	Active power [MW] Reactiv power [MW]
Load	Active power [MW] Reactiv power [MW]
Storage system	Active power [MW] Reactive power [MW] Energy capacity [MWh]

Quasi-Dynamic Simulation

A quasi-dynamic simulation was used in this master's thesis. Quasi-dynamic simulation calculates a series of power flow simulations in a period. In Pandapower, simulation controllers update the values of different elements in each time step. The simulation controllers also enable the user to simulate control strategies by building a controller in an object-oriented framework.

The simulation controllers in Pandapower can be divided into *ConstControl* and *BasicControl*. Const-Control is mainly used to update the values for loads and generators in each step, where this controller reads data from a data source and writes it back to the network. BasicControl is a base controller class used when own controllers are built.[84] Both of the controller were used in thesis, where the BasicControl was used to update the state of charge and the charging/discharging power for each BESS and to build the two controllers presented in Section 4.2.

Figure 4.1.1 illustrates the steps in a time series simulation. During each step, a controller simulation is started for each controller. In the controller simulation, initialize setting of each controller is called, and a power flow is calculated. This process is repeated in ascending order until all of the controllers have converged. The sequence is determined by the user.[84]

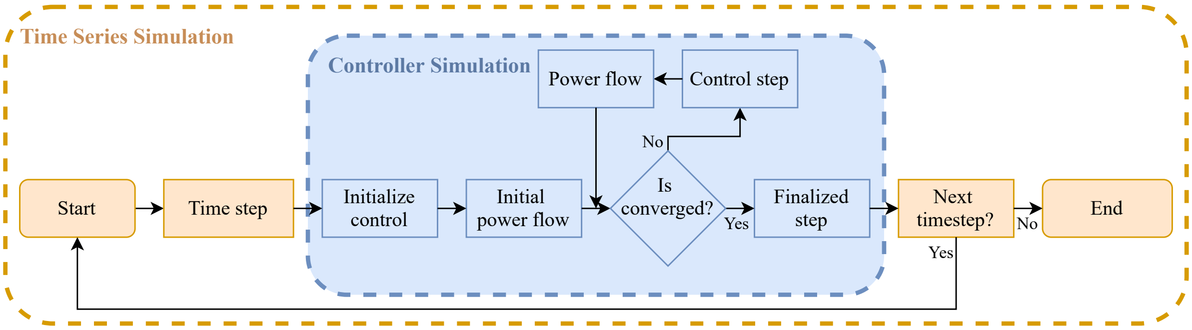


Figure 4.1.1: *Flow chart of the time series simulation and controller simulation. Inspired by [84]*

4.1.2 Description of the Modeling Process

This section describes the modeling process of the network. The high voltage (HV) distribution network was modeled, in addition to the selected low voltage (LV) distribution grid, to consider the voltage variations caused by the two wind turbines and the load variations in the rest of the grid. Detailed information or a single-line diagram of the HV distribution grid will not be given as this can be considered as sensitive information according to preparedness regulation paragraph §6-2. According to the paragraph, sensitive information is defined as specific and in-depth information about the energy supply that can damage systems or affect essential functions of the energy supply [85]. However, the information is considered irrelevant to understand the distributed control strategy.

The distribution grid modeled in Pandapower can be divided into three parts: the HV distribution grid at Karmøy, the HV distribution grid at Utsira, and the LV distribution grid. The distribution grid at Utsira is supplied by Stava substation, where the section between the submarine cable and Stava is referred to as the HV distribution grid at Karmøy. It was decided to include a simplified model of this grid, as the voltage variations at Utsira depend on the loading at Karmøy. Therefore, the distribution grid at Karmøy was modeled with 20 loads, representing either distribution transformers or 22 kV lines or cables that continue in other directions than Utsira. Further, an external grid was connected to this part of the grid to represent the regional network. The external grid is modeled as a slack bus, with an angle set point of 0° and a voltage set point of 0.98 p.u. The voltage set point was determined based on information from Haugaland Kraft Nett. Table 4.1.2 provides information about the elements used to model the HV distribution grid at Karmøy.

Table 4.1.2: *Elements used to model the HV distribution grid at Karmøy.*

Element	Number of elements
Bus	48
Load	20
Line or Cable	47
External grid	1

The HV distribution grid at Utsira was modeled with 11 transformers. Two of them are connected to their respective wind turbine. The wind turbines were modeled as static generators, which are modeled as a PQ-bus in Pandapower. This means that injected active and reactive power is set to a given value, while the voltage at the point of common connection follows the voltage in the network. A static generator was selected due to the old control system of the wind turbines and the limited ability to regulate the reactive power. Therefore, only active power was inserted into the model during the simulations, where reactive power was set to zero.

The rest of the transformers were either connected to a load or the modeled LV distribution grid. The loads represent the consumption from each substation. A three-winding transformer was modeled to connect the LV distribution grid and a final load. Table 4.1.3 provides information about the elements used to model the HV distribution grid at Utsira.

Table 4.1.3: *Elements used to model the HV distribution grid at Utsira.*

Elements	Number of elements
Bus	23
Load	9
Line or Cable	11
Static generator	2
Transformer	11 (10 two-winding and 1 three-winding)

The LV distribution grid consists of five feeders, where households and cottages are connected to three and residential street lights connected to two. Only the feeders with households and cottages were modeled. Line and cable data used in the simulation is presented in Table A.1.1 in Appendix A.1. Standard lines were created in Pandapower to simplify the modeling process. Instead of defining all parameters individually for each line, the created standard types can be extracted when creating a new line or cable. The standard types were created based on information from *Planbok - REN* and are given in Table A.1.2 in Appendix A.1 [86].

The transformer connected to the LV distribution grid has a nominal turn ratio of 22kV/240V, with the possibility to regulate the turn ratio in both directions. Such changes are called tap changing. A common practice is to set the distribution transformer to emit a voltage around 240-245 V to get a good margin for voltage drops along the feeder. However, as the desire was to recreate the grid at Utsira, the turn ratio was changed to coincide with the voltages measured at Utsira. An average voltage value was calculated for both simulated and measured values for the period 09.07.2020-15.10.2020, where the measured voltage values consisted of daily minimum, maximum and average voltage values. The step position of the transformer was changed until the two voltage values were approximately the same. A step position of +2.5% gave an average simulated voltage value of 239 V, where the average measured voltage value was 242 V.

PV systems and energy storage systems were also modeled in Pandapower. Similar to the wind turbine, the PV systems were modeled as static generators. As the focus of this master's thesis was to regulate active power for voltage support, the PV systems were modeled with a power factor equal to one. Further, the battery storage systems were modeled with the use of the storage system element in Pandapower. A charging and discharging efficiency were included when the state of charge for each time step was calculated to consider the losses in the storage system. Parameters of the battery storage system will be given in Section 4.3.3.

4.1.3 Assumptions, Limitations and Verification of the Model

Some assumptions and limitations were made to simplify the modeling process and development time. The assumptions are listed below, along with a discussion of consequences and limitations. Verification of the model is given at the end of this section.

Assumptions

- System in steady-state
- Balanced, symmetrical system
- No faults or disturbances occur during simulation
- The wind turbine cannot provide reactive power support

Limitations

As the simulation only considers steady-state conditions, stability issues caused by switching on and off production units and connection of battery storage systems were not captured. Switching on and off production units can especially be critical in networks with low short circuit performance. The purpose of this thesis was to design a control strategy to mitigate voltage issues, and stability issues were, therefore, not considered.

The simulation only considers symmetrical loads. This assumption is usually correct when considering the entire LV distribution network but is often incorrect at the individual customer level. The consequence of this simplification is that the voltage variations for individual customers at the end of a radial is modeled too optimistic, as asymmetrical loads will lead to more significant voltage drops at the most loaded phase. However, the performance of the control strategy should not be strongly influenced by this assumption.

The data used in the simulation were based on hourly energy consumption. Therefore, variations in power consumption during each hour were not included, hence the voltage variations. In addition, the loads and productions in each time interval were kept constant. As a completely deterministic system is not realistic, a future model should consider random occurrences.

As mention earlier, the wind turbines and PV systems were modeled as static generators. Therefore, the variability in power due to sudden changes in wind speed or solar irradiance will not be considered. A static generator was selected due to development time and available data. This also accounts for the modeling of the battery storage systems, where the storage systems were modeled as a combination of a load and a generator.

A final limitation is that overloading of system elements in the grid was not considered. This can be solved by implementing additional control parameters in the central controller and should be done in a future model. The main task in this thesis was to investigate voltage issues caused by high penetration of renewable energy resources and how it can be solved and was therefore not included in this model.

Verification of the model

It was discovered that the simulated model did not achieve the same voltage variations as the voltages measured at Utsira. Figure 4.1.2 illustrates a simulated voltage profile and voltage profiles based on AMS measurements for substation 61003. The AMS data include maximum, average, and minimum voltage measurements for each hour during 09.08.2020-15.10.2020. Substation 61003 was used to illustrate the model's performance as this substation is the largest in the distribution grid at Utsira and due to hourly measured voltage data, which was not available for substation 61020. As it can be observed from the figure, the shape of the profile is similar. However, the simulated voltage value is within the range of 1.018 and 1.065 pu, compared to 1.009 and 1.099 for the AMS measurements.

The deviation between simulated and measured values can be a sum of several reasons. The first reason can be that the modeled network includes planned or recent changes done in the network. For example, an overhead line in the HV distribution grid at Utsira has recently been changed to a cable, and the voltage level in parts of the grid has been changed from 11 to 22 kV. These measures may have resulted in better voltage performance in the grid compared to when the measurements were taken. Other reasons can be due to the presented assumptions and limitations, especially the assumptions regarding the balanced system, simplified modeling of the wind turbines, and that the data used in the simulation was based on hourly energy consumption.

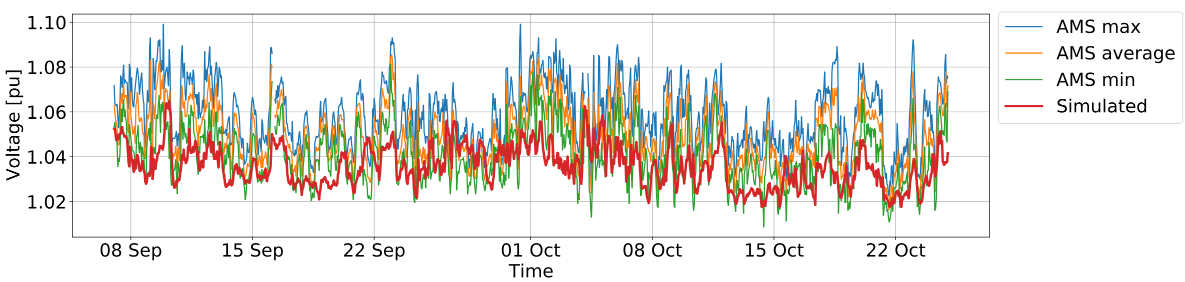


Figure 4.1.2: *Simulated voltage profile at substation 61003 in the period 09.08.2020-15.10.2020. The simulated voltage profile is compared against the maximum, minimum, and average hourly AMS measurements for substation 61003.*

Due to reduced voltage variations in the simulated model, the model did not simulate any voltage violations. Therefore, the upper allowable voltage limit was reduced to 1.07 pu, and the lower limit was increased to 0.975 pu. The limits were selected based on the two simulated weeks used to validate the performance of the control strategy (Section 4.3). In addition, the limits seemed reasonable according to the load demand and production in the grid. The main purpose is to illustrate the performance of the distributed control strategy, which the given limits did.

4.2 Control Modeling

The control strategy modeled in this thesis is based on the distributed control concept, where the aim is to maximize the economic benefit for the system owner and, at the same time, provide voltage support. The control strategy consists of a central controller and local controllers. The local controllers aim to reduce the electricity bill by increasing the customers' self-consumption or taking advantage of the electricity price variations using an optimization-based energy management system. As not everyone with a PV system owns a battery storage system, over-voltage issues can occur. Therefore, the central controller aims to utilize the active power capability of the battery storage systems to improve the voltage quality in the grid. Periods with voltage violations are referred to as critical periods. During a critical period, the distribution system operator (DSO) is given partial control over the active power settings of the battery storage systems, in addition, to a certain percentage of the battery capacity.

The proposed control strategy was inspired by [70], [75] and [72]. In contrast to these strategies, the proposed strategy considers critical periods caused by both wind production and solar production. Due to different production patterns for the two resources, the critical periods are more unpredictable compared to when only considering voltage problems caused by solar production. In addition, the critical periods may occur more frequently and have a longer duration. Therefore, a different operation of the central and local controllers is required. In addition, the proposed control strategy can also mitigate under-voltage issues caused by high loading in the system, where most of the papers consider only over-voltage issues. The distribution control strategy proposed in this master's thesis will be described in this section.

4.2.1 Local controller

An AC-coupled configuration of the PV system and battery energy storage system (BESS) is considered for the optimization-based energy management system, where an illustration of the configuration is given in Figure 4.2.1.

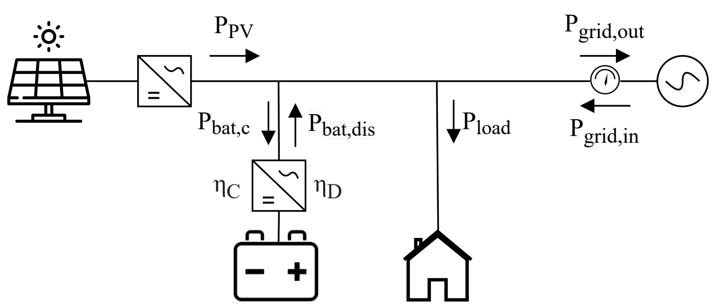


Figure 4.2.1: *AC-coupled configuration of the battery storage and PV system. Arrows indicate the direction of the power flow. The figure is inspired by [75].*

The operation of the BESS is controlled with the aim of minimizing the electricity bill for the customer, where the BESS is operated accordingly:

- The BESS charges all surplus power produced from the PV system. If the BESS is fully charged, surplus power is injected into the grid.
- The BESS charges from the grid if the price variation is large enough to cover the cost of losses due to charging and discharging, in addition to the tariff for buying electricity. On the other hand, the BESS discharges to the grid if selling energy is higher than consuming it locally.

Based on these operation criteria, the objective function can be formulated as

$$min \sum_{t=0}^{N} (P_{grid,in}(t) \cdot C^{buy}(t) + P_{grid,out}(t) \cdot C^{sell}(t)) \tag{4.2.1}$$

where $P_{grid,in}$ is the power extracted from the grid, $P_{grid,out}$ is the power injected into the grid, C^{buy} is the cost for electricity, and C^{sell} is the price for injecting power to the grid. As extracting power from the grid and injecting power into the grid cannot occur simultaneously, Equations 4.2.2-4.2.4 will ensure that this situation does not occur. δ_E is the binary variable for extracting power from the grid and δ_I is the binary variable for injecting power to the grid.

$$\delta_E(t) + \delta_I(t) = 1 \qquad \delta_I, \delta_E \in [0, 1] \tag{4.2.2}$$

$$P_{grid,in}(t) \cdot \delta_E(t) = P_{grid,in}(t) \tag{4.2.3}$$

$$P_{grid,out}(t) \cdot \delta_I(t) = P_{grid,out}(t) \tag{4.2.4}$$

The size of the circuit breaker, P_{CB}, sets limits on the amount of power that can be extracted from or injected into the grid. This is accounted for by the following constraint:

$$-P_{CB} \leq P_{grid,out}(t) \leq 0 \qquad 0 \leq P_{grid,in}(t) \leq P_{CB} \tag{4.2.5}$$

The operation of the BESS is subjected to several constraints, where the first consider the law of power, and that the energy balance should be satisfied. This is constraint as:

$$P_{load}(t) - P_{bat,c}(t) - P_{bat,dis}(t) - P_{grid,in}(t) - P_{grid,out}(t) - P_{PV}(t) = 0 \tag{4.2.6}$$

where notations P_{load}, $P_{bat,c}$, $P_{bat,dis}$, and P_{PV} are specified in Figure 4.2.1. P_{load} and P_{PV} are fixed parameters, where the charging and discharging power are variables and restricted by the rated power of the BESS, P_{rated}, given by following constraints:

$$-P_{rated} \leq P_{bat,c}(t) \leq 0 \qquad 0 \leq P_{bat,dis}(t) \leq P_{rated} \tag{4.2.7}$$

As the charging and discharging power are divided into two different variables, Equations 4.2.8-4.2.10 ensure that the two actions do not occur simultaneously, where δ_C and δ_D are binary variables for charging and discharging power, respectively.

$$\delta_C(t) + \delta_C(t) = 1 \qquad \delta_C, \delta_D \in [0, 1] \tag{4.2.8}$$

$$P_{bat,c}(t) \cdot \delta_C(t) = P_{bat,c}(t) \tag{4.2.9}$$

$$P_{bat,dis}(t) \cdot \delta_D(t) = P_{bat,dis}(t) \tag{4.2.10}$$

Further, the state of charge (SoC) should be maintained within certain limits to prolong the battery's lifetime. The SoC limits is given as Equation 4.2.11, where SoC_{min} and SoC_{max} express the upper and lower limits, respectively. The SoC is calculated for each time step according to Equation 4.2.12, where η_C and η_D are the charging and discharging efficiency of the battery converter. SoC_{init} is the energy level in the BESS at the beginning of the control horizon.

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{4.2.11}$$

$$SoC(t) = \begin{cases} SoC_{init} - P_{bat,c}(t) \cdot \eta_C - \dfrac{P_{bat,dis}(t)}{\eta_D}, & \text{if} \quad t = 0 \\ SoC(t-1) - P_{bat,c}(t) \cdot \eta_C - \dfrac{P_{bat,dis}(t)}{\eta_D}, & \text{otherwise} \end{cases} \tag{4.2.12}$$

A full charge or maximum SoC at the end of the charging is recommended for prolong the lifetime of the BESS. This will not always be possible if there is not enough surplus power to fully charge the BESS. However, Equations 4.2.13 and 4.2.14 restrict the battery to one cycle per day, where E_{nom} is the rated energy capacity.

$$\sum_{t=0}^{N} P_{bat,c}(t) \leq E_{nom} \cdot (SoC_{min} - SoC_{max}) \tag{4.2.13}$$

$$\sum_{t=0}^{N} P_{bat,dis}(t) \leq E_{nom} \cdot (SoC_{max} - SoC_{min}) \tag{4.2.14}$$

A finite BESS constraint is included to control the energy level at the end of the control horizon, SoC_{end}, where the constraint is given by Equation 4.2.15. Normally, SoC_{init} and SoC_{end} will be set equal to each other to have the same starting point for each day. However, if critical periods occur at the end of a control period, this may not be possible. In these situations, SoC_{end} will be adjusted until a feasible solution is found.

$$\sum_{t=0}^{N} (P_{bat,c}(t) \cdot \eta_C + \frac{P_{bat,dis}(t)}{\eta_D}) = SoC_{init} - SoC_{end} \tag{4.2.15}$$

The constraints given above consider the operation of the BESS without any interruption from the central controller. However, suppose a critical period is predicted during a day. In that case, the agreement between the DSO and the BESS owner states that the DSO gets partial control over the active power settings of the BESS, in addition to a percentage of the total battery capacity. Therefore, the BESS owner cannot utilize the BESS to its full potential. During a critical period, the BESS is operated according to:

- During over-voltage times:
  - As the DSO must have the possibility to charge during the critical period, the owner is not allowed to discharge during the period: $P_{bat,dis}(t) = 0 : t \in \Delta T_{critical}$
  - As the DSO has been allocated a share of the rated charging power (P_{DSO}) during the critical period, the owner can only charge with a power equal to the rest of the rated power. P_{DSO} is constant during the critical period. The lower boundary for charging during the critical period is changed to: $P_{bat,c}(t) \geq -P_{rated} + P_{DSO} : t \in \Delta T_{critical}$
  - Similarly, the maximum power extracted from the grid must be changed to consider the power allocated to the DSO. The upper bound for maximum power extracted from the grid during the critical period is changed to: $P_{grid,in} \leq P_{CB} - P_{DSO} : t \in \Delta T_{critical}$
  - As the DSO is allocated a percentage of the total battery capacity, the owner cannot charge the BESS above a set SoC limit. It is the DSO that determines the SoC limit. The upper boundary for SoC during the critical period is changed to: $SoC(t) \leq SoC_{DSO} : t \in \Delta T_{critical}$
- During under-voltage times:
  - As the DSO must have the possibility to discharge during the critical period, the owner is not allowed to charge during the period: $P_{bat,c}(t) = 0 : t \in \Delta T_{critical}$
  - As the DSO has been allocated a share of the rated discharging power (P_{DSO}) during the critical period, the owner can only discharge with a power equal to the rest of the rated power. P_{DSO} is constant during the critical period. The upper boundary for discharging during the critical period is changed to: $P_{bat,dis}(t) \leq P_{rated} - P_{DSO} : t \in \Delta T_{critical}$
  - Similarly, the maximum power injected to the grid must be changed to consider the power allocated to the DSO. The lower bound for minimum power injected to the grid during the critical period is changed to: $P_{grid,out} \geq -P_{CB} + P_{DSO} : t \in \Delta T_{critical}$
  - As the DSO is allocated a percentage of the total battery capacity, the owner cannot discharge the BESS below a set SoC. It is the DSO that determines the SoC limit. The lower boundary for SoC during the critical period is changed to: $SoC(t) \geq SoC_{DSO} : t \in \Delta T_{critical}$

The optimization is a constrained non-linear problem, where the optimization modeling language *Pyomo* was used with the *Gurobi* solver. The optimization problem is solved for each BESS at the beginning of each day, with a control horizon of 24 hours ($N = 23$). As the energy regulated by the DSO is not considered in the charging and discharging schedule, a new optimization problem must be solved right after each critical period. The planning horizon for the new optimization problem is from right after the critical period to the end of the same day.

4.2.2 Central controller

The central controller is a rule-based controller, where the aim is to utilize the residential BESSs for voltage regulation. The central controller is only activated during critical periods. Critical periods are periods when voltage violations can occur and are identified by predicting the system performance at the beginning of each day based on a worst-case scenario, a system without BESSs. If there are less than four hours between two critical periods, the periods are merged into one. This arrangement is to avoid voltage distortion between two critical periods.

A voltage sensitivity matrix is used to determine the BESS with greatest impact on the system performance to participate in the voltage regulation and to calculate the active power adjustment. If a voltage violation is detected, the BESS with the highest sensitivity coefficient ($\frac{\partial P}{\partial V}$) is selected to participate in the voltage regulation. Further, the active power adjustment can be found by multiplying the sensitivity coefficient with the voltage variation, ΔV, given by Equation 4.2.16.

$$\Delta P_{VR} = \Delta V \cdot \frac{\partial P}{\partial V} \tag{4.2.16}$$

The algorithm for the central controller is illustrated in a flow chart in Figure 4.2.2. The algorithm starts by predicting and identifying critical periods. Once the critical periods for the given day are identified, the periods are sent to the local controllers with information about required power settings, P_{DSO}, and the SoC limit the BESS owner has to take into account when determining the scheduling of the BESS. If no voltage violations are predicted, no restrictions will be given to the local controller.

For each time step, a power flow calculation is performed with predicted load and production data. The highest and lowest voltage (V_{calc}) extracted from the calculation is compared against the limits. If the voltage is below or above the limit, the DSO has to check if the time step is within a critical period, as the DSO has only permission to adjust the power settings within the period. If the time step is within the critical period, the DSO must first check if there is available storage for regulation. The amount of energy intended to be used for voltage regulation is determined at the beginning of each day. Due to prediction errors, the DSO may have underestimated the amount of energy required. If storage is available, the BESS with the highest sensitivity coefficient with available storage capacity is selected to participate in the voltage regulation. The active power adjustment is calculated based on Equation 4.2.16. However, the power cannot exceed specific values, and different control steps have to be performed. For example, the required power must be checked against the charging/discharging power allocated to the DSO (P_{DSO}) and a rated power (P_{rated}). The rated power ensures that the BESS is not charged/discharged at a higher rate than the available storage capacity. When the regulated power is determined, a new power flow calculation is performed with the new settings. This step is necessary, as the voltage problem may persist due to the power constraints. If there are still voltage issues, the process is repeated. The algorithm is performed for a control horizon of 24 hours.

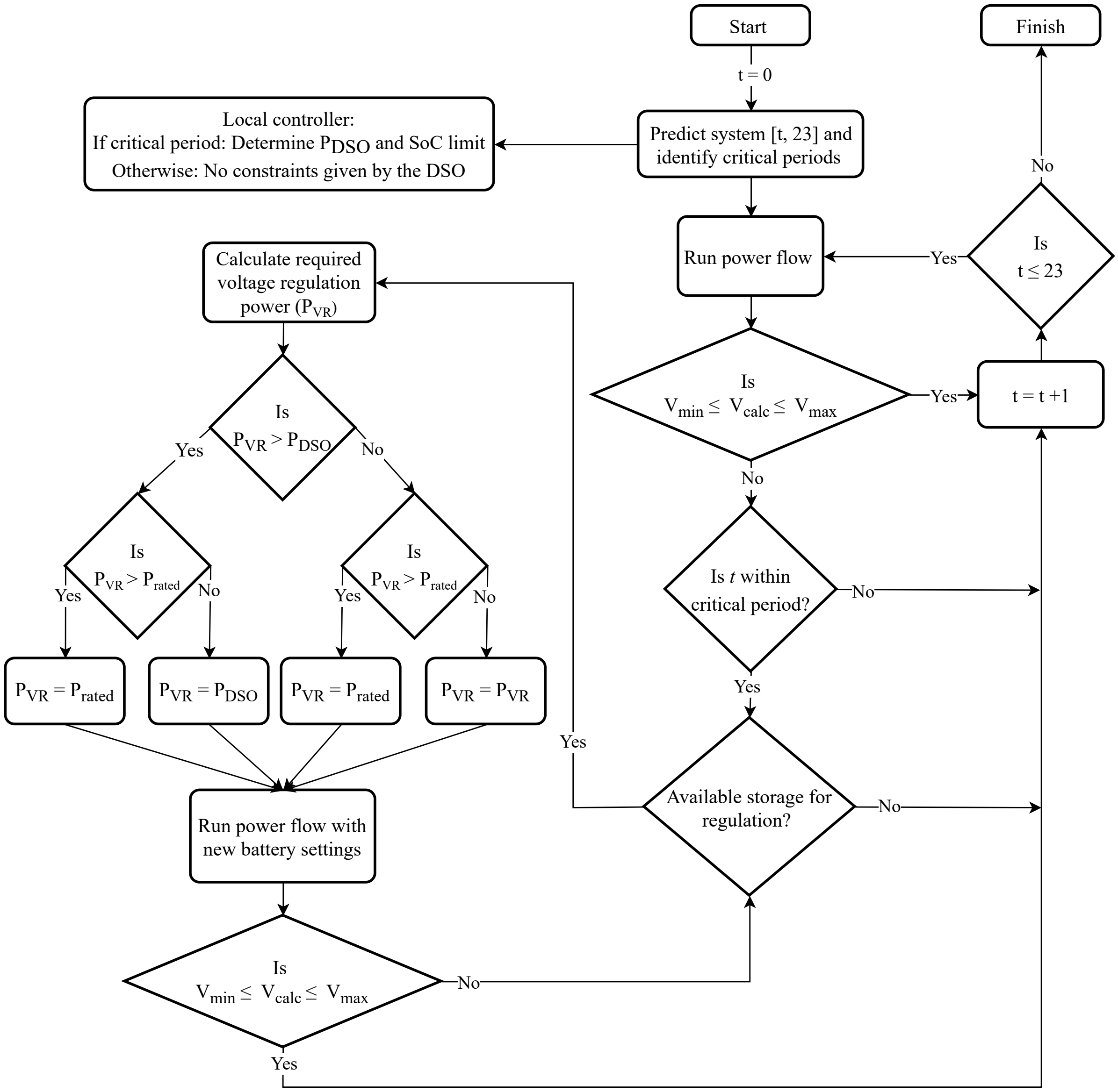


Figure 4.2.2: *Flow chart of the central controller in the distributed control strategy.*

Suppose the LV distribution network consists of several feeders. In that case, it is essential to cluster the BESSs based on where they are located and the effect they have on the different nodes. Control each cluster separately will also give better voltage support as the feeders may have different voltage profiles. The central control will be performed for each of the clusters with support from the BESSs belonging to the respective cluster. With the given algorithm, the control of the different clusters is solved in sequence, where the cluster with the highest calculated voltage is solved first. As the voltage issues in each cluster are solved in sequence, the interaction between the clusters will be included.

4.3 Scenario Description

It was desired to investigate if the distributed control strategy can mitigate voltage issues, both under- and over-voltage, during different system conditions. In order to best reproduce different conditions in the distribution network, the season should be taken into account—especially the extremes such as summer and winter. In the summer, consumption is usually lower in all consumer groups. This means that the voltage is generally higher at all voltage levels. In the winter, other challenges arise. The consumption is often high and over a longer period. High consumption increases the utilization factor in the transmission network, hence the voltage drop. As a consequence, the voltage decreases at the customer level. Considering both the summer and the winter season is essential to test the distributed control strategy at the extremes.

High voltages are experienced at Utsira when the load is low at both Karmøy and Utsira, in addition to high production from the two wind turbines. A week in June, 22-29 June 2020, was selected to represent the network at Utsira in a worst-case scenario. The selected week had the lowest energy consumption during the summer of 2020, in addition to several hours with a relatively low load. A week was selected as it was desirable to investigate the control strategy with different load and production profiles.

On the contrary, low voltages are experienced at Utsira when the load is high at both Karmøy and Utsira, in addition to low wind production. The week 11-18 January in 2021 was selected to represent the network at Utsira in a worst-case scenario with low voltages. This week had the highest energy consumption, in addition to several hours with a high load. The wind production during this week was also either low or equal to zero.

4.3.1 Relevant Scenarios

Table 4.3.1 provides information about the two scenarios and the different simulations that were performed. A base-case scenario was simulated for both scenarios, where this scenario simulates the network without any BESS. Further, the distributed control strategy was simulated with different values of different simulation parameters. The simulation parameters were battery capacity, DSO utilization percentage, and DSO power. The DSO utilization percentage is a share of the battery capacity allocated to the DSO during a critical period, while DSO power is a share of the rated power allocated to the DSO. The aim of the simulations was to find the minimum required value to solve the voltage problem in each critical period. The performance of the simulations was compared by using a voltage improvement index (Section 4.3.2). Finally, the results from the previous simulations were combined and tested in a final model. Solar production was only considered in the over-voltage issues, as solar production is generally low in winter.

Table 4.3.1: *Description of the scenarios and the different simulations.*

Scenario	Simulation	Description
Over-voltage	Base-case	Production: Wind and solar Without BESS
	Changing of simulation paramters	Production: Wind and solar Simulation parameters: Battery capacity, DSO utilization percentage, and DSO power. Different values were tested for each parameter. The performance was compared with the use of a voltage improvement index.
	Final model	Production: Wind and solar Including parameters found in previous simulations
Under-voltage	Base-case	Production: Wind Without BESS
	Changing of simulation parameters	Production: Wind Simulation parameters: Battery capacity, DSO utilization percentage, and DSO power. Different values were tested for each parameter. The performance was compared with the use of a voltage improvement index.
	Final model	Production: Wind Including parameters found in previous simulations

4.3.2 Voltage Improvement Index

It was necessary to find a numerical value that could be used to compare different simulations. Therefore, a self-made voltage improvement index was used. This index is found for each critical period and each node in the system. The voltage improvement index can be found by calculating different steps explained in this section.

First, the difference between the simulated voltage (new voltage profile) and the voltage limit (V_{limit}) is calculated for each time step within the critical period. If the simulated voltage is within the limit, the difference is set to zero. This calculation is also done for the base-case voltage profile. Next, the calculated values for the base-case voltage profile and new voltage profile are summed separately. The voltage improvement index is the percentage change between these two calculations compared to the base case. Figure 4.3.1 aims to clarify the calculation process. A voltage improvement index of 0% indicates no change in the voltage profile compared to the base-case scenario, while a 100% voltage improvement means that the voltage problems are completely mitigated.

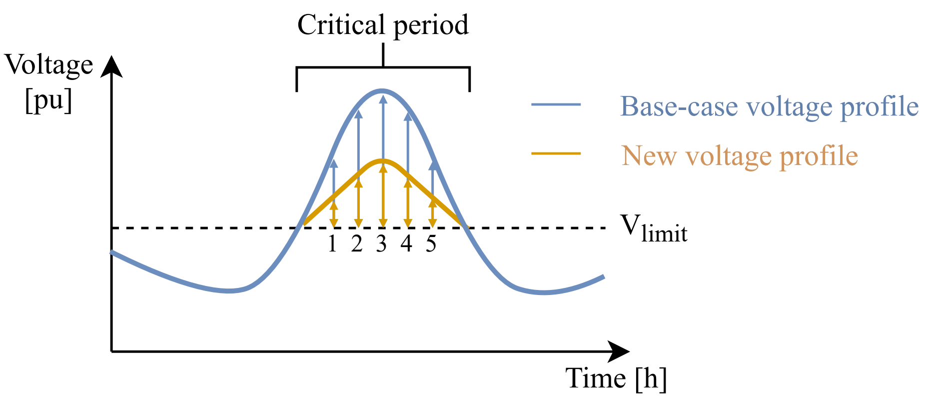


Figure 4.3.1: *Illustrates the calculation of the voltage improvement index. The numbers indicate each time step.*

The voltage improvement index gives the total voltage improvement over the critical period and not for each time step, which can be a delimitation. However, the index gives a good indicator of how the voltage profiles are affected by changing parameters.

4.3.3 Battery Storage Systems and PV systems

The PV systems were placed at all nodes with regular energy consumption. The rest of the nodes had either abnormal energy consumption or an energy consumption equal to zero. An assessment was made that these nodes were not suitable for a PV installation. Figure 4.3.2 shows the location of the PV systems and BESSs in the LV distribution grid. The optimal location of BESS is often far from the substation as the voltage limits and power flows are tighter in these areas. Therefore, three BESSs were placed at the end of the two radial with PV systems. The fourth BESS was placed closer to the substation to encounter over-voltage issues caused by the wind turbines.

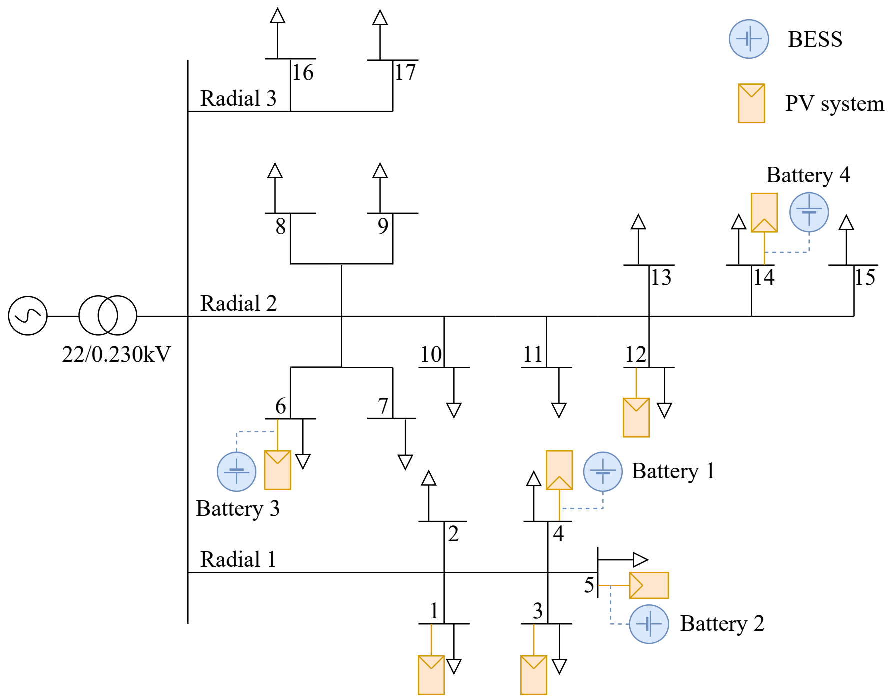


Figure 4.3.2: *Single-line diagram of the LV distribution grid at Utsira with BES systems and PV systems.*

As mentioned earlier, clustering of the BESSs is required to achieve effective voltage regulation. The clustering was based on which radial the BESSs were located in and is listed in Table 4.3.2. As BESSs and PV systems were only located in radial 1 and 2, results of these two radials will only be shown.

Table 4.3.2: *Clustering of battery storage systems in the LV distribution grid at Utsira.*

Battery nr	House nr	Cluster
1	4	Radial 1
2	5	Radial 1
3	6	Radial 2
4	14	Radial 2

The battery characteristics were assumed to be identical for all of the BESSs and are presented in Table 4.3.3. The battery capacity is not listed, as this parameter was changed during the simulations. The state of charge at the beginning of each day is different depending on the season. In the summer, the BESSs are mainly charged by the PV panels. As it is desirable to use all of the energy locally, a state of charge of 20% will ensure that some of the energy can be used during the morning hours. In the winter, the BESSs usually charge during the morning hours due to low electricity costs. Therefore, a low SoC at the beginning of the simulation is desirable. Further, the PV systems were also assumed to be identical with a capacity of 3 kWp.

Table 4.3.3: *Parameters of the battery storage systems used in the simulations.*

Parameter	Value
P_{CB}	8 kW
P_{rated}	5 kW
η_C, η_D	98%
SoC_{min}, SoC_{max}	20%, 90%
$SoC_{init,summer}, SoC_{init,winter}$	20%, 10%

4.4 Data Collection

This section describes the data collection required to simulate the loads and the production from the wind turbines and PV systems. Haugaland Kraft Nett provided most of the data used in this study. However, the solar production data was obtained from an open-source, and the electricity prices were extracted from NordPool.

4.4.1 Load Data

The load profiles used for all loads at Utsira were designed using AMS measurements either taken from households or substations. AMS measurements from the period 01.01.2020 - 27.11.2020 and 14.12.2020-28.01.2021 were provided by Haugaland Kraft Nett. The data included both active and reactive power production and consumption, where both were used in the simulations. Due to several missing measurements and indirect measurements, the data had to be processed before it was used.

Missing measurements were found with interpolation. However, this process is only sufficient if few measurements in a row are missing, as the inaccuracy increases for each missing value. However, it was observed that no measurements were missing in the data set for the two simulated weeks. Installations with indirect measurements are typically larger installations such as substations, industry buildings, stores, and schools. AMS measurements from these installations must be multiplied by a scaling factor, where the scaling factor depends on the size of the installation. As the energy consumption is measured in ascending order, the energy consumed or produced per hour is found by calculating the difference between the two measurements. The processing of the data was performed by using *Excel* and *Python*.

AMS measurements taken from substations were used to simulate networks at Utsira that were not modeled. However, AMS data for two of the substations were not available. Therefore, the AMS measurements from all the customers connected to these substations were aggregated and used instead. The load profiles used for the loads at Karmøy were designed based on an average load profile for Stava substation for 2019, 2020, and parts of 2021. The average load profile, given in percentage, was multiplied by the maximum load for each of the loads at Karmøy.

4.4.2 Production Data

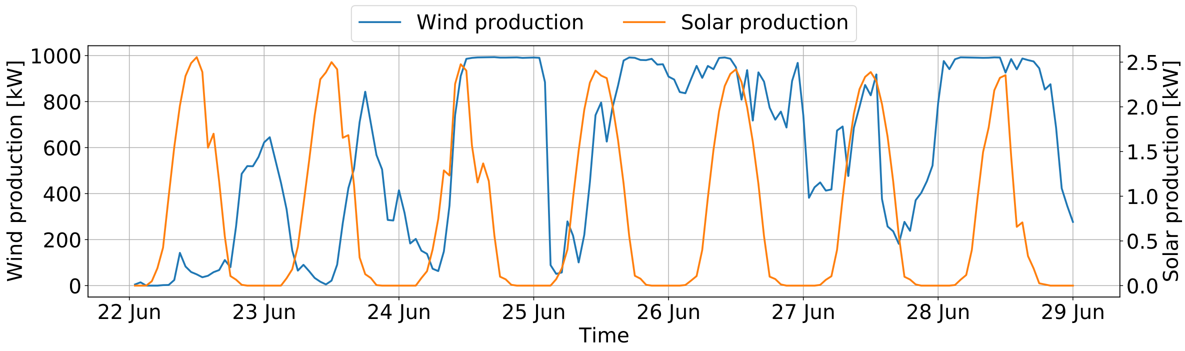
Haugaland Kraft Nett provided wind production data of the two turbines for 01.01.2020 - 27.11.2020 and 14.12.2020-28.01.2021, where the data had a time resolution of one hour. Only one of the wind turbines was in operation in the summer of 2020. Therefore, it was determined to use the same production profile for both turbines to amplify the voltage variations in the over-voltage scenario.

Solar production data from the Photovoltaic Geographical Information System (PVGIS) from the European Commission was used.[87] PVGIS allows downloading radiation on an hourly, daily, and monthly basis, in addition to simulated PV output power for almost any location. The simulation option was used, and the selected input parameters in PVGIS are shown and explained in Table 4.4.1. The same PV production profiles were used for all customers with PV systems, where a week with generally high production was selected (06.08.2016-12.08.2016).

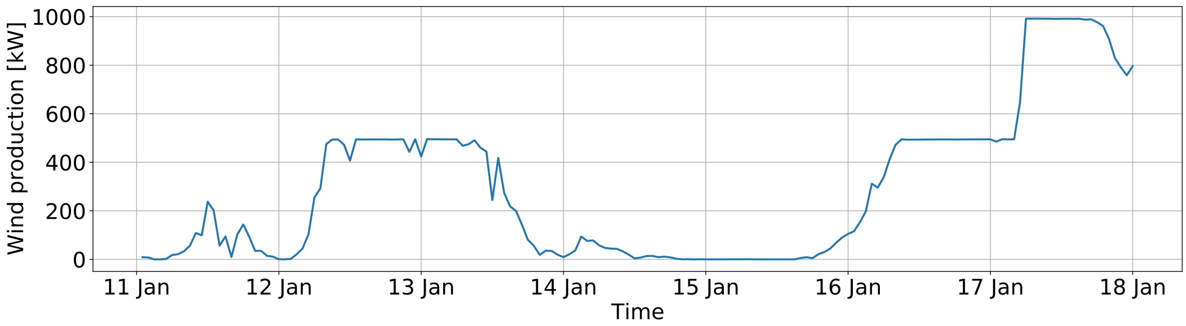
Table 4.4.1: *Input parameters in PVGIS from the European Commission which simulates the hourly energy production based on local solar radiation data in 2016.*

Parameter	Value/Selected option	Comment
Solar radiation database		PVGIS-ERA5
Year	2016	Latest data available
PV mounting type	'Fixed'	
Slope [°] and azimuth [°]	'Optimize slope and azimuth'	
PV technology	'Crystalline silicon'	The most commonly used technology in the market
Installed peak power [kWp]	3	Commonly
System loss [%]	14	Default
Latitude/Longitude [DD]	59.302/4.900	Cursor at Utsira

Figure 4.4.1 illustrates the wind and solar production profiles used in the over-voltage scenario and the wind production profile used in the under-voltage scenario.



(a) *Over-voltage scenario*



(b) *Under-voltage scenario*

Figure 4.4.1: *(a) Wind and solar production profile for the over-voltage scenario. (b) Wind production profile for the under-voltage scenario.*

4.4.3 Electricity Price Data

The electricity price used in the simulation were extracted from NordPool, where the electricity prices are taken from the same days as the simulated weeks. The costs for buying energy from the grid consider both the spot price and the network tariff, where a network tariff that Haugaland Kraft Nett offers household customers was used. The price for selling energy to the grid is equal to the spot price. The values are presented in Appendix A.2.

Chapter 5

Results and Discussion

In this chapter, the performance of the distributed control strategy proposed in this thesis will be presented. The control strategy will be tested to mitigate both over-and under-voltage problems. Based on the results, an evaluation of the control strategy will be provided. As a proper business model is needed to realize the control strategy, proposals to business models will be given. At the end of the chapter, further work will be presented.

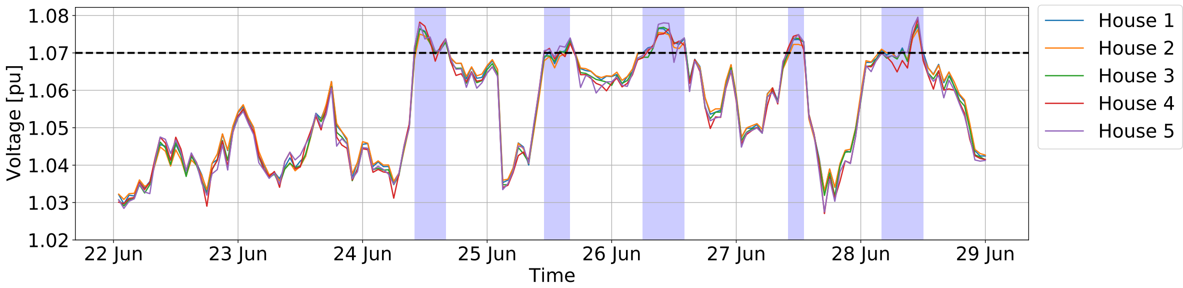
5.1 Over-voltage Scenario

Over-voltage problems often occur as a result of high production and low load. A week in June was selected to represent the island in a worst-case scenario. In this thesis, a voltage above 1.07 pu is considered as a voltage violation. According to the regulation of delivery quality, the voltage variation should be within $\pm 10\%$ of nominal voltage. The reason why a lower limit was selected was mentioned in Section 4.1.3.

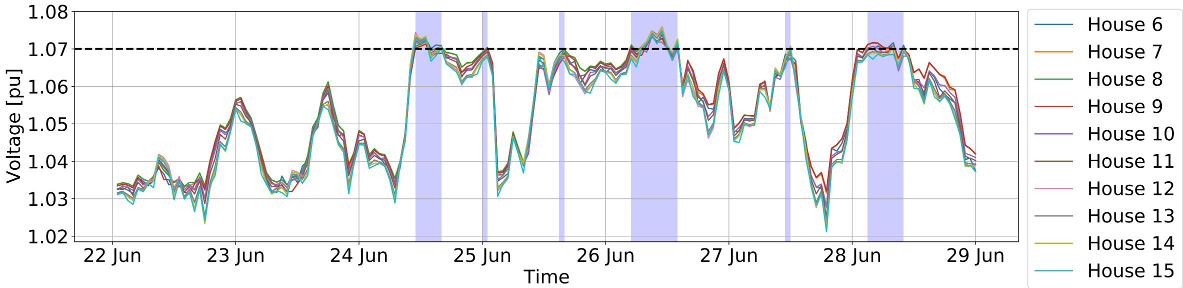
This section provides results from the over-voltage scenario. First, a base-case scenario will be presented. The critical periods will be determined based on this scenario. Further, results of different values of the three simulation parameters will be presented, where the aim will be to find the minimum value that can be used to solve the voltage problems. Finally, the findings from the previous simulations will be set together to a final model, where the performance of the distributed control strategy will be provided.

5.1.1 Base Case Scenario

The base case scenario simulates the grid without battery energy storage systems (BESS). Figure 5.1.1 illustrates the voltage variations at each node in the two radials over the given week. From the figure, voltages above the limit of 1.07 pu can be observed. Periods with voltages above this limit are referred to as a critical periods. As mentioned earlier, the critical periods were merged if there were less than four hours between two periods. The critical periods are marked in the figure with a blue color.



(a) *Radial 1*



(b) *Radial 2*

Figure 5.1.1: *(a) Voltage variations at the point of common connection at each house in radial 1. The simulation illustrates a worst-case scenario with low loading, high production, and no BESS in the system. The critical periods are marked with a blue color. (b) Illustrates the voltage variations in radial 2 with the same conditions as in (a).*

An overview of the critical periods in radial 1 is given in Table 5.1.1. The table contains information about the day the critical period occurs, the duration, what triggered the voltage variation (solar or wind), the highest simulated voltage, and critical nodes. As observed from the table, the critical period started between 10:00-11:00 and lasted until 12:00-16:00, coinciding with peak PV production hours. However, the voltage variations are highly dependent on the amount of wind production on the island. On Monday and Tuesday, the wind production was relatively low. Therefore, there were no voltage issues due to injected solar power.

Table 5.1.1: *Overview of the critical periods in radial 1 due to over-voltage issues.*

Critical Period	**1**	**2**	**3**	**4**	**5**
Day	Wen	Thu	Fri	Sat	Sun
Duration	7 h	6 h	9 h	4 h	9 h
Hour	10:00-16:00	11:00-16:00	06:00-14:00	10:00-12:00	04:00-12:00
Reason	S	S	S	S	W(04:00-06:00)+S
Highest voltage	1.078	1.074	1.078	1.075	1.079
Critical node	4,5	4,5	1,4,5	4,5	1,2,5
Period name	CP1-1	CP2-1	CP3-1	CP4-1	CP5-1

Table 5.1.2 gives an overview of the critical periods in radial 2. This radial had nodes closer to the substation, meaning that voltage violations due to high wind production may be experienced more often than in radial 1. As there is often low load during the night, voltage violations due to high wind production often occur during these hours. This is observed from the table on Thursday, Friday, and Sunday. It is possible to ascertain whether wind production and solar production triggered the voltage violation by examining the nodes with the highest voltage during the critical period. Critical

periods caused by solar production started around 08:00-12:00 and lasted until 14:00-17:00 and were experienced at nodes 6, 12, and 14, where the PV systems were located.

Table 5.1.2: *Overview of the critical periods in radial 2 due to over-voltage issues.*

Critical Period	1	2	3	4	5	6
Day	Wen	Thu	Thu	Fri	Sat	Sun
Duration	6 h	1 h	1 h	10 h	1 h	8 h
Hour	11:00-16:00	01:00-2:00	16:00-17:00	05:00-14:00	12:00-13:00	03:00-10:00
Reason	S	W	S	W(05:00-07:00)+S	S	W(03:00-08:00)+S
Highest voltage	1.073	1.070	1.070	1.076	1.071	1.072
Critical node	6,12,14	8	6	6,8,12,14	12	6,9
Period name	CP1-2	CP2-2	CP3-2	CP4-2	CP5-2	CP6-2

5.1.2 Changing of Different Simulation Parameters

Several simulations were performed in order to investigate the effect of changing the three simulation parameters described in Section 4.3.1. The results will be presented in this section.

Battery Capacity

The battery capacity is the most important parameter in order to solve the over-voltage issues. If the battery gets fully charged during a critical period, it cannot participate in voltage regulation, and the over-voltage issues may persist. A sensitivity analysis was performed to find the minimum battery capacity required to solve the over-voltage issues in each radial. The capacity of each battery was increased by 1 kWh for each simulation until the over-voltage problem was completely mitigated. Since the aim of the simulations was to investigate the minimum required capacity to mitigate over-voltage problems, the batteries were charged only if an over-voltage was detected. Further, the batteries were only regulated between a state of charge of 20-90% to prolong the life of the batteries.

The battery capacity and PV system should be dimensioned according to expected consumption for each household. Optimal sizing of the battery and PV system has not been a part of the scope for this master's thesis. However, as a higher battery capacity may be required to solve the voltage problems compared to the capacity needed to cover the usage for the customer, it was desired to find a suitable battery capacity for each customer that could be used as a reference size. As the load varies from day to day and thus the utilization of the battery, an approximate value was found. A battery capacity between 10-13 kWh was found to be a suitable size for batteries 1 and 2 (radial 1) and 7-9 kWh for batteries 3 and 4 (radial 2). The reference size was found based on the balance between no surplus power injected into the grid and a high utilization factor.

A battery capacity of 7 kWh was determined as a starting point for the sensitivity analysis, where the results can be illustrated in Figures 5.1.2 and 5.1.3. The figures show the lowest voltage performance index in each radial as a function of battery capacity. It can be observed from the figures that the required capacity for each critical period in the radials is quite scattered. However, from Table 5.1.1, it was shown that several of the critical periods in radial 1 had a long duration and high voltage. For example, CP3-1 and CP5-1 had relatively similar critical periods, where both had a duration of nine hours and the highest measured voltage of 1.078 pu and 1.079 pu, respectively. However, CP3-1 required a battery capacity of 18 kWh, while CP5-1 only required 9 kWh. CP3-1 required a significantly larger battery capacity as this period had a high voltage for a more extended period than CP5-1. CP5-1 had only a high voltage at the end of the critical period. CP1-1 and CP4-2 also had high voltages over a more extended period, which resulted in a need for high battery capacity.

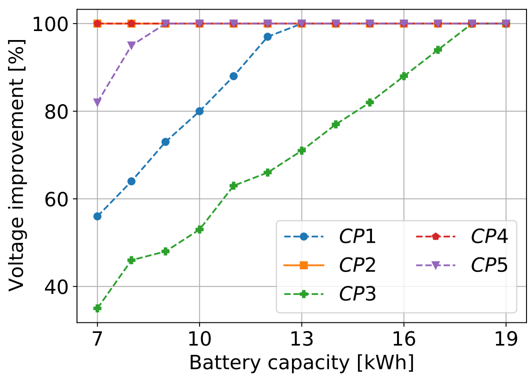


Figure 5.1.2: *Voltage improvement in radial 1 as a function of battery capacity for the over-voltage scenario. CP - critical period.*

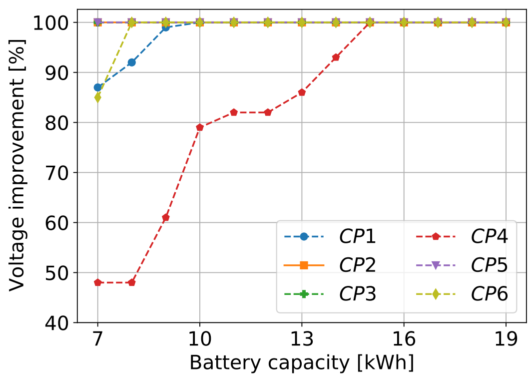


Figure 5.1.3: *Voltage improvement in radial 2 as a function of battery capacity for the over-voltage scenario. CP - critical period.*

For radial 1, the capacity of the two batteries must be equal to 18 kWh to solve the over-voltage issues in all of the critical periods. This results in an increase of 5-8 kWh compared to the reference size. As 13 kWh was enough to solve the voltage problems in all critical periods except for CP3-1, it can be challenging to justify the additional capacity required to solve the voltage problem in this critical period. Utilizing other voltage regulation techniques, such as PV curtailment and reactive power compensation, can be more cost-efficient in these cases. In addition, the simulations were based on a worst-case scenario, which means that voltage issues similar to the one in CP3-1 rarely occur. Therefore, a battery capacity of 13 kWh for the two batteries in radial 1 will be used in further simulations. Equal battery capacity within the same radial was used for simplicity.

In radial 2, a capacity of 15 kWh was required for the two batteries to mitigate over-voltage issues completely. However, the battery capacity can be lowered to 10 kWh and mitigate over-voltage problems in five of six critical periods. Similarly to radial 1, it can be challenging to justify the 5 kWh increase of two batteries to solve voltage issues experienced in a single critical period. In addition, a capacity of 10 kWh will only result in an additional capacity of 1-3 kWh compared to the reference size. A capacity of 10 kWh for the batteries in radial 2 will be used further in this report.

Another observation is that the voltage profiles were improved approximately linearly with the battery capacity, except for CP4-2. CP4-2 consisted of two voltage peaks, the first peak was solved with a capacity of 11 kWh, and both were solved with a capacity of 15 kWh. Therefore, the voltage improvement index increased linearly from 8 to 10 kWh and from 12 to 15 kWh. The linear improvement is due to the voltage sensitivity-based control method for the regulation of active power. With this method, the active power is regulated to maintain the voltage level close to the threshold. Therefore, the voltage profile improvement will have an approximately linear relationship to the battery capacity in the network.

DSO Utilization Percentage

Several simulations were performed to investigate the minimum required DSO utilization percentage to solve the over-voltage problems. The results from the simulations are given in Figures 5.1.4 and 5.1.5. By comparing the figures with the characteristics of the critical periods, it can be shown that critical periods with a long duration required a DSO percentage of 40%. In contrast, shorter critical periods required a DSO percentage of 10% or 20%. The DSO percentage of CP1-1 deviates from this trend, where a percentage of 80% was required. The local controller does not include any restrictions on when the customer should charge the battery. For example, that the customer should charge mostly during a critical period. As all of the usable capacity was required to solve the voltage issues in CP1-1, the only solution was to set the DSO utilization percentage to 80%. Further, the voltage improvement for CP3-1 and CP4-2 did not reach 100% as the total capacity in the radials was not large enough to solve the voltage violation.

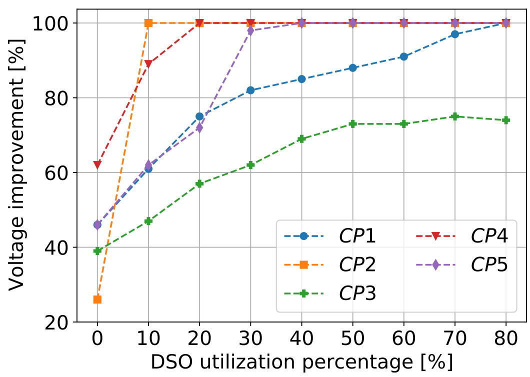


Figure 5.1.4: *Voltage improvement in radial 1 as a function of DSO utilization percentage for the over-voltage scenario. CP - critical period.*

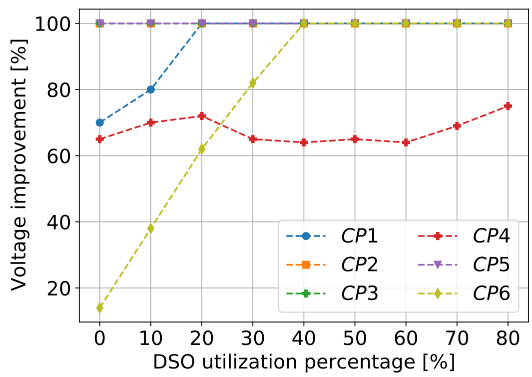


Figure 5.1.5: *Voltage improvement in radial 2 as a function of DSO utilization percentage for the over-voltage scenario. CP - critical period.*

CP1-1 and CP5-1 had both a high voltage magnitude and long duration. However, only CP1-1 required a DSO utilization percentage of 80%. CP5-1 was on a Sunday, where the load curve does not necessarily have the typical peaks in the morning and evening. Consequently, the customer used the battery system less as the production from the PV panels was used directly. Therefore, the DSO was given more freedom in how they utilized the allocated battery capacity. Prediction of the loads should therefore be considered in the determination of the DSO utilization percentage.

In radial 2, it can be observed that CP2-2, CP3-2, and CP5-2 had a 100% voltage improvement with a DSO percentage of 0%. As the customer had partial control over the battery system during the critical period, the customer indirectly solved the voltage issues by charging surplus power from the PV system. However, as the system operator does not have access to the charging and discharging schedule of the batteries, the DSO should consider these critical periods.

DSO Power

Voltage improvement as a function of DSO power for the two radials are illustrated in Figures 5.1.6 and 5.1.7. It can be observed that the DSO required a charging power of 1-3 kW for radial 1 and 0.5-1 kW for radial 2 to solve the over-voltage issues. In general, higher voltages were measured in radial 1 compared to radial 2. Consequently, a higher DSO power was required. Changing the DSO power did not significantly affect the voltage improvement in CP3-1 and CP4-2 as the total battery capacity in the radials was not enough to solve the voltage problem.

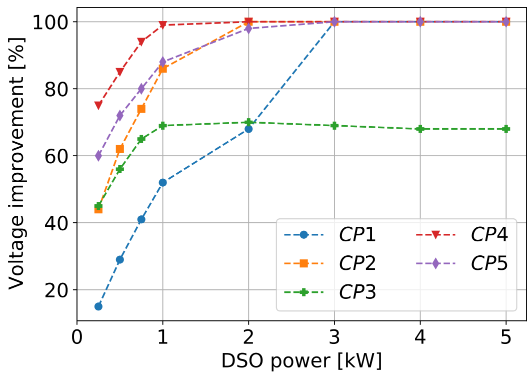


Figure 5.1.6: *Voltage improvement in radial 1 as a function of DSO power for the over-voltage scenario. CP - critical period.*

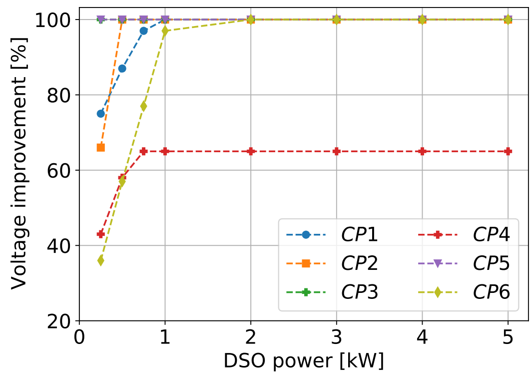


Figure 5.1.7: *Voltage improvement in radial 2 as a function of DSO power for the over-voltage scenario. CP - critical period.*

It was expected that a higher DSO power could affect the utilization of the battery, as the customer would have less control over the battery during a critical period. However, the results indicated that it had no significant impact. The utilization ratio was either kept constant or increased as the battery participated more in the voltage regulation.

The control method selects the battery that has the greatest impact on the system performance. Giving the system operator a larger share of the rated power means that the most appropriate battery can be utilized more. A result can be a decrease in required power. However, no considerable changes were observed. This is mainly because the electrical distance between the batteries and the critical nodes was approximately the same, with one exception, node 14 that was closer to battery 4 compared to battery 3.

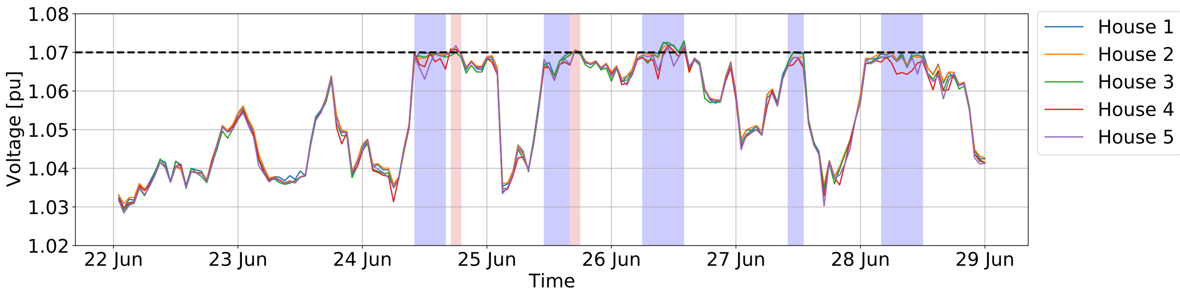
5.1.3 Summary

This section provides the results of the distributed control strategy with the parameters found in the previous section to mitigate over-voltage issues. A battery capacity of 13 kWh was used for the two batteries in radial 1, and 10 kWh was used for the two batteries in radial 2. The DSO utilization percentage used in the different critical periods for the two radials are summarized in Table 5.1.3. Further, a DSO power of 3 kW was used.

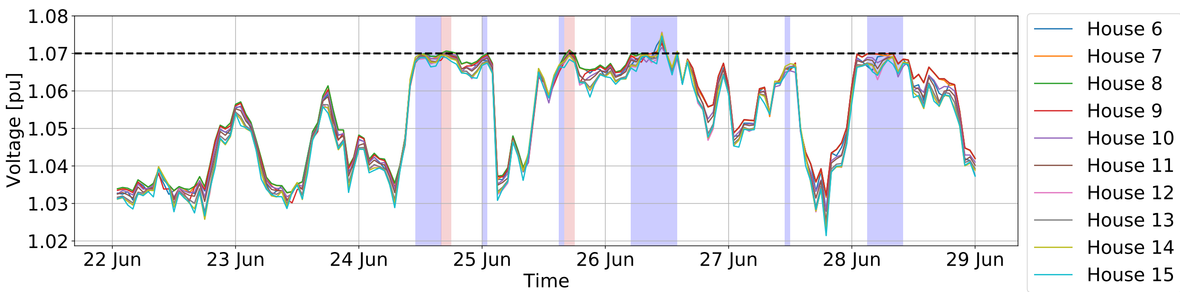
Table 5.1.3: *DSO utilization percentage used in the different critical periods and radials for the over-voltage scenario. The values were determined based on previous results.*

Critical period	**1**	**2**	**3**	**4**	**5**	**6**
Radial 1	80	10	40	20	40	-
Radial 2	20	10	10	40	10	40

Figure 5.1.8 illustrates the performance of the distributed control strategy. It can be observed that the voltage violations were completely mitigated in all of the critical periods, except for CP3-1 and CP4-2. Another observation was that new voltage violations right after some critical periods emerged, illustrated with a red color. This is a common problem when shifting loads from one period to another, where uniform price signals can amplify this problem. Solutions to prevent new voltage violations will be discussed in Section 5.4.3.



(a) *Radial 1*

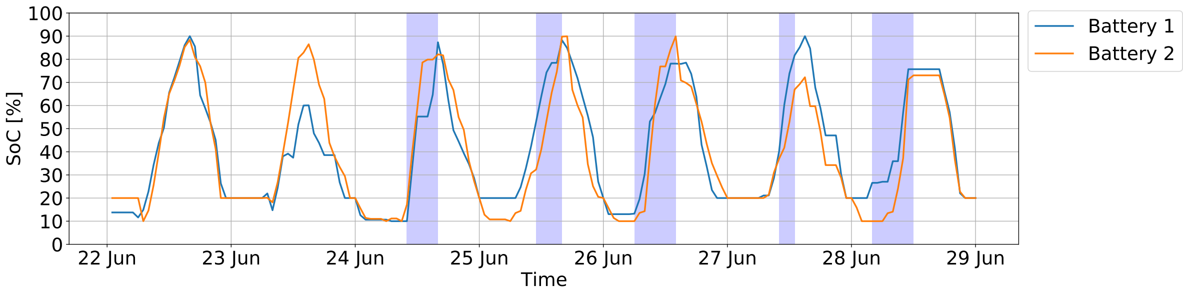


(b) *Radial 2*

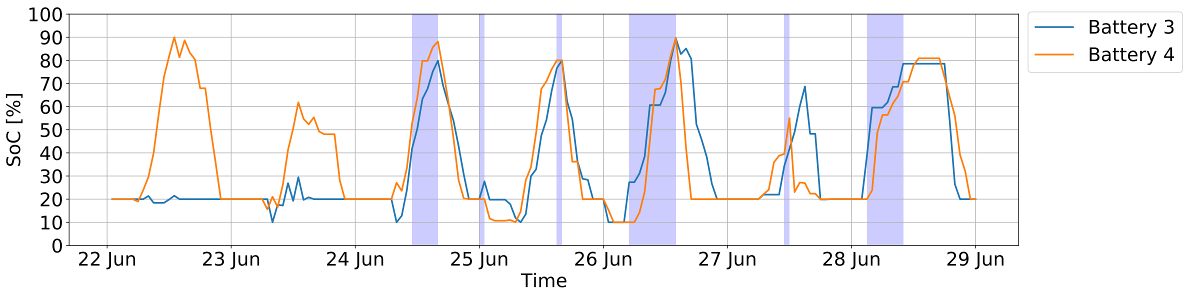
Figure 5.1.8: *(a) Voltage variations at the point of common connection at each house in radial 1. A distributed control strategy was used to control the BESS in the system to solve over-voltage issues. The critical periods are marked with a blue color, while the red color highlights new voltage violations. (b) Illustrates the voltage variations in radial 2 with the same conditions as in (a).*

As CP3-1 and CP4-2 occur approximately simultaneously and both required a considerable large battery capacity to solve the over-voltage issues completely, it was desired to investigate the load profile at Karmøy and Utsira. When the load demand at Utsira and Karmøy was investigated, it was observed that the load demand at Karmøy was lower compared to other days during the same period. In addition, the critical period occurred in the morning, which means that the load is generally low. As the critical period also lasted over a more extended period, and the production from the wind turbines and PV system were high, all these factors resulted in a need for a large battery capacity.

Figure 5.1.9 illustrates the state of charge of the four batteries during the given week. It can be observed that the batteries were almost fully charged five out of seven days. This proves that the size of the batteries was not overdimensioned. The load changes from day to day, and the utilization of the batteries will therefore not be the same for each day. The performance of the four residential battery energy systems with the distributed control strategy are given in Figure B.1.1 in Appendix B.1. The appendix also includes a figure of the voltage profiles where only the local controller was used (Figure B.1.2), in addition to a figure of the state of charge of the batteries with the same conditions (Figure B.1.3).



(a) *Radial 1*



(b) *Radial 2*

Figure 5.1.9: *(a) State of charge variation of the two BESS in radial 1. A distributed control strategy was used to schedule the charging and discharging of the BESS in the over-voltage scenario. The critical periods are marked with a blue color. (b) Illustrates the state of charge variation of the two BESS in radial 2 with the same conditions as in (b).*

Table 5.1.4 provides the utilized capacity of the DSO utilization percentage and the number of hours the DSO used the batteries during the critical period. It can be observed that battery 1 was utilized more than battery 2, both in terms of percentage utilized and the number of hours used. This implies that battery 1 was better located to solve the over-voltage issues. High voltages were often measured at nodes 1, 4, and 5 during critical periods. By considering the sensitivity coefficient for the two batteries at node 1, the coefficient was almost the same. Battery 1 had a sensitivity coefficient of 1.00568 V/MW, and battery 2 had a coefficient of 1.00484 V/MW. As battery 1 had a slightly higher coefficient, this battery was selected to participate in the voltage regulation. Battery 2 was only selected if battery 1 was fully charged or the highest voltage was measured at node 5, where battery 2 was located.

Table 5.1.4: *Utilized capacity of the DSO utilization percentage and number of hours the batteries were occupied by the DSO compared to the duration of the critical periods. Values were extracted from the over-voltage scenario. The total is the number of hours either one or both of the batteries was utilized compared to the duration of the critical period.*

Radial	Battery nr	1		2		3		4		5		6	
		[%]	h	[%]	h	[%]	h	[%]	h	[%]	h	[%]	h
1	1	96	4/10	98	1/6	-	-	100	3/4	100	5/9	-	-
	2	90	6/10	98	1/6	-	-	40	1/4	56	2/9	-	-
Total		-	10/10	-	1/6	-	-	-	3/4	-	6/9	-	-
2	3	50	2/6	80	1/1	0	0/1	-	-	0	0/1	100	2/8
	4	100	5/6	0	0/1	0	0/1	-	-	0	0/1	95	3/8
Total		-	6/6	-	1/1	-	0/1	-	-	-	0/1	-	4/8

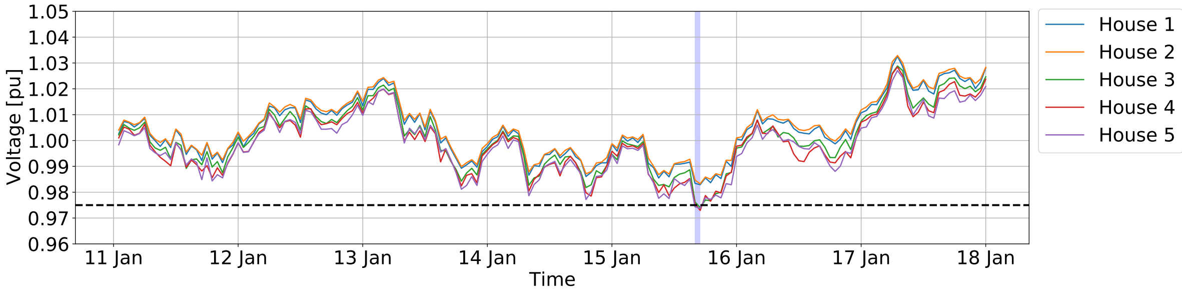
In radial 2, the utilization of the batteries was better distributed. This is a result of placing one battery near the substation and the other closer to the end of the radial. The battery near the substation will respond to voltage violations caused by high wind production, while the battery at the end of the radial will mostly solve voltage violations caused by solar production. As observed from the table, battery 3 was fully utilized in the critical periods caused by wind production (CP2-2 and CP6-2). On the contrary, battery 4 was fully utilized in critical periods caused by solar production (CP1-2). Battery 3 was used for two hours in CP1-2 as battery 4 reached a 100% utilization ratio in the fifth hour.

5.2 Under-voltage Scenario

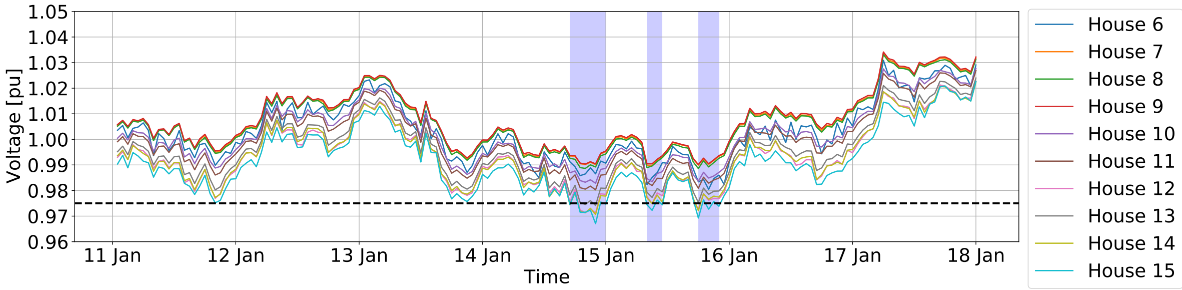
The main scope of this master's thesis was to investigate how residential battery energy storage systems can be utilized for voltage support in distribution networks with high penetration of renewable energy resources. However, under-voltage problems are also a well-known issue in the Norwegian power system. By discharging power into the grid when low voltages are measured in the system, the battery energy storage system can effectively solve under-voltage issues. Under-voltage problems typically occur in the winter, when the load demand is high and production is low. This section presents the performance of the distributed control strategy for under-voltage support. A week in January was selected to represent the island in a worst-case scenario. In this thesis, voltages below a limit of 0.975 pu were considered as a voltage violation.

5.2.1 Base-Case Scenario

The base-case scenario simulates the grid in a worst-case scenario with no battery storage systems. Figure 5.2.1 illustrates the voltage variations at each node in the two radials. Voltages below the limit can be observed during Thursday and Friday. Low or zero production from the wind turbines was observed during these days, including Monday, where low voltages were also experienced.



(a) *Radial 1*



(b) *Radial 2*

Figure 5.2.1: *(a) Voltage variations at the point of common connection at each house in radial 1. The simulation illustrates a worst-case scenario with high load demand, low production, and no BESS in the system. The critical periods are marked with a blue color. (b) Illustrates the voltage variations in radial 2 with the same conditions as in (a).*

In radial 1, a single critical period was experienced during the simulated week. Information about the period is given in Table 5.2.1. The critical period lasted for two hours and occurred between 15:00-17:00, during peak hours. The under-voltage problems were predicted to occur at house 4 and 5, which were located at the end of the radial.

Table 5.2.1: *Overview of the critical periods in radial 1 due to under-voltage issues.*

Critical Period	**1**
Day	Fri
Duration	2 h
Hour	15:00-17:00
Lowest voltage	0.973
Critical node	4,5
Period name	CP1-1

Radial 2 consisted of a few more nodes compared to radial 1. Due to heavier load demand, under-voltage problems can therefore occur more often. Table 5.2.2 provides information about the critical periods in radial 2. The critical periods occurred during Thursday and Friday when there was no wind production. Further, it can be observed that the period coincides with the typical morning and evening peak hours. Similar to radial 1, the lowest predicted voltages were found at the two nodes at the end of the radial.

Table 5.2.2: *Overview of the critical periods in radial 2 due to under-voltage issues.*

Critical Period	**1**	**2**	**3**
Day	Thu	Fri	Fri
Duration	8 h	4 h	5 h
Hour	16:00-00:00	07:00-11:00	17:00-22:00
Lowest voltage	0.967	0.972	0.969
Critical node	14,15	15	15
Period name	CP1-2	CP2-2	CP3-2

5.2.2 Changing of Different Simulation Parameters

Several simulations have been performed in order to investigate the effect of changing the three simulation parameters. The results for the under-voltage scenario will be presented in this section.

Battery Capacity

A sensitivity analysis was also executed for the under-voltage scenario, where the results are illustrated in Figures 5.2.2 and 5.2.3. It was decided to have different starting points for the sensitivity analysis of the two radials due to different magnitude of voltage violation.

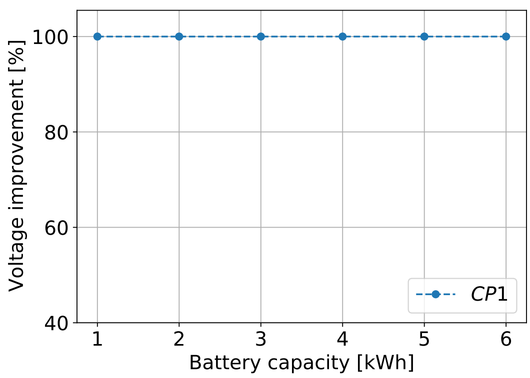


Figure 5.2.2: *Voltage improvement in radial 1 as a function of battery capacity for the under-voltage scenario. CP - critical period.*

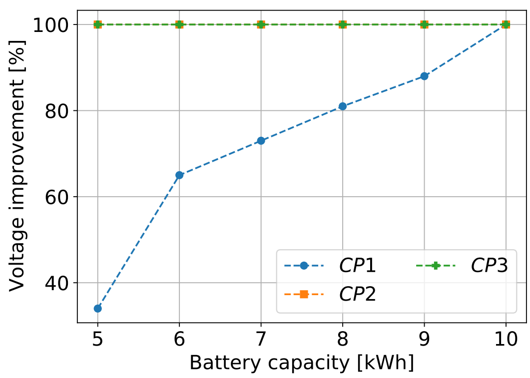


Figure 5.2.3: *Voltage improvement in radial 2 as a function of battery capacity for the under-voltage scenario. CP - critical period.*

The critical period in radial 1 had a short duration and voltages just below the limit. Consequently, the required battery capacity to solve the voltage problem can be as small as 1 kWh. As the over-voltage scenario required a battery capacity of 13 kWh to solve most of the voltage issues, this indicates that the radial is more fragile for over-voltage issues than under-voltage issues. Therefore, the profitability of investing in larger residential batteries for voltage support may be reduced. Further, as 1 kWh battery capacity is abnormal for a residential battery unit, 13 kWh will be used for the two batteries in radial 1 in further simulations.

In radial 2, a capacity of 10 kWh was required to solve all the voltage issues in the three critical periods. This capacity coincides with the capacity used in the over-voltage scenario. Therefore, a battery capacity of 10 kWh can be profitable even though CP2-2 and CP3-2 could have been solved with a lower capacity. A capacity of 10 kWh will be used for the two batteries in radial 2 in further simulations.

DSO Utilization Percentage

Results with different values for the DSO utilization percentage are illustrated in Figures 5.2.4 and 5.2.5. The under-voltage problem in radial 1 had a short duration, and the lowest predicted voltage was right below the limit. Therefore, a DSO utilization percentage of 10% was enough to solve the under-voltage problem. For radial 2, a DSO utilization percentage of 20% was required to solve the voltage problem in two critical periods. CP1-2 required more energy to solve the voltage issues due to the long duration and a predicted voltage of 0.967 pu. Therefore, a DSO utilization percentage of 80% was required.

Further, it can be observed that the voltage profiles were improved even though the DSO percentage was equal to 0%. This is because the critical periods coincide with when the customers would initially have discharged. Therefore, the voltage problem was indirectly solved by the customer.

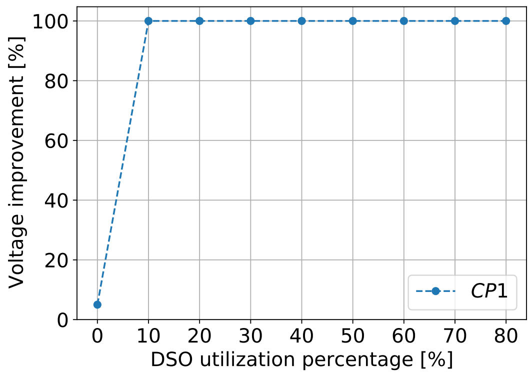


Figure 5.2.4: *Voltage improvement in radial 1 as a function of DSO utilization percentage for the under-voltage scenario.*

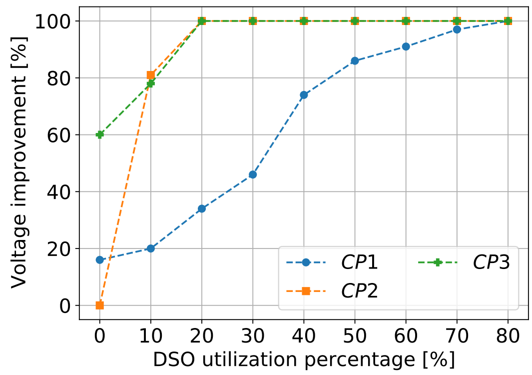


Figure 5.2.5: *Voltage improvement in radial 2 as a function of DSO utilization percentage for the under-voltage scenario.*

The major difference between over-voltage problems and under-voltage problems is the location of the critical nodes. Critical nodes due to over-voltage problems are usually located with a generation unit or near the substation. On the other hand, critical nodes due to under-voltage issues are located at the end of the radial. Battery 3 was located in the middle of radial 2, which means that the electrical distance to the end of the radial was much longer than for battery 4. Consequently, a higher amount of power was required by using battery 3 compared to battery 4. For example, a voltage of 0.967 pu was measured at 21:00 during CP1-2. At this time, the sensitivity index was calculated to be 0.0007 V/kW for battery 3 and 0.0019 V/kW for battery 4. If a single battery had solved the voltage issue, battery 3 had required a total power of 11.3 kW, while battery 4 had required as little as 4.2 kW. Utilizing battery 4 as much as possible will, in this situation, be most efficient, and a high DSO utilization percentage will therefore be required. The presented situation does not account for radial 1, as both batteries were located at the end of the radial.

DSO Power

The DSO power had a larger impact on the performance of distributed control strategy for under-voltage problems than over-voltage problems due to the location of the critical nodes. Selecting an appropriate DSO power was especially important for CP1-2 due to the magnitude of the voltage violation and the electrical distance from the batteries to the critical node. The voltage improvement as a function of DSO power for both radials are illustrated in Figures 5.2.6 and 5.2.7. The minimum required DSO utilization percentage found in the previous subsection was used in the simulations. CP1-2 required a minimum DSO power of 4 kW to mitigate the under-voltage completely, while the rest of the critical periods were solved with a DSO power of 0.75-1 kW. Due to the small voltage violation in radial 1, the require DSO power was equal to 0.5 kW.

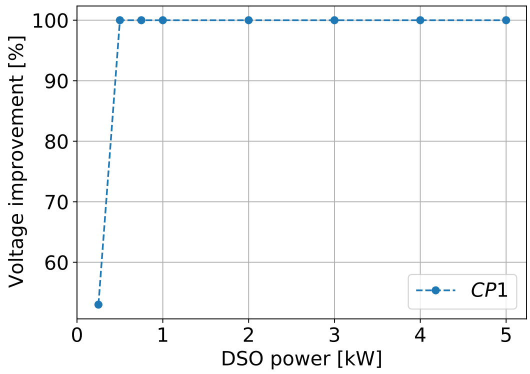


Figure 5.2.6: *Voltage improvement in radial 1 as a function of DSO power for the under-voltage scenario. CP-Critical period.*

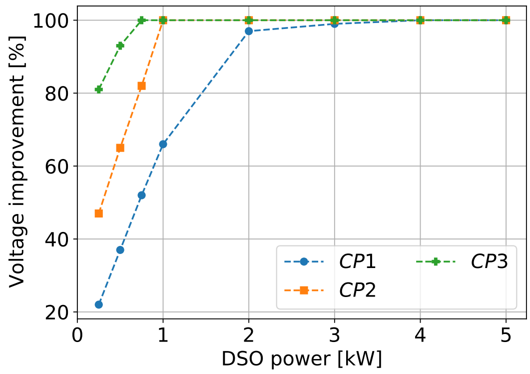


Figure 5.2.7: *Voltage improvement in radial 2 as a function of DSO power for the under-voltage scenario. CP-Critical period.*

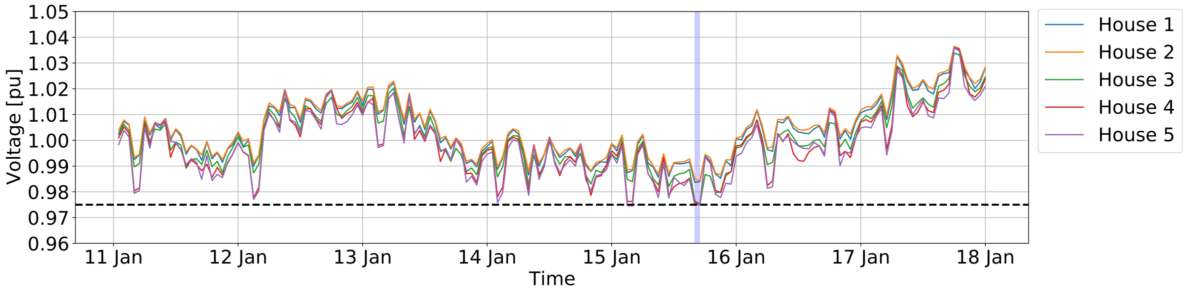
5.2.3 Summary

This section provides the results of the distributed control strategy to mitigate under-voltage issues with the simulation parameters found in the previous section. The DSO utilization percentage used in the different critical periods is provided in Table 5.2.3, where a DSO power of 4 kW was used.

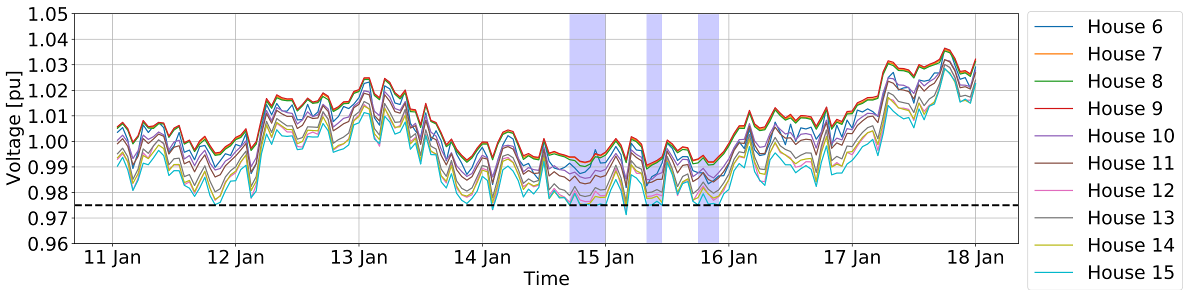
Table 5.2.3: *DSO utilization percentage used in the different critical periods and radials for the under-voltage scenario. The values were determined based on previous results.*

Critical period	1	2	3
Radial 1	10	-	-
Radial 2	80	20	20

Figure 5.2.8 illustrates the voltage variations at the point of common connection for each house in radial 1 and radial 2. It can be observed that the voltage issues during the critical periods were completely mitigated. However, several voltage sags can be observed as a consequence of simultaneously charging from the grid. Some of the sags also cause new voltage issues. Measures must be implemented to prevent this occurrence, especially in networks with multiple battery systems.



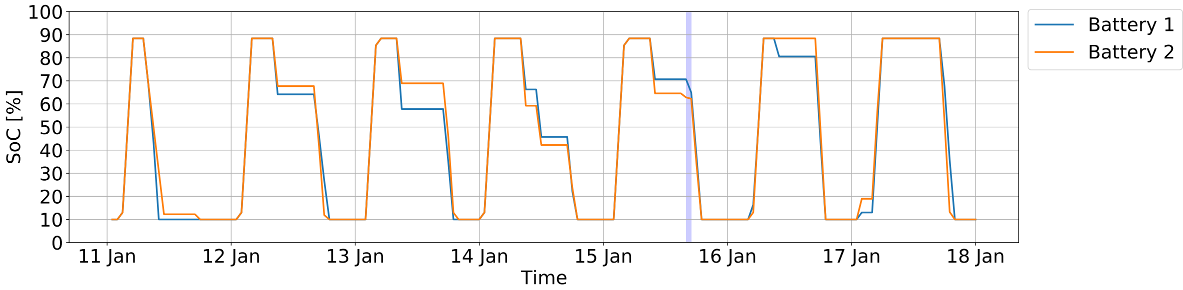
(a) *Radial 1*



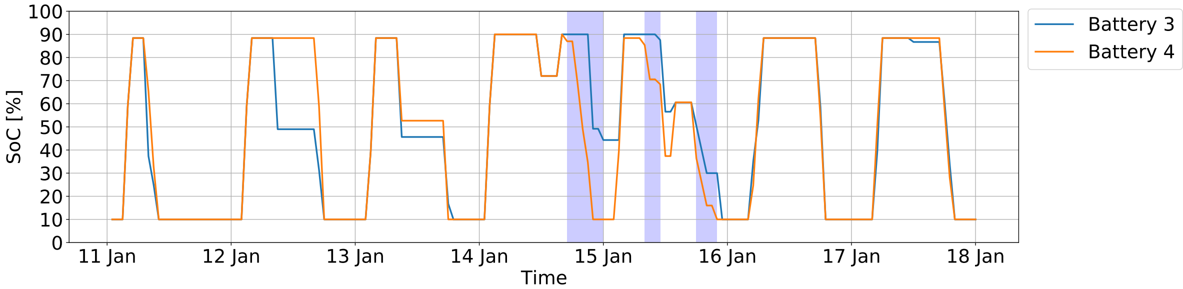
(b) *Radial 2*

Figure 5.2.8: *(a) Voltage variations at the point of common connection at each house in radial 1. A distributed control strategy was used to control the BESS in the system to solve under-voltage issues. The critical periods are marked with a blue color. (b) Illustrates the voltage variations in radial 2 with the same conditions as in (a).*

Figure 5.2.9 illustrates the state of charge variation of the four batteries. As observed from the figure, the batteries charged during the morning hours when the electricity prices were low and discharged during evening peak hours when the electricity prices were high. The customers who own the batteries were not largely affected by the central controller as the critical periods coincide with the peak hours. However, battery 2 had a SoC of 40% at the end of January 15 as the DSO did not fully utilize this battery. Consequently, as the capacity was reserved for the DSO, the customer had to charge from the grid to cover their electricity demand. The performance of the four residential battery energy systems with the distributed control strategy are given in Figure B.2.1 in Appendix B.2. The appendix also includes a figure of the voltage profiles where only the local controller was used (Figure B.2.2), in addition to a figure of the state of charge of the batteries with the same conditions (Figure B.2.3).



(a) *Radial 1*



(b) *Radial 2*

Figure 5.2.9: *(a) State of charge variation of the two BESS in radial 1. A distributed control strategy was used to schedule the charging and discharging of the BESS in the under-voltage scenario. The critical periods are marked with a blue color. (b) Illustrates the state of charge variation of the two BESS in radial 2 with the same conditions as in (b).*

The utilized battery capacity of the DSO utilization percentage and the number of hours the batteries were occupied by the DSO for each battery and critical period are provided in Table 5.2.4. Radial 1 experienced only one critical period during the simulated week with a voltage violation just below the limit. Both battery units contributed in the voltage regulation, where 6% of the total battery capacity was used to solve the voltage problem in the first hour, where 2% used in the other. Based on the percentage given in the table, a smaller DSO utilization percentage could have been used.

For radial 2, it can be observed that battery 4 was utilized the most, where battery 4 was fully utilized in all critical periods. On the other hand, battery 3 functioned almost as a backup storage unit, where this battery was only activated if battery 4 was fully charged. This is a result of the location of the two batteries, which have been discussed in more detail in Section 5.2.2. Further, it can be observed that voltage support was not needed at all hours. This observation is particularly evident in CP3-2. CP3-2 coincides with when the batteries were discharged due to high electricity costs. As the DSO was allocated 4 kW out of the 5 kW (Rated power), the discharge power of 1 kW from battery 4 was enough to solve the voltage issues in the rest of the critical period.

Table 5.2.4: *Utilized capacity of the DSO utilization percentage and number of hours the batteries were occupied by the DSO compared to the duration of the critical periods. Values were extracted from the under-voltage scenario. The total is the number of hours either one or both of the batteries was utilized compared to the total duration of the critical period.*

Radial	Battery nr	1		2		3	
		[%]	h	[%]	h	[%]	h
1	1	60	1/2	-	-	-	-
	2	20	1/2	-	-	-	-
Total		-	2/2	-	-	-	-
2	3	56	2/6	10	1/4	0	0/5
	4	100	5/6	100	3/4	100	2/5
Total		-	6/6	-	3/4	-	2/5

5.3 Evaluation of the Distributed Control Strategy

The proposed distributed control strategy was able to mitigate both over-and under-voltage issues completely. This section aims to discuss strengths and shortcomings with the control strategy.

Local Controller

The strength of this distributed control strategy is that the local controller mainly does the charging/discharging scheduling. Therefore, the customer can freely determine the main usage of their battery storage system. The local controller only needs to ensure that the battery system is operated within certain limits during a critical period. As most of the control is done locally, the economic benefit will either be the same or higher than if the customer did not provide voltage support.

The local controller was designed with the purpose of minimizing the customer's electricity bill. It was decided that the optimization problem should not include any network constraints, as this could lead to an increase in the cost function. However, a consequence of not including any network constraint was shown in the over-voltage scenario where a 80% DSO utilization percentage had to be allocated to the DSO to solve the over-voltage issues completely. By implementing when the customer should mostly charge during days with critical periods could have reduced the DSO utilization percentage and thus the interaction from the DSO. Such restriction was included in [75]. As this restriction is only included when there is a critical period, the customer will get financial incentives for changing their charging schedule. Therefore, the overall economic benefit will increase, although the cost function of the optimization problem may decrease.

Another factor that affects the cost function is the planning horizon for the charging/discharging scheduling. The desire SoC level at the beginning and at the end of the planning horizon must be determined in order to run the optimization problem. Consequently, the customer may be forced to charge power from or discharge power into the grid at inconvenient times to ensure that this restriction is met. This situation was also observed in the results, which also caused new voltage violations. It was a desire to investigate each day separately, and the planning horizon was selected accordingly. However, it may be more realistic to determine the scheduling continuously, where the scheduling is rearranged several times during a day. In this way, the battery unit will be better utilized and thus increase the economic profit. The only restriction is the announcement of hourly clearing prices for the next 24-hours, as the scheduling is based on the day-ahead market.

Central Controller

The central controller selects the battery unit that has the greatest impact on the system to participate in the voltage regulation. The advantage of this strategy is that the total power required to solve the voltage issues can be reduced. This can especially be advantageous in networks where the electric distance between the different battery units is relatively far from each other. However, the highest or lowest voltages are often experienced at the same node each time, which means that some battery units will be selected more frequently than others. Consequently, these battery units may degrade faster. Therefore, when the electric distance between the battery units and the critical node is approximately the same, the required power to solve the voltage issue should be evenly distributed between the battery units. To utilize the battery units in the system fairly, the DSO should analyze the network and determine which strategy should be used in different situations.

The central controller is designed in a way that it reacts immediately to a voltage violation, where the system never senses the voltage outside the limit. This is only possible if the controller has access to accurate predictions of the system. If the controller should respond to predicted values, a prediction error must be considered in the calculating of the adjusted power required to solve the voltage problems. On the other hand, if the controller response to real-time voltage measurements from the network, a computational and communicational delay should be included in the control strategy. Furthermore, an event-based trigger mechanism should be used, which starts whenever an over-voltage is detected. A control strategy based on real-time measurements and event-based trigger mechanism is presented in [72].

The local controller primarily determines the operation of the battery unit. This means that there is no requirement for frequent information sharing between the central and the local controllers, which reduces the communication burden. Furthermore, as the operation of the battery is divided into two controllers based on the operational preferences, the DSO does not have to solve any complex optimization problem to utilize the multiple residential battery units. Finally, as a percentage of the battery capacity is allocated to the DSO during a critical period, the DSO is guaranteed to have battery capacity available to respond to voltage violations.

5.4 Business Model

The results showed that the proposed distributed control strategy could solve voltage issues by utilizing residential battery energy storage systems (BESS). However, this can only be realized with a proper business model. A proper business model will not only motivate the customers to invest in a BESS, but also ensure that the customer and the distribution system operator will benefit from the installation. This section will provide commercially viable business models divided into cost-sharing models and price mechanism models.

5.4.1 Cost-Sharing Model

In a cost-sharing model, the investment cost of the BESS is shared between the customer and the DSO. The DSO has only control over the BESSs during periods with voltage problems, referred to as critical periods. The rest of the day, the customer can use the BESS to increase their self-consumption or decrease their electricity bill by taking advantage of price variations.

It is essential to identify how often the DSO needs to regulate the BESS in a cost-sharing model. In this way, the investment share can be found. However, before different cost-sharing models are presented, it is important to determine how the BESS should be operated during a critical period. Two parameters should be determined and specified in an agreement or contract between the DSO and the customer. The two parameters are the BESS's active power settings and the percentage of the battery capacity allocated to the DSO during a critical period.

The DSO can either get full or partial control over the active power setting of the BESS during a critical period. Partial control gives the customer some level of control during a critical period, which has been found to increase the acceptance rate to participate in demand response programs. The customer can use their share of the charging/discharging power to charge surplus power from the PV system or respond to price variations. However, the control is limited as the DSO has the main control of the BESS during a critical period. If the DSO uses the BESS for over-voltage issues, the customer cannot discharge. The opposite accounts for under-voltage issues. As mentioned in the previous section, the partial control approach had little effect on the utilization of the BESSs. On the other hand, full control over the active power settings of the BESSs can contribute to more efficient voltage regulation, as the DSO can utilize the BESS that has the greatest impact on the system with fewer restrictions. A result can be a reduction in the total amount of power required to solve the voltage problem and reduce the total number of cycles used.

The percentage of the battery capacity allocated to the DSO can either be the same for each period or depend on the magnitude of the voltage violation. An equal amount for each critical period reduces the need for accurate prediction of the system. DSO only needs to state when a critical period may occur and the duration. This approach also creates higher predictability for the customer. However, as observed from the results, the percentage required to mitigate the voltage problems completely varied from 10 to 80%. Therefore, it may be a better solution to reserve a percentage depending on the magnitude of the voltage variation, both due to profitability and to guarantee that the voltage problem will be solved. In addition, it may be desirable to reserve different percentages depending on the BESS location, as the BESS will have different effects on the system. With this approach, prediction of the load and production will be required to determine the percentage required for each critical period.

Three cost-sharing models will be proposed and discussed further in this section. The cost-sharing models are based on the number of cycle, percentage of total capacity, and the number of hours the BESS is utilized.

Cycle Life

The BESS lifetime can be measured based on the number of charging and discharging cycles before losing performance. Therefore, the investment cost could be based on the number of cycles the different parties use over a specific period. A prerequisite for this model is that the number of over-and under-voltage issues experienced in the grid is roughly the same. A dominating over-voltage problem in the grid causes a higher number of charging cycles used by the DSO compared to discharging cycles. The opposite will be the case with a dominating under-voltage problem. Consequently, the investment share will not be distributed correctly according to the number of cycles each party uses.

Utilization of Total Capacity

In a distribution network where one of the voltage problems dominates, the investment cost can be shared based on a utilization percentage. In this context, a utilization percentage is a percentage of the total capacity used for voltage support. Due to significant changes in load demand and production during a year, this percentage should be calculated based on a yearly perspective. However, the percentage may vary depending on the magnitude of voltage violation, which is illustrated in Section 5.1 and 5.2. Therefore, the investment share must reflect the variation of the different required utilization percentages.

Hourly-based

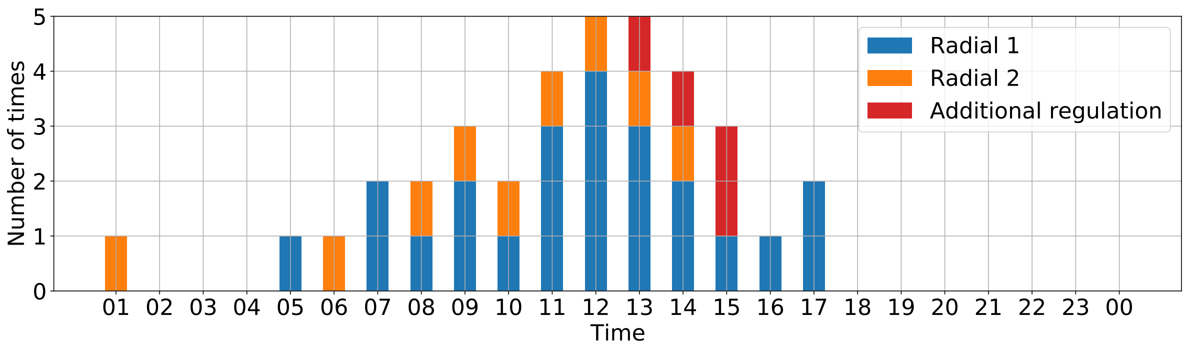
Another model is to share the investment cost based on the number of hours the DSO utilizes the BESS during a specific period. Therefore, an approximate number of hours the BESS used for voltage support must be calculated. As this model does not consider the number of cycles or the total energy used, contracts that specify a reasonable battery usage in critical periods are crucial. The contract ensures that both parties will benefit from the model. Furthermore, the number of hours used to calculate the investment share must consider hours shut in between two critical periods as these hours may be challenging to utilize by the customer. As observed from Table 5.1.4, the utilization percentage more often coincides with the predicted percentage compared to the number of hours utilized to coincide with the duration of the critical period. The observation indicates that an hourly-based cost-sharing model may pose higher demands on accurate predicting than a utilization percentage of the total capacity.

5.4.2 Price mechanism model

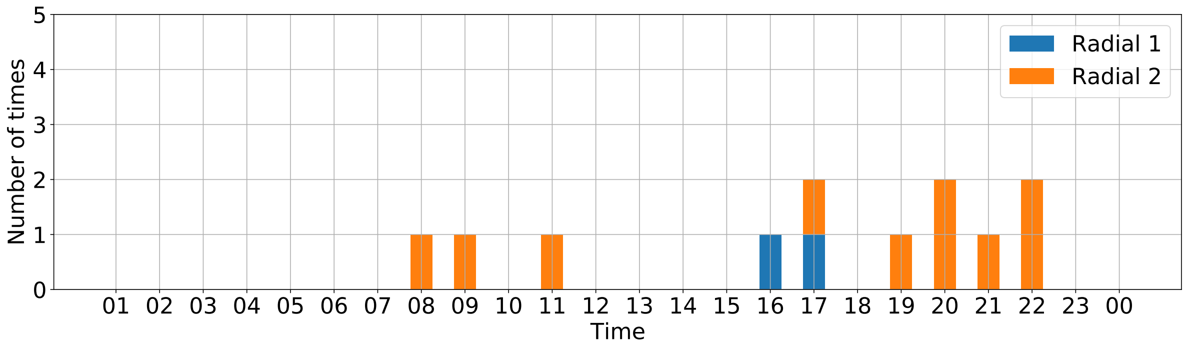
A price mechanism model gives the customer financial incentives if they decide to provide voltage support. With a proper compensations from the DSO, the economic benefit of installing a residential BESS can increase. However, it is essential that the price mechanism model compensates fairly for the service provided. This section discusses some possible price mechanism models.

Incentives from the DSO can be anything from price per a defined period (e.g., year, month, week, etc.), price per utilized power (kW), or price per utilized energy (kWh). The price for flexibility for a defined period can be found using the same models as proposed in the cost-sharing model. The agreement or contract will also be the same. The major difference between the cost-sharing models and price mechanism models is the number of times the value of generated flexibility is calculated. In a cost-sharing model, this value is calculated only at the time the investment cost is shared between the two parties. On the contrary, in a price mechanism model, this value is calculated each time a price signal is given.

The price will depend on the demand for flexibility in the system. For example, Figure 5.4.1 illustrates the number of times the DSO regulated the BESS in the scenarios simulated in the previous section. The red boxes illustrate the additional regulation required to mitigate over-voltage issues in all critical periods completely. From Figure 5.4.1(a), it can be observed an increase for flexibility between 11:00 to 14:00, which coincides with when the solar irradiance is at its highest. Therefore, the incentive level should be higher during these hours. However, the demand for flexibility may change from day to day, and from season to season. As the solar production is lower during the winter season and the load is usually higher, over-voltage issues may occur. These issues often occur during the morning and evening peak hours, as also shown in Figure 5.4.1(b). Therefore, higher incentive levels should be provided during peak hours due to under-voltage issues.



(a) *Summer period*



(b) *Winter period*

Figure 5.4.1: *(a) Number of times the system operator regulated the BESS due to over-voltage issues in the two radials. (b) Number of times the system operator regulated the BESS due to under-voltage issues in the two radials. The red boxes is the additional regulation required to mitigate over-voltage issues in all critical periods completely.*

Another model can be to determine the price according to a utilization percentage. For this model, Table 5.1.4 is used as an example. In CP1-1, 80% of the battery capacity was reserved, where 96% and 90% of the capacity were used. As almost all reserved capacity was used, a high incentive level should be given. However, for battery 2 in CP4-1, only 40% of the reserved capacity was used. Therefore, a lower incentive level should be given. The DSO has no desire to reserve a BESS if they did not intend to utilize the reserved capacity. However, due to prediction errors, this can happen. Reservation and activation prices should be used in this situation to reflect the service provided. An equal reservation price should be given to all the customers that get their BESS reserved, while the activation price reflects the utilization of the reserved capacity. The DSO should analyze the reservation and activation price setting and the difference between those two. For example, the reservation price can be fixed, while the activation price can depend on the amount of reserved capacity used-

Indirect price models can also be an alternative. In this model, the customer responds to price signals given by the DSO. A typical price signal may be a feed-in-tariff, as proposed in [73]. To be profitable for the customer to participate in voltage support, the price signal should be minimum equal to the electricity price and the network tariff. Furthermore, a degradation cost of the BESS may also be considered for such price signals. However, the model cannot ensure that the voltage issues will be completely mitigated as the DSO does not directly control the BESS.

5.4.3 Reactivation of Batter Energy Storage Systems

When BESSs are used for voltage support, the energy is shifted from one period to another. If the shifted energy from multiplied BESS in a network is released simultaneously into the grid, new voltage violations can emerge. This situation was observed in the results in the over-and under-voltage scenario (Figure 5.1.8 and 5.2.8). New critical periods emerged right after some of the periods in the over-voltage scenario as the prices were highest during this period. The DSO can prevent this situation by reserving the BESSs for a few more minutes after the critical period. Then, the BESSs will be reactivated at different time steps. The additional time the BESSs will be reserved depends on the system.

Another alternative is to provide different price signals to each of the customers in the same radial. This method can be a promising approach in systems with multiple residential BESS, especially if the BESS are installed to respond to price variations. In the under-voltage scenario, several voltage sags were observed due to simultaneous charging from the grid. Different price signals can decrease the magnitude of the voltage sags.

5.5 Further Work

There are several directions in which future work can be carried out to get even more insights and exciting results. This section will provide some suggestion for further work.

The results showed that the selected battery capacities were not large enough to solve the voltage issues in all critical periods. The active power capability is restricted by the battery capacity, whereas the reactive power support can be regulated continuously. Utilizing the reactive power support from the converter when the active power capability is insufficient could have solved the voltage issues in all the critical periods. Therefore, reactive power support should be implemented in the control strategy.

As mentioned in Section 4.1.3, overloading of the cables and transformers was not considered. Violation of thermal limits may be just as critical as voltage violations, especially in low voltage distribution networks with high penetration of renewable energy resources. In order to increase the hosting capacity, the central controller should react to both thermal and voltage violations.

Deterministic data was used to validate the performance of the control strategy. As the measured data can varies considerably from predicted values, it is important to test the control strategy with random occurrence. This should be done in further work.

The short circuit performance has not been considered in the simulation. As low short circuit performance may damage components due to faults in the network, it can be discussed whether batteries are reasonable alternatives in terms of safety. Therefore, it is essential to investigate how converted-connected units affect the network before promoting residential battery storage systems for voltage regulation. In addition, it should also be investigated how the on and off switching of production and storage units effect the network, as this can especially be critical in networks with low short circuit performance.

Potential business models to realize voltage support from residential battery systems were provided in this thesis. However, no numerical values were given. Consequently, suggestions to prices for providing voltage support could not be stated, hence the profitability of investing in a battery. Therefore, this should be investigated in further work. The price that ensures a profitable residential battery systems investment is considered as the minimum price for flexibility. It could also be interesting to find the maximum price for flexibility. This can be found by considering the necessary cost required for grid reinforcement if flexibility is not utilized.

In a distribution network, the customer can provide flexibility from other resources than residential battery storage systems. As the central controller regulates the battery units according to a power rate and energy level, other controllable loads can be considered in the control strategy. This requires that a local controller can give information about the power rate and duration the flexible load can be regulated with the given power rate. Other characteristics that also should be considered are controllability and delivering time.

Chapter 6

Conclusion

This thesis has proposed a distributed control method for residential battery energy storage systems (BESS) to solve voltage issues in the distribution network. The proposed method consists of a local and a central controller, where most of the operational decisions are made by the local controller. The objective with the local controller is to minimize the customer's electricity bill, while the central controller regulates the voltage during critical periods. The distributed control method was validated through a simulation study of the distribution network at Utsira, where the method successfully maintained the voltage within its limits.

A decisive factor to completely mitigate voltage issues was the total battery capacity in the network. Through a sensitivity study, it was found that an additional 5-8 kWh per BESS was required to completely mitigate voltage issues in all critical periods compared to a battery size that met the customer's need. However, the number could be decreased to 1-3 kWh if two critical periods were disregarded. The financial incentives the distribution system operator can provide the customer will be crucial in determining the most profitable battery size.

The BESS with the greatest impact on the system performance was selected to participate in the voltage regulation and was found based on a voltage-sensitivity control method. The method aims to reduce the total amount of required power for voltage support. Since the electrical distance between the BESSs and the critical node in the over-voltage scenario was approximately the same, the method had no significant impact on the total amount of required power. In the under-voltage scenario, the total amount of required power could be reduced from 11.3 kW to 4.2 kW by selecting the BESS with the highest impact on the system. This result indicates that it is important to analyze the network and the BESS's impact on the system to utilize the residential BESSs effectively.

A proper business model must be designed to realize the distributed control method. This thesis has proposed different business models divided into cost-sharing and price mechanism models. The models consider how the provided service generates value and how the created value is shared between the customer and the distribution system operator.

A future control method should implement reactive power support from the BESS's converter when the active power capability is insufficient to investigate if the required capacity for voltage support can be decreased. In addition, the method should also consider congestion, as this is just as critical as voltage violations in distribution grids with high penetration of renewables.

Bibliography

[1] Gudmund Bartnes Jonas Skaare Amundsen and Eirik Øyslebø. Kraftmarkedsanalyse 2016-2030. Technical Report 2-2017, Norges vassdrags- og energidirekorat, NVE, 1 2017.

[2] Haoran Zhao, Qiuwei Wu, Shuju Hu, Honghua Xu, and Claus Nygaard Rasmussen. Review of energy storage system for wind power integration support. *Applied Energy*, 137:545–553, January 2015.

[3] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, and A. H. A. Bakar. Photovoltaic penetration issues and impacts in distribution network – A review. *Renewable and Sustainable Energy Reviews*, 53:594–605, January 2016.

[4] IRENA. Demand-side flexibility for power sector transformation, 2019. International Renewable Energy Agency, Abu Dhabi.

[5] BloombergNEF. Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh, December 2020. Section: Press Release.

[6] Yong Li, Li He, Fang Liu, Canbing Li, Yijia Cao, and Mohammad Shahidehpour. Flexible Voltage Control Strategy Considering Distributed Energy Storages for DC Distribution Network. *IEEE Transactions on Smart Grid*, 10(1):163–172, January 2019. Conference Name: IEEE Transactions on Smart Grid.

[7] S. Lee, J. Kim, C. Kim, S. Kim, E. Kim, D. Kim, K. K. Mehmood, and S. U. Khan. Coordinated Control Algorithm for Distributed Battery Energy Storage Systems for Mitigating Voltage and Frequency Deviations. *IEEE Transactions on Smart Grid*, 7(3):1713–1722, May 2016. Conference Name: IEEE Transactions on Smart Grid.

[8] Y. Wang, K. T. Tan, X. Y. Peng, and P. L. So. Coordinated Control of Distributed Energy-Storage Systems for Voltage Regulation in Distribution Networks. *IEEE Transactions on Power Delivery*, 31(3):1132–1141, June 2016. Conference Name: IEEE Transactions on Power Delivery.

[9] Yue Zhang and Anurag Srivastava. Voltage Control Strategy for Energy Storage System in Sustainable Distribution System Operation. *Energies*, 14(4):832, January 2021. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[10] Vahid Behravesh, Reza Keypour, and Asghar Akbari Foroud. Control strategy for improving voltage quality in residential power distribution network consisting of roof-top photovoltaic-wind hybrid systems, battery storage and electric vehicles. *Solar Energy*, 182:80–95, April 2019.

[11] Xiaolong Jin, Qiuwei Wu, and Hongjie Jia. Local flexibility markets: Literature review on concepts, models and clearing methods. *Applied Energy*, 261:114387, March 2020.

[12] Shaojun Huang, Qiuwei Wu, Lin Cheng, Zhaoxi Liu, and Haoran Zhao. Uncertainty Management of Dynamic Tariff Method for Congestion Management in Distribution Networks. *IEEE Transactions on Power Systems*, 31(6):4340–4347, November 2016. Conference Name: IEEE Transactions on Power Systems.

[13] Energifakta Norge. Strømnettet. [Updated: 10.04.2019, Extracted: 06.05.2021], `https://energifaktanorge.no/norsk-energiforsyning/kraftnett/`.

[14] American public power association. *What Is Electricity?*, [Extracted 06.05.2021]. `https://www.publicpower.org/public-power/electricity-basics`.

[15] N. B. G. Brinkel, M. K. Gerritsma, T. A. AlSkaif, I. Lampropoulos, A. M. van Voorden, H. A. Fidder, and W. G. J. H. M. van Sark. Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles. *International Journal of Electrical Power & Energy Systems*, 118:105741, June 2020.

[16] B. Bakhshideh Zad, H. Hasanvand, J. Lobry, and F. Vallée. Optimal reactive power control of DGs for voltage regulation of MV distribution systems using sensitivity analysis method and PSO algorithm. *International Journal of Electrical Power & Energy Systems*, 68:52–60, June 2015.

[17] Henrik Kirkeby Bendik Nybakk Torsæter. Simuleringsstudie av spenningskvalietet i lavspenningsnett med plusskunder, 2017. SINTEF.

[18] Soheila Karimi, Petr Musilek, and Andrew M. Knight. Dynamic thermal rating of transmission lines: A review. *Renewable and Sustainable Energy Reviews*, 91:600–612, August 2018.

[19] Rich Seguin, Jeremy Woyak, David Costyk, Josh Hambrick, and Barry Mather. High-Penetration PV Integration Handbook for Distribution Engineers. Technical Report NREL/TP-5D00-63114, National Renewable Energy Lab. (NREL), Golden, CO (United States), January 2016.

[20] AEMO. System strength, March 2020. Australian Energy Market Operator.

[21] Helge Seljeseth Henrik Kirkeby. Utfordrende elektriske apparater, 2014. NEF Teknisk Møte.

[22] DNV GL Energy. Strømnettet i et fullelektrisk norge. Technical Report 2019-0218, Rev. 3, DNV GL Energy, Høvik, 10 2019.

[23] NVE. Reguleringsmyndigheten. [Extracted: 06.05.2021], `https://www.nve.no/reguleringsmyndigheten/`.

[24] NVE. Plusskunder. [Updated: 04.02.2021, Extracted: 30.04.2021], `https://www.nve.no/reguleringsmyndigheten/nettjenester/nettleie/tariffer-for-produksjon/plusskunder/`.

[25] Olje- og energidepartementet. *Forskrift om leveringskvalitet i kraftsystemet*. LOVDATA, 11

2004. [Extracted: 15.10.20209], `https://lovdata.no/dokument/SF/forskrift/2004-11-30-1557`.

[26] NVE. Nettleie. [Updated: 31.10.2019, Extracted: 06.05.2021], `https://www.nve.no/stromkunde/nettleie/`.

[27] Annhild Meling Kjell Rune Verlo, Bjørnar Araberg Fladen and Urd Sira. Oppsummering av høring og anbefaling til endringer i nettleiestrukturen. Technical Report 6-2020, Norges vassdrags- og energidirekorat, NVE, 1 2020.

[28] Sheridan Few, Predrag Djapic, Goran Strbac, Jenny Nelson, and Chiara Candelise. Assessing local costs and impacts of distributed solar PV using high resolution data from across Great Britain. *Renewable Energy*, 162:1140–1150, December 2020.

[29] T. Aziz and N. Ketjoy. Enhancing PV Penetration in LV Networks Using Reactive Power Control and On Load Tap Changer With Existing Transformers. *IEEE Access*, 6:2683–2691, 2018. Conference Name: IEEE Access.

[30] Delong Zhang, Jianlin Li, and Dong Hui. Coordinated control for voltage regulation of distribution network voltage regulation by distributed energy storage systems. *Protection and Control of Modern Power Systems*, 3(1):3, December 2018.

[31] Tanmay Tewari, Abheejeet Mohapatra, and Sandeep Anand. Coordinated Control of OLTC and Energy Storage for Voltage Regulation in Distribution Network With High PV Penetration. *IEEE Transactions on Sustainable Energy*, 12(1):262–272, January 2021. Conference Name: IEEE Transactions on Sustainable Energy.

[32] Junjie Hu, Mattia Marinelli, Massimiliano Coppo, Antonio Zecchino, and Henrik W. Bindner. Coordinated voltage control of a decoupled three-phase on-load tap changer transformer and photovoltaic inverters for managing unbalanced networks. *Electric Power Systems Research*, 131:264–274, February 2016.

[33] Mohammad Nazmul Islam Sarkar, Lasantha Gunaruwan Meegahapola, and Manoj Datta. Reactive Power Management in Renewable Rich Power Grids: A Review of Grid-Codes, Renewable Generators, Support Devices, Control Strategies and Optimization Algorithms. *IEEE Access*, 6, 2018. Conference Name: IEEE Access.

[34] M. Zeraati, M. E. H. Golshan, and J. M. Guerrero. Voltage Quality Improvement in Low Voltage Distribution Networks Using Reactive Power Capability of Single-Phase PV Inverters. *IEEE Transactions on Smart Grid*, 10(5):5057–5065, September 2019. Conference Name: IEEE Transactions on Smart Grid.

[35] Abdul Motin Howlader, Staci Sadoyama, Leon R. Roose, and Saeed Sepasi. Distributed voltage regulation using Volt-Var controls of a smart PV inverter in a smart grid: An experimental study. *Renewable Energy*, 127:145–157, November 2018.

[36] M. N. Kabir, Y. Mishra, G. Ledwich, Z. Y. Dong, and K. P. Wong. Coordinated Control of Grid-Connected Photovoltaic Reactive Power and Battery Energy Storage Systems to Improve the

Voltage Profile of a Residential Distribution Feeder. *IEEE Transactions on Industrial Informatics*, 10(2):967–977, May 2014. Conference Name: IEEE Transactions on Industrial Informatics.

[37] F. Zhang, X. Guo, X. Chang, G. Fan, L. Chen, Q. Wang, Y. Tang, and J. Dai. The reactive power voltage control strategy of PV systems in low-voltage string lines. In *2017 IEEE Manchester PowerTech*, pages 1–6, June 2017.

[38] Angelos I. Nousdilis, Georgios C. Christoforidis, and Grigoris K. Papagiannis. Active power management in low voltage networks with high photovoltaics penetration based on prosumers' self-consumption. *Applied Energy*, 229:614–624, November 2018.

[39] Abdul Motin Howlader, Staci Sadoyama, Leon R. Roose, and Yan Chen. Active power control to mitigate voltage and frequency deviations for the smart grid using smart PV inverters. *Applied Energy*, 258:114000, January 2020.

[40] A. N. M. M. Haque, P. H. Nguyen, T. H. Vo, and F. W. Bliek. Agent-based unified approach for thermal and voltage constraint management in LV distribution network. *Electric Power Systems Research*, 143:462–473, February 2017.

[41] D. Kim, H. Kim, and D. Won. Operation Strategy of Shared ESS Based on Power Sensitivity Analysis to Minimize PV Curtailment and Maximize Profit. *IEEE Access*, 8:197097–197110, 2020. Conference Name: IEEE Access.

[42] Shakti Singh, Shubhangi Jagota, and Mukesh Singh. Energy management and voltage stabilization in an islanded microgrid through an electric vehicle charging station. *Sustainable Cities and Society*, 41:679–694, August 2018.

[43] Tao Jiang, Zening Li, Xiaolong Jin, Houhe Chen, Xue Li, and Yunfei Mu. Flexible operation of active distribution network using integrated smart buildings with heating, ventilation and air-conditioning systems. *Applied Energy*, 226:181–196, September 2018.

[44] Chao Gao, Xisheng Tang, and Li Kong. Research on Coordinated Control Strategy for Improving the Frequency and Voltage Quality of Power System Based on Adaptive Fuzzy Control Using Wind Power and Energy Storage. In *2017 IEEE International Conference on Energy Internet (ICEI)*, pages 142–147, April 2017.

[45] Yih-Der Lee, Jheng-Lun Jiang, Huai-Jhe Su, Yuan-Hsiang Ho, and Yung-Ruei Chang. Ancillary voltage control for a distribution feeder by using energy storage system in microgrid. In *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, pages 1–7, June 2016. ISSN: 2329-5767.

[46] Chao Zhang, Yi-Li Wei, Peng-Fei Cao, and Meng-Chang Lin. Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews*, 82:3091–3106, February 2018.

[47] Mohammad Rasol Jannesar, Alireza Sedighi, Mehdi Savaghebi, and Josep M. Guerrero. Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovoltaic penetration. *Applied Energy*, 226:957–966, September 2018.

[48] Huiying Zhao, Mingguo Hong, Wei Lin, and Kenneth A. Loparo. Voltage and Frequency Regulation of Microgrid With Battery Energy Storage Systems. *IEEE Transactions on Smart Grid*, 10(1):414–424, January 2019. Conference Name: IEEE Transactions on Smart Grid.

[49] DNV GL. Batterier i distribusjonsnettet. Technical Report 2-2018, Norges vassdrags- og energidirekorat, NVE, 1 2018.

[50] Per Hallberg Chair. Decentralised storage: Impact on future distribution grids. Technical Report 29, Eurelectric, 12 2012.

[51] Meysam Qadrdan, Nick Jenkins, and Jianzhong Wu. Chapter II-3-D - Smart Grid and Energy Storage. In Soteris A. Kalogirou, editor, *McEvoy's Handbook of Photovoltaics (Third Edition)*, pages 915–928. Academic Press, January 2018.

[52] H. Wenzl. BATTERIES AND FUEL CELLS | Lifetime. In Jürgen Garche, editor, *Encyclopedia of Electrochemical Power Sources*, pages 552–558. Elsevier, Amsterdam, January 2009.

[53] Frank Jossi Writer, Rise. Best Home Battery Storage Options: 2021 Guide, November 2020.

[54] O. M. Babatunde, J. L. Munda, and Y. Hamam. Power system flexibility: A review. *Energy Reports*, 6:101–106, February 2020.

[55] Cherrelle Eid, Elta Koliou, Mercedes Valles, Javier Reneses, and Rudi Hakvoort. Time-based pricing and electricity demand response: Existing barriers and next steps. *Utilities Policy*, 40:15–25, June 2016.

[56] Cherrelle Eid, Paul Codani, Yannick Perez, Javier Reneses, and Rudi Hakvoort. Managing electric flexibility from Distributed Energy Resources: A review of incentives for market design. *Renewable and Sustainable Energy Reviews*, 64:237–247, October 2016.

[57] Matteo Muratori and Giorgio Rizzoni. Residential Demand Response: Dynamic Energy Management and Time-Varying Electricity Pricing. *IEEE Transactions on Power Systems*, 31(2):1108–1117, March 2016. Conference Name: IEEE Transactions on Power Systems.

[58] Hva er NorFlex? [Published: 27.08.2019] `https://www.ae.no/var-virksomhet/fornyelse/norflex-prosjektet/hva-er-norflex/`.

[59] Xiaojing Xu, Chien-fei Chen, Xiaojuan Zhu, and Qinran Hu. Promoting acceptance of direct load control programs in the United States: Financial incentive versus control option. *Energy*, 147:1278–1287, March 2018.

[60] Smart Grid Task Force. Regulatory Recommendations for the Deployment of Flexibility. Technical Report STGF-EG3, Interregeurope, 2015.

[61] M. McGranaghan and F. Goodman. Technical and system requirements for Advanced Distribution Automation. In *CIRED 2005 - 18th International Conference and Exhibition on Electricity Distribution*, pages 1–5, June 2005. ISSN: 0537-9989.

[62] NVE. Smarte strømmålere (AMS). [Updated: 30.04.2021, Extracted:

07.05.2021], https://www.nve.no/reguleringsmyndigheten/stromkunde/smarte-strommalere-ams/.

[63] Giuseppe Fusco, Mario Russo, and Michele De Santis. Decentralized Voltage Control in Active Distribution Systems: Features and Open Issues. *Energies*, 14(9):2563, January 2021. Number: 9 Publisher: Multidisciplinary Digital Publishing Institute.

[64] Yang Zhang, Anders Lundblad, Pietro Elia Campana, F. Benavente, and Jinyue Yan. Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: A case study in Sweden. *Energy Conversion and Management*, 133:249–263, February 2017.

[65] Filomeno M. Vieira, Pedro S. Moura, and Aníbal T. de Almeida. Energy storage system for self-consumption of photovoltaic energy in residential zero energy buildings. *Renewable Energy*, 103:308–320, April 2017.

[66] Yannick Riesen, Christophe Ballif, and Nicolas Wyrsch. Control algorithm for a residential photovoltaic system with storage. *Applied Energy*, 202:78–87, September 2017.

[67] Iromi Ranaweera, Ole-Morten Midtgård, Magnus Korpås, and Hossein Farahmand. Control strategies for residential battery energy storage systems coupled with PV systems. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, pages 1–6, June 2017.

[68] Giuseppe Fusco and Mario Russo. A Decentralized Approach for Voltage Control by Multiple Distributed Energy Resources. *IEEE Transactions on Smart Grid*, pages 1–1, 2021. Conference Name: IEEE Transactions on Smart Grid.

[69] M. Zeraati, M. E. Hamedani Golshan, and J. M. Guerrero. Distributed Control of Battery Energy Storage Systems for Voltage Regulation in Distribution Networks With High PV Penetration. *IEEE Transactions on Smart Grid*, 9(4):3582–3593, July 2018. Conference Name: IEEE Transactions on Smart Grid.

[70] Yongzhu Hua, Xiangrong Shentu, Qiangqiang Xie, and Yi Ding. Voltage/Frequency Deviations Control via Distributed Battery Energy Storage System Considering State of Charge. *Applied Sciences*, 9:1148, March 2019.

[71] Lei Wang, Daniel H. Liang, Andrew F. Crossland, Philip C. Taylor, Darren Jones, and Neal S. Wade. Coordination of Multiple Energy Storage Units in a Low-Voltage Distribution Network. *IEEE Transactions on Smart Grid*, 6(6):2906–2918, November 2015. Conference Name: IEEE Transactions on Smart Grid.

[72] Iromi Ranaweera and Ole-Morten Midtgard. Centralized control of energy storages for voltage support in low-voltage distribution grids. In *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, pages 1–6, June 2016.

[73] Iromi Ranaweera and Ole-Morten Midtgård. *Techno-economic Optimum Control of Grid-connected Residential Battery Energy Storage Units*. Energynautics GmbH, 2016. Accepted: 2018-02-19T13:21:32Z Publication Title: 443-448.

[74] Hideharu Sugihara, Kohei Yokoyama, Osamu Saeki, Kiichiro Tsuji, and Tsuyoshi Funaki. Economic and Efficient Voltage Management Using Customer-Owned Energy Storage Systems in a Distribution Network With High Penetration of Photovoltaic Systems. *IEEE Transactions on Power Systems*, 28(1):102–111, February 2013. Conference Name: IEEE Transactions on Power Systems.

[75] Iromi Ranaweera, Ole-Morten Midtgård, and Magnus Korpås. Distributed control scheme for residential battery energy storage units coupled with PV systems. *Renewable Energy*, 113, June 2017.

[76] Zhimin Wang, Chenghong Gu, and Furong Li. Flexible operation of shared energy storage at households to facilitate PV penetration. *Renewable Energy*, 116:438–446, February 2018.

[77] Mulukutla S. Sarma J. Duncan Glover and Thomas J. Overby. *Power system analysis and design*, volume 1 of *1*, chapter 6, pages 294–342. Global Engineering: Christopher M. Shortt, ISBN-13: 978-1-111-42577-7, 5 edition, 7 2010.

[78] ENOVA. Pilot for smart energistyring, microgrids og fleksibilitetsmarked. [Extracted: 04.05.2020] `https://www.enova.no/om-enova/om-organisasjonen/teknologiporteføljen/pilot-for-smart-energistyring-microgrids-og-fleksibilitetsmarked\-pa-utsira/`.

[79] Frida Bratlie. Flexibility market development for utsira. Specialization Project, Norwegian University of Science and Technology (NTNU). Unpublished, 12 2020.

[80] Utsira kommune. Energi. Extracted[28.05.2021], `https://www.utsira.kommune.no/tema/natur-og-miljo/energi`.

[81] Lucas Bauer. Enercon E-40/6.44 - 600,00 kW - Wind turbine. [Extracted: 21.11.2020], `https://en.wind-turbine-models.com/turbines/68-enercon-e-40-6.44`.

[82] SSB. Kommunefakta. [Extracted: 21.11.2020], `https://www.ssb.no/kommunefakta/utsira`.

[83] Vil du delta i pilotprosjektet på Utsira?, March 2021.

[84] L. Thurner, A. Scheidler, F. Schäfer, J. Menke, J. Dollichon, F. Meier, S. Meinecke, and M. Braun. pandapower — an open-source python tool for convenient modeling, analysis, and optimization of electric power systems. *IEEE Transactions on Power Systems*, 33(6):6510–6521, Nov 2018.

[85] LOVDATA. Forskrift om sikkerhet og beredskap i kraftforsyningen (kraftberedskapsforskriften), 2013. Olje- og Energidepartement.

[86] SINTEF Energi. Planbok.

[87] JRC Photovoltaic Geographical Information System (PVGIS) - European Commission. `https://ec.europa.eu/jrc/en/pvgis`.

Appendix A

A.1 Cable Data

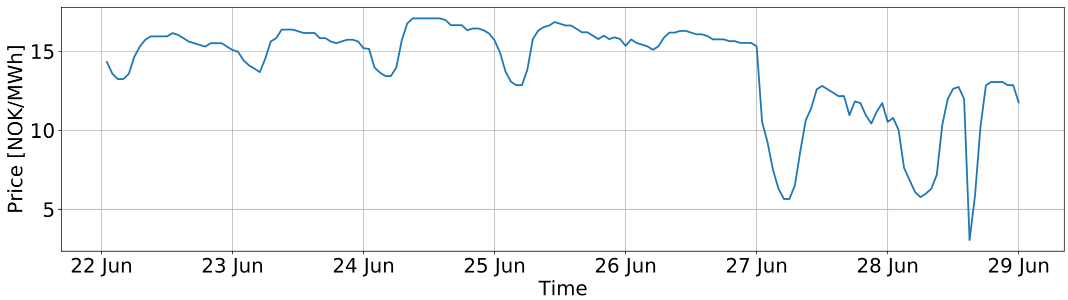
Table A.1.1: *Line and cable date for the LV distribution grid.*

Node 1	Node 2	Length $[km]$	Type
SS6020	61020-B1	0.466	TFXP 4x240 Al
61020-B1	node1	0.028	EX 3x25 Al
61020-B1	node2	0.031	EX 3x25 Al
61020-B1	61020-B2	0.063	TFXP 4x240 Al
61020-B2	#1	0.031	TFXP 4x50 Al
#1	node3	0.022	PFSP 3x25 Al
61020-B2	node4	0.119	TFXP 4x50 Al
61020-B2	#2	0.076	EX 3x95 Al
#2	node5	0.05	PFSP 3x25 Al
SS61020	61020-C1	0.28	TFXP 4x240 Al
61020-C1	node8	0.106	TFXP 4x95 Al
61020-C1	node9	0.096	TFXP 4x50 Al
61020-C1	#3	0.094	TFXP 4x50 Al
#3	node9	0.033	EX 3x25 Al
61020-C1	#4	0.081	TFXP 4x50 Al
#4	node7	0.016	PFSP 3x25 Al
61020-C1	#5	0.02	TFXP 4x95 Al
#5	#6	0.044	EX 3x95 Al
#6	node10	0.045	EX 3x25 Al
#6	#7	0.043	EX 3x95 Al
#7	node11	0.02	EX 3x25 Al
#7	#8	0.082	EX 3x95 Al
#8	node13	0.018	EX 3x25 Al
#8	node12	0.026	EX 3x25 Al
#8	#9	0.027	EX 3x95 Al
#9	node14	0.015	EX 3x25 Al
#9	#10	0.062	EX 3x25 Al
#10	node15	0.06	EX 3x25 Al
61011LV	61020-A1	0.076	TFXP 4x240 Al
61020-A1	#11	0.007	TFXP 4x95 Al
#11	61020-A2	0.069	EX 3x50 Al
61020-A2	node16	0.028	PFSP 3x25 Al
61020-A1	node17	0.208	PFSP 3x50 Al

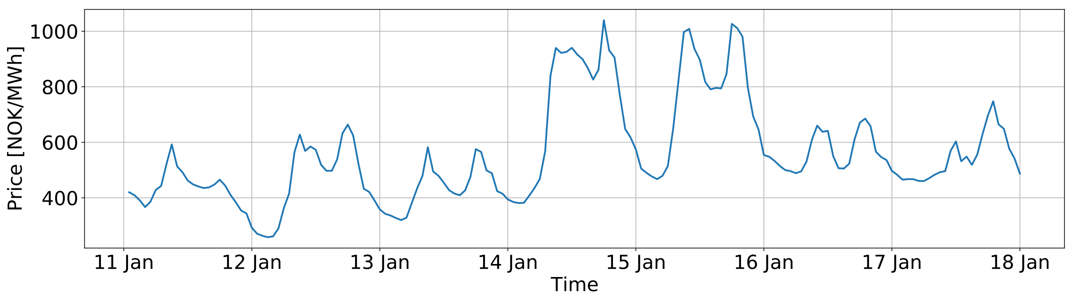
Table A.1.2: *Information about the resistance, reactance and capacitance per kilometer, and rated current for 1 and 24 kV single and thee cord cables and overhead lines (50Hz).[86]*

Cable type	**R** $[\Omega/km]$	**X** $[\Omega/km]$	C_d $[nF/km]$	I_{th} $[kA]$
EX 3x25 Al	1.2	0.083	0.55	0.115
EX 3x50 Al	0.641	0.079	0.8	0.18
EX 3x95 Al	0.32	0.077	1.09	0.28
FEAL 3x50	0.359	0.373	9.79	0.303
DKBA 3x25 Cu	0.727	0.135	190	0.074
PFSP 3x25 Al	1.2	0.082	700	0.15
PFSP 3x50 Al	0.641	0.079	1080	0.22
TFXP 4x25 Al	1.2	0.082	820	0.125
TFXP 4x50 Al	0.641	0.079	1080	0.18
TFXP 4x95 Al	0.32	0.075	1100	0.26
TFXP 4x240 Al	0.125	0.072	1260	0.435
TXRA x3x25 Cu	0.727	0.135	190	0.09775
1X50 Cu	0.357	0.395	9.27	0.278
TXSE 3x1x50 Al	0.641	0.14	170	0.185
TXSE 3x1x95 Al	0.32	0.12	200	0.275
TXSE 3x1x240 Al	0.125	0.11	280	0.455
TSLE 3x1x95 Al	0.32	0.12	200	0.275
TSLF 3x1x95 Al	0.32	0.12	200	0.275
TSLF 3x1x240 Al	0.125	0.11	280	0.455

A.2 Electricity Price Data



(a) *Summer*



(b) *Winter*

Figure A.2.1: *(a) illustrates the spot price variations in the period 22-29 June 2020.(b) illustrates the spot price variations in the period 11-18 January 2021.*

Table A.2.1: *Network tariff used in the local controller.*

Segment	Price [øre/kWh]
Energy segment	26.998
Consumption tax	20.86
Enova tax	1.25
Total	49.108

Appendix B

B.1 Over-Voltage Scenario

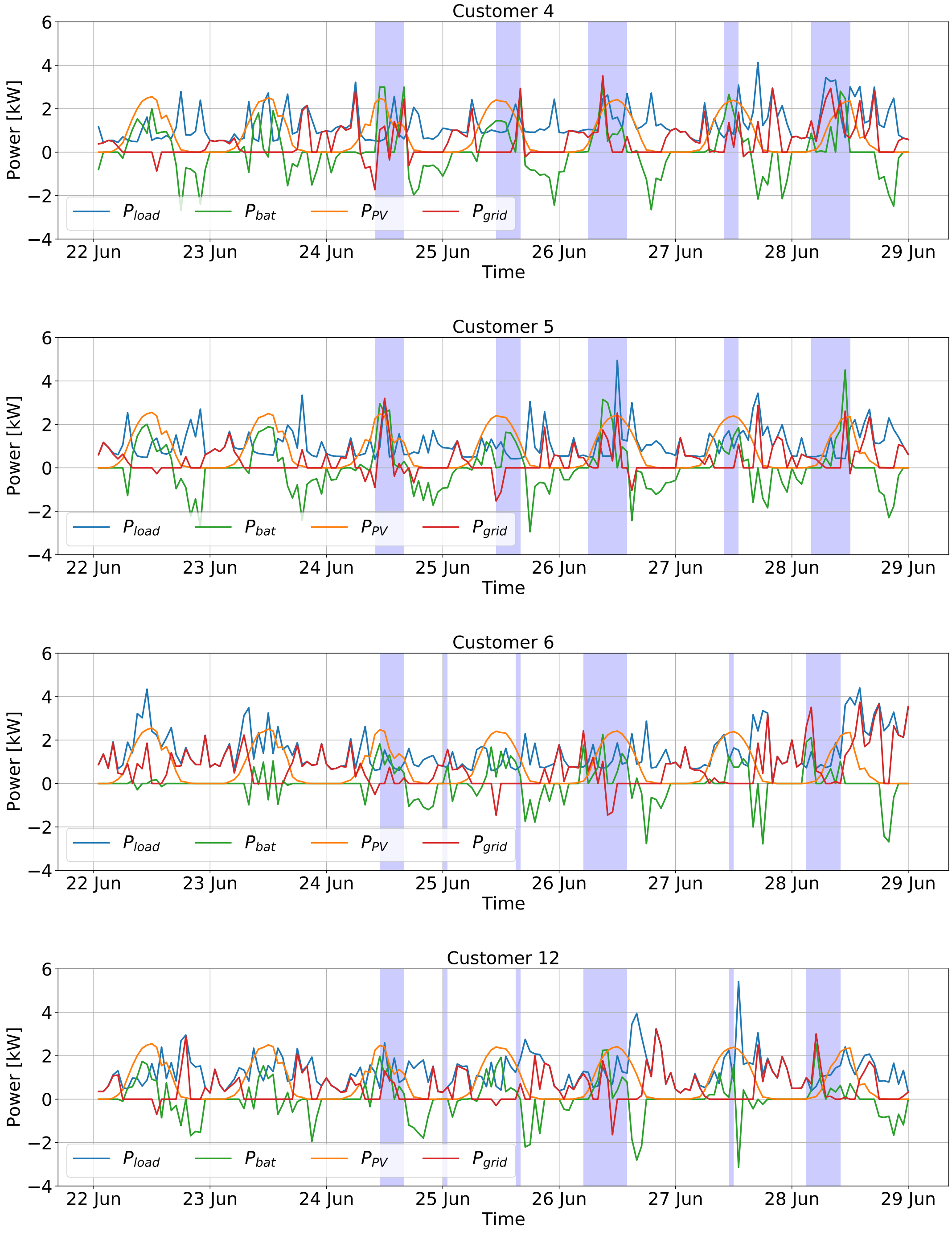
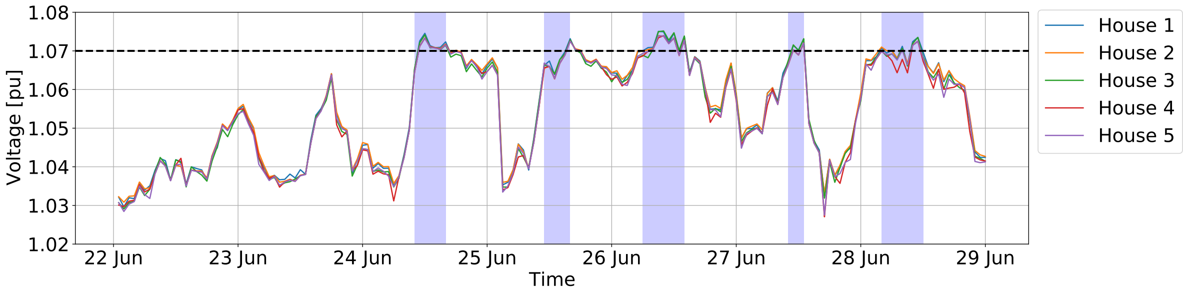
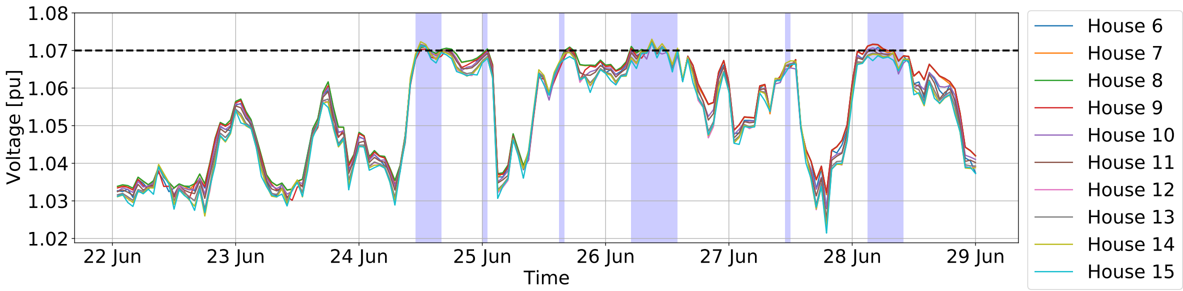


Figure B.1.1: *Performance of the four residential energy systems with the proposed distributed control strategy for the over-voltage scenario.*

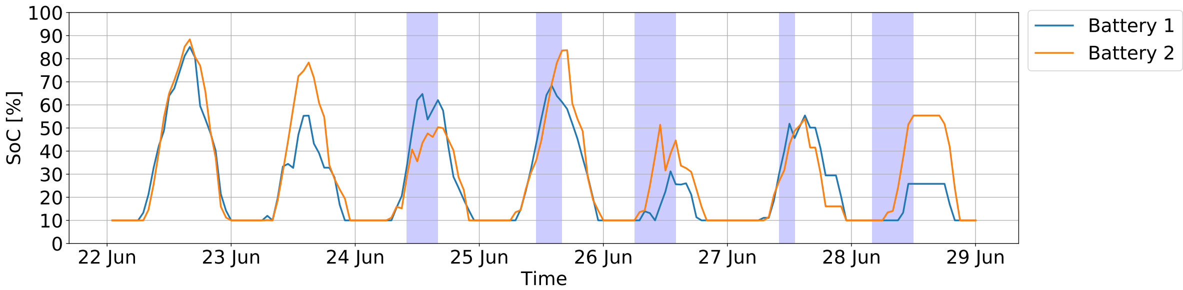


(a) *Radial 1*

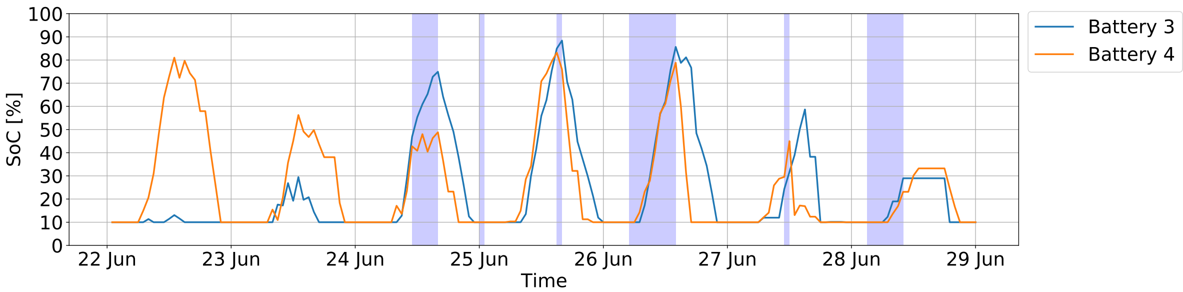


(b) *Radial 2*

Figure B.1.2: *(a) Voltage variations at the point of common connection at each house in radial 1 for the over-voltage scenario. The local controller was used to schedule the charging and discharging of the two BESS. The critical periods are marked with a blue color. (b) Illustrates the voltage variations in radial 2 with the same conditions as in (a).*



(a) *Radial 1*



(b) *Radial 2*

Figure B.1.3: *(a) State of charge variation of the two batteries in radial 1. The local controller was used to to schedule the charging and discharging of the two BESS for the over-voltage scenario. The critical periods are marked with a blue color. (b) State of charge variation of the two batteries in radial 2 with the same conditions as in (a).*

B.2 Under-Voltage Scenario

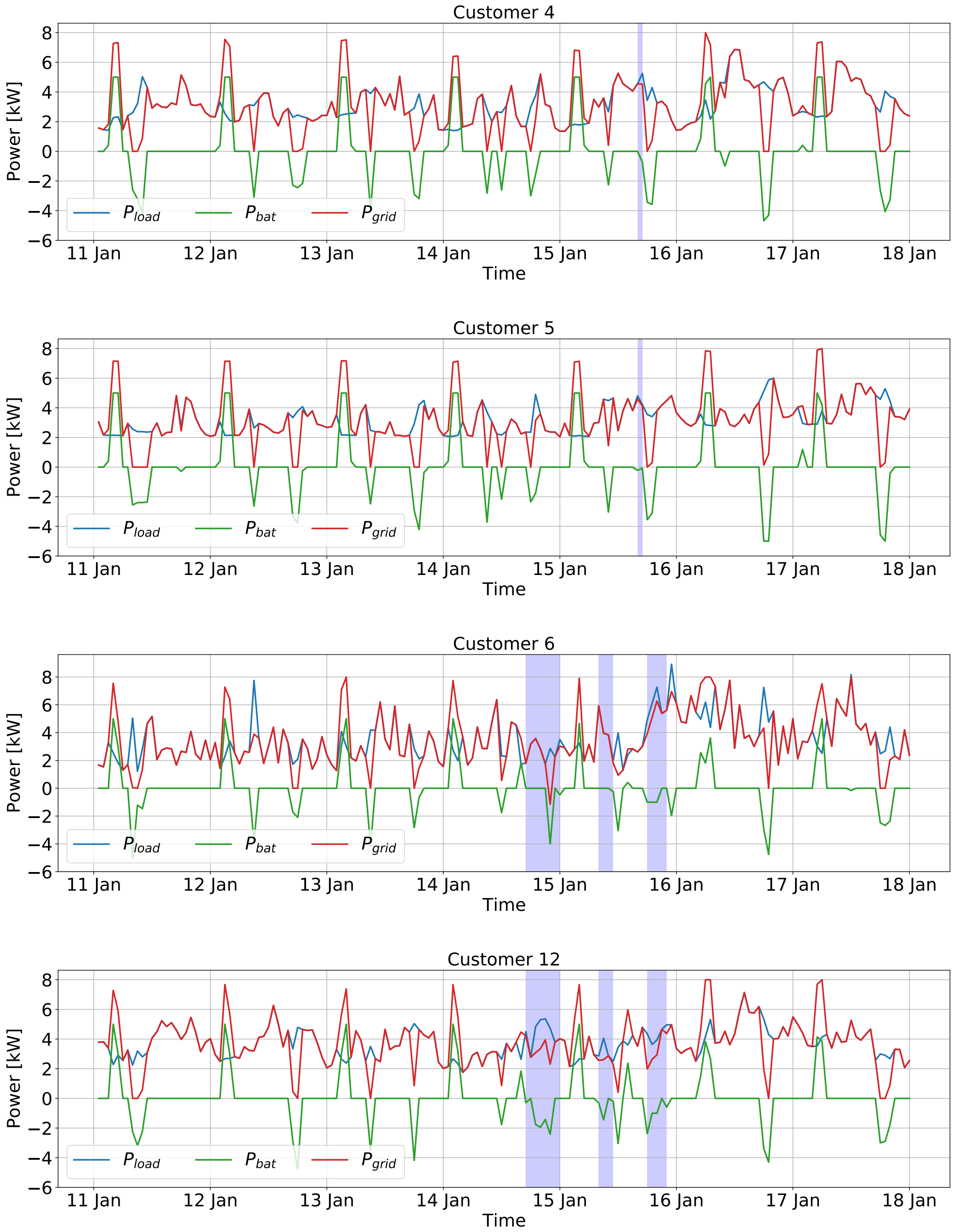
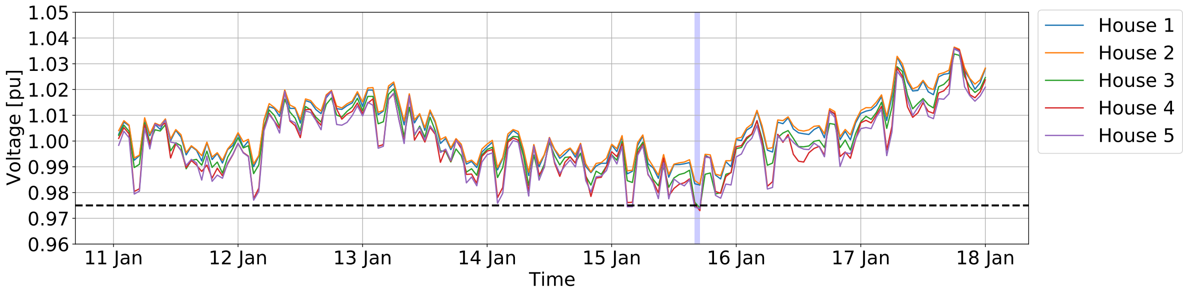
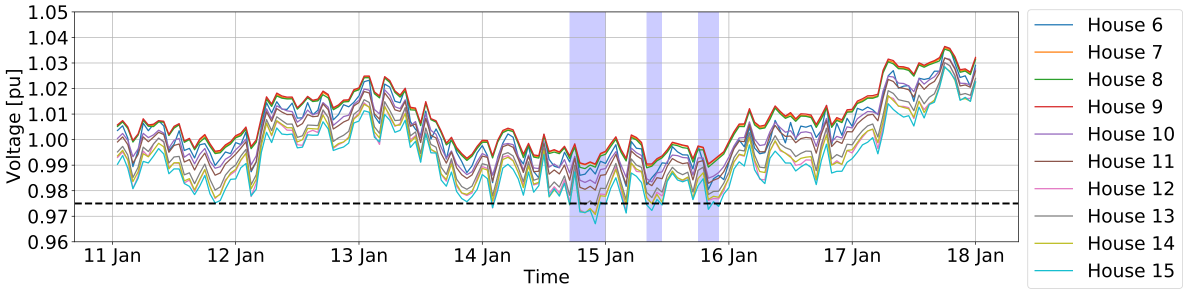


Figure B.2.1: *Performance of the four residential energy systems with the proposed distributed control strategy for the under-voltage scenario.*

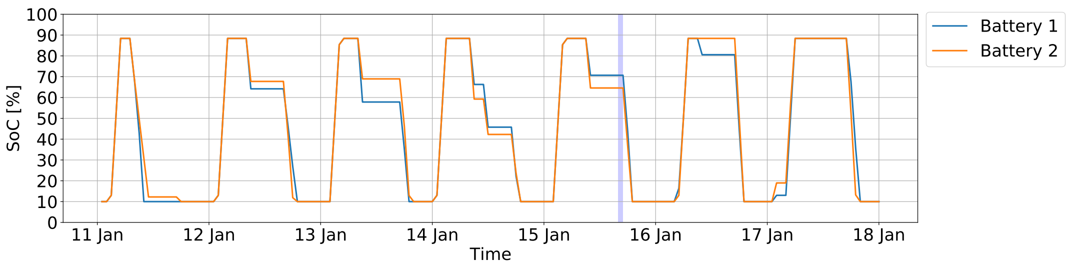


(a) *Radial 1*

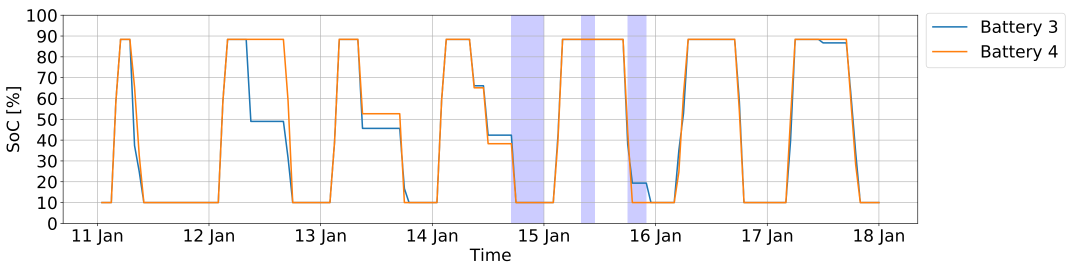


(b) *Radial 2*

Figure B.2.2: *(a) Voltage variations at the point of common connection at each house in radial 1 for the under-voltage scenario. The local controller was used to schedule the charging and discharging of the two BESS. The critical periods are marked with a blue color. (b) Illustrates the voltage variations in radial 2 with the same conditions as in (a).*



(a) *Radial 1*



(b) *Radial 2*

Figure B.2.3: *(a) State of charge variation of the two batteries in radial 1. The local controller was used to to schedule the charging and discharging of the two BESS for the under-voltage scenario. The critical periods are marked with a blue color. (b) State of charge variation of the two batteries in radial 2 with the same conditions as in (a).*

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