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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Interaction Strategies for an Optimal Grid Integration of Microgrids

Master's thesis in Energy and Environmental Engineering
Supervisor: Olav Bjarte Fosso, NTNU
Co-supervisor: Bendik Nybakk Torsæter, SINTEF Energi AS
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Preface

This master's thesis was completed in the spring 2019 at the Department of Electric Power Engineering and concludes our studies at the Norwegian University of Science and Technology, NTNU.

The thesis was suggested after we completed a specialization project within the same theme autumn 2018. We hereby want to thank our co-supervisor and representative from the research centre CINELDI lead by SINTEF, Bendik Nybakk Torsæter, for his helpful advice, fast response, and engagement for this subject. Professor Olav Bjarte Fosso, our supervisor, deserves our greatest gratitude for important guidance, academic input and help regarding the understanding of events. We are grateful to have been through a well working cooperation, both between ourselves and with our supervisors.

We would also like to thank Jonas Rudshaug for inspecting the thesis and helping us improve our figures.

In the end, we want to thank all our fellow students in the institute for interesting discussions and a great social environment through the last year of our study.

Trondheim, June 2019

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Abstract

A microgrid is a power system with clearly defined electrical and geographical boundaries which consists of loads, energy generation units and energy storage units. It is expected that if microgrids are operated appropriately, they can increase the reliability of the power system, postpone some grid investments and facilitate more renewable energy production. There are no clear guidelines regarding which role microgrids are going to have in the Norwegian power system. Many questions regarding how microgrids can be integrated into the present power system, how the interaction between microgrids and the system operator is going to be and which regulation strategies that must be implemented are unanswered.

Several elements regarding the integration of microgrids are studied in this master's thesis. A microgrid has the possibility to contribute with different ancillary services to the system operator. This thesis investigates which services that are suitable for microgrids and how they can be performed. Demand response programs are applicable for systems where the system loads can be controlled and can contribute to demand curve changes. Two different demand response programs, where the microgrid participates, are investigated in this thesis. Furthermore, regulatory challenges regarding different types of microgrid owners are addressed with some proposed solutions.

A model of a fictional 22 kV distribution power system is developed in Python by using the Pandapower package. A representation of a microgrid including energy generation from PV modules and wind turbines, a battery energy storage system, household loads and a hospital load is made and can be connected to the distribution system on a selected bus. Six different strategies chosen based on the findings in the literature study are established to test the impacts a microgrid can have on the distribution system with different strategies. The strategies and a base case are listed as follows;

- **Base case**: The microgrid is not connected to the distribution power system.
- **Microgrid generation**: The microgrid is connected to the distribution power system without using the battery.
- **Microgrid generation and storage**: The microgrid is connected to the distribution power system using a simple battery strategy.
- **Microgrid generation and battery regulation**: The microgrid is connected to the distribution power system using a voltage regulation strategy on the battery.
- **Microgrid regulates with all units**: The microgrid is connected to the distribution power system using a voltage regulation strategy on the battery and the generation units.
- **Microgrid with PBP strategy**: The microgrid is connected to the distribution power system using a price based demand response strategy.
- **Microgrid with Peak shaving strategy**: The microgrid is connected to the distribution power system using a peak shaving demand response strategy.

The simulations are conducted with weather data from three different days and with the microgrid connected to three different placements in the distribution network. A load flow is performed for every hour through those days for all the cases. This thesis examines and compares how all these different cases affect the voltage and line loading levels in the distribution system.

The results indicate that the operation of a microgrid can have a significant impact on a distribution power system and that an appropriate operation strategy can be essential to integrate a microgrid successfully. A voltage regulation strategy performed by a microgrid based on reactive power can have both positive and negative impacts on the voltage curves in the system. For lines with low R/X ratios, the voltage regulation will result in increased voltage profiles, while for high R/X ratios, the voltage regulation strategy will result in reduced voltage profiles. The voltage regulation strategies result in a negative impact on the line loading in the system for lines upstream of the microgrid. Furthermore, demand response can both benefit a microgrid and improve both the voltage and the line loading in systems when appropriate price signals are implemented. On the other hand, it can have a negative impact if local aspects are not considered in the price signals.

Sammendrag

Et mikronett er et geografisk og elektrisk avgrenset kraftsystem som inneholder laster, energiproduksjon og energilagringsenheter. Mikronett er forventet å blant annet kunne bidra til mer pålitelige kraftsystemer, utsettelse av nettinvesteringer og legge til rette for implementering av mer fornybar energiproduksjon. Det finnes enda ingen klare retningslinjer på hvilken rolle mikronett skal ta i Norges kraftsystem. Det er mange ubesvarte spørsmål rundt hvordan mikronett kan integreres, hvordan interaksjonen mellom mikronett og systemoperatøren skal være og hvilke reguleringer som må bli innført.

I denne oppgaven er flere elementer rundt integrering av mikronett studert. Et mikronett har muligheten til å bidra med forskjellige hjelpetjenester til nettselskap. Det er derfor studert hvilke tjenester som er mest passende for mikronett å bidra med og hvordan de kan utføres. Forbrukerfleksibilitet kan utnyttes i systemer med regulerbare laster, som vil være aktuelt for et mikronett. Ulike forbrukerfleksibilitetsstrategier kan endre lasten i et mikronett forskjellig, og to strategier er studert i denne oppgaven. Det er flere utforinger med tanke på lover og reguleringer som må løses før mikronett kan integreres. Utfordringene er studert med utgangspunkt i forskjellige eiere av mikronettet, og enkle forslag på løsninger er foreslått.

En modell av et fiksjonelt 22 kV distribusjonsnett er utviklet i Python ved bruk av pakken Pandapower. I samme modell er det laget en representasjon av et mikronett som inneholder generering av elektrisk energi fra solceller og vindturbiner, batterilagringssystem, husholdningslaster og sykehuslast. Mikronettet er laget slik at det kan kobles på ulike steder i distribusjonsnettet. Seks forskjellige strategier er valgt basert på funnene i litteraturstudiet. Strategiene er representert i modellen for å teste hvilke innvirkninger forskjellige strategier har på distribusjonsnettet. Strategiene og en grunntilstand er som følger:

- **Grunntilstand**: Mikronettet er ikke koblet til distribusjonsnettet.
- **Mikronettet genererer**: Mikronettet er koblet til distribusjonsnettet uten bruk av batteri.
- **Mikronettet genererer og lagrer**: Mikronettet er koblet til distribusjonsnettet med en enkel batteristrategi.
- **Mikronettet genererer og regulerer med batteriet**: Mikronettet er koblet til distribusjonsnettet med spenningsregulering fra batteriet.
- **Mikronettet genererer og regulerer med alle enheter**: Mikronettet er koblet til distribusjonsnettet med spenningsregulering fra batteriet og produksjonsenhetene.
- **Mikronett med prisbasert forbrukerfleksibilitetstrategi**: Mikronettet er koblet til distribusjonsnettet med pris basert forbrukerfleksibilitetstrategi
- **Mikronett med effektbasert forbrukerfleksibilitetstrategi**: Mikronettet er koblet til distribusjonsnettet med forbrukerfleksibilitetstrategi basert på kutting av effekttopper

Simuleringene er gjort med værdata fra tre forskjellige dager med mikronettet tilkoblet tre forskjellige plasser i distribusjonsnettet. Det er deretter kjørt en lastflytanalyse for

hver time gjennom dagene. Alle de forskjellige casene er analysert og sammenlignet for å se hvilke innvirkninger de har på spenningen og linjebelastningen i distribusjonsnettet.

Resultatene viser at driften av mikronettet kan ha stor innvirkning på et distribusjonsnett og at en hensiktsmessig driftstrategi kan være essensiell for å kunne integrere mikronett i dagens kraftsystem. Spenningsregulering basert på reaktiv effekt kan ha både positive og negative virkninger på spenningen i distribusjonsnettet. For linjer med lav R/X rate kan spenningsreguleringen gi økt spenning, mens for høye R/X rater vil spenningsreguleringen føre til enda lavere spenning. Spenningsreguleringsstrategiene har negativ innvirkning på linjebelastningene for linjer oppstrøms mikronettet. Det er erfart at forbrukerfleksibilitet-strategier som baserer seg på prissignal kan forbedre både spenningen og linjebelastningen i distribusjonsnettet hvis gode prissignaler er implementert. På den andre siden kan forbrukerfleksibilitet føre til større utfordringer i nettet om prissignalene ikke reflekterer når på døgnet det er lokale problemer.

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Abbreviations

AVR Automatic Voltage Regulator

BESS Battery Energy Storage System

BM The Balancing Market

CHP Combined Heat and Power

DER Distributed Energy Resource

DG Distributed Generation

DSO Distribution System Operator

ESS Energy Storage System

GR Generators Rescheduling

IBP Incentive-Based Program

LEC Local Energy Community

MBP Market Based Program

NVE The Norwegian Water Resources and Energy Directorate (Norges vassdrags- og energidirektorat)

OED Ministry of Petroleum and Energy (Olje- og energidepartementet)

PBP Priced Based Program

PCC Point of Common Coupling

RMS Root mean square

ROM The Reserve Option Market

SoC State of Charge

SVC Static VAR Compensator

TSO Transmission System Operator

USEF Universial Smart Energy Framework

Chapter 1

Introduction

1.1 Motivation

The power system structure is changing from a traditional system with large energy production units placed in the transmission system, to a structure with more decentralized generation. When a lot of distributed generation is implemented in a power system, it can have a significant impact on the system. It is, therefore, necessary to have clear strategies and regulations considering the implementation. To assemble nearby loads with their accompanying distributed generation to microgrids or other local energy communities can be one strategy to orderly structure the implementation.

It is an ongoing trend that the electrical power demand from consumers is increasing due to digitization, electrification and development of new technologies. Especially, the electrification of the transport sector and the fast growing amount of electric vehicles in Norway. This can cause significantly higher local and regional power demand peaks that might lead to different challenges for the system operator. Some of these challenges might be higher voltage drops, higher line and cable losses, decreased network capacity and congestion problems. The Norwegian power system is expected to go through a massive network investment in the near future where 145 billion NOK is predicted to be invested until 2026. A microgrid that utilizes its power flexibility for the benefit of the grid can be one strategy to postpone some of these grid investments [13–15].

1.2 Background

This master's thesis is written in cooperation with and is a part of FME CINELDI. It is one of the centres for environmentally-friendly energy research in Norway, lead by SINTEF Energy AS in cooperation with NTNU. The objective of CINELDI is to enable a cost-efficient realization of the future flexible and robust electricity distribution grid. CINELDI is organized in six Work Packages (WP), where each focus on different aspects of Intelligent Electricity Distribution. This master's thesis is a part of Work Package 4 (WP4), which has the objective to develop concepts, technologies and models for microgrids and their interaction with the distribution system.

The main plan for this master's thesis is given by CINELDI with suggested subjects and is divided into two main parts;

- Investigate different aspects related to integration of microgrids in distribution systems, in particular related to interaction between microgrids and DSOs.
- Explore how the grid-support capabilities of microgrids should be utilized in the future smart grid, and how this functionality should be incorporated in the demand management systems of the DSO.

The findings and possible useful approaches and models developed in this thesis are supposed to be further investigated and developed in WP4. Important aspects of the suggested subjects from CINELDI, that can be further used in the Work Package if they are solved appropriate, are listed as follows;

- This master's thesis can illuminate important aspects regarding the integration and regulation of microgrids, and increase the knowledge regarding challenges and possible solutions in the Work package. It can also be convenient to get a new point of view on subjects that are already explored.
- This master's thesis can make suggestions for solutions on different challenges, which can be further investigated and tested.
- Reasonable approaches developed in this thesis can be inspiration for further development of approaches.
- Developed simulation models in this thesis can be reused or used as inspiration for further development of simulation models for distribution systems and microgrids.

1.3 Scope and researches topics

This master's thesis focuses on how a possible interaction between a system operator and a microgrid might unfolded. The interaction is investigated through two different approaches; 1) theoretical investigation of regulation solutions and 2) through a simulation model. The model is made using Pandapower in the programming language Python and aims to investigate the impacts a microgrid might have on the distribution system. The goal is to disclose the ability of a microgrid to support the distribution system operator by providing different services. In this master's thesis, voltage regulation with reactive power compensation and two different demand response programs, peak shaving and price based program, are investigated as possible services. Their effect on the voltage profiles and line loading will be presented.

The research of the development of microgrids can be divided into different aspects. There are a lot of challenges regarding the implementation of microgrids and how they are going to be operated. The following topics are addressed in this thesis;

- What is a microgrid, and which advantages and disadvantages can be experienced due to the implementation of microgrid systems?
- Some important types of ancillary services a microgrid can provide to support the system operator. Which of these services are important to a distribution system operator?

- Which challenges regarding the regulation of microgrids exist, and which solutions can be applicable?
- Which role can the microgrid have in the power system, and which role will the DSO have regarding the microgrid?
- What is the effect on the voltage profiles in a distribution system of different voltage control strategies applied by the microgrid?
- How can different demand response strategies implemented in microgrids affect the distribution system.
- How will different weather conditions affect the effect of the voltage control and demand response strategies?
- How will the line loading in the distribution system be affected by the voltage control and demand response strategies?
- What is the best connection point of a microgrid in a distribution system regarding different aspects as; voltage profiles, line loading, active and reactive power losses?

1.4 Limitations

This thesis is completed within a limited amount of time where the focus of the research and which elements to be tested have been decided during the writing period when more knowledge about the theme was gained. This, in addition to the fact that the development of the test system has taken a lot of time, has caused that the analysis have been done with certain limitations and simplifications. The choices that are made will have impact on the results and how the results are presented. Some important simplifications and approaches to handle limitations are listed as follows;

- **Planning phase** - The planning phase of the microgrid is not taken into account. This means that the authors have not considered where the microgrid can be built.
- **One unit representation** - The operation within the microgrid is not considered in this thesis, meaning that the microgrid is seen as one single unit from the system operators point of view.
- **Development of network** - No real life data is received nor used to develop both the microgrid and the distribution system. Necessary assumptions and choices regarding the structure and lines are done to make a representation of the system. The power system can therefore differ from a real power system.
- **Development of production profiles** - The development of the production profiles is based on one weather station in Norway. The obtained weather data for this measuring point might therefore not illustrate the most optimal place to implement distributed generation as wind and solar power. The obtained data only illustrates the weather data for three days.
- **Development of load profiles** - The load profiles are only based on high demand hours and might therefore deviate from the actual demand that would occur at the

investigated days. The placements of the different load customers are not based on theoretical perspectives, but done to obtain a comprehensive load demand.

- **Strategies** - The investigated scenario strategies only represent some possible strategies a microgrid can follow. When an alternative to a grid investment for a distribution system is planned, more strategies should probably be investigated.
- **Lack of pattern analysis** - This thesis will only investigate three different scenario days during a year. Therefore, periodical data and patterns of the strategy will not be enlightened. Thus, the result will only represent the pattern for typical condition days as investigated in this thesis and not obtain an overall overview the implemented strategy will perform on a distribution system on longer term.

1.5 Topic structure

The rest of this master's thesis is structured into different chapters elaborated as follows;

- *Chapter 2: Microgrid* - This chapter aims to give an overview of the microgrid concept. The concept is defined and explained through different sections for motivational and understanding perspectives.
- *Chapter 3: Review of power system aspects relevant for microgrid integration* - This chapter is divided into three main sections. First, an introduction to the Norwegian power system and market is presented. Second, theoretical aspects regarding ancillary services a microgrid can contribute are discussed. Third, the demand response aspect is explained and the potential of demand response in Norway is elaborated.
- *Chapter 4: Interaction between microgrid and DSO* - This chapter presents some regulatory questions and aspects regarding an interaction between a DSO and a microgrid. A simple possible strategy is discussed.
- *Chapter 5: Model construction* - This chapter aims to present the construction of the simulation model. The chosen tool is introduced and the different methods for calculating data will be elaborated.
- *Chapter 6: Development of test scenarios* - This chapter explains deeper the different scenarios the simulation model investigates. Some algorithms regarding the execution of the scenarios are explained.
- *Chapter 7: Analysis of results* This chapter presents the results from the simulated scenarios. The presented results are discussed.
- *Chapter 8: Conclusion and further work* - The last chapter contains the conclusions of the work and possible further work.

Chapter 2

Microgrid

This chapter introduces microgrids as alternative power systems. The chapter will include the microgrid definitions, the assembling of a microgrid and microgrid control. Major parts of this chapter are based on the literature study provided in the project report *Microgrids: An Overview, Integration Problems and Solution Strategies* [16] written by the authors. A more detailed description of microgrids and some problems related to the integration of microgrids can be obtained in the project report.

2.1 Microgrid definitions

A microgrid can be defined in different means. Two acknowledged definitions are listed as follows [17];

The U.S. Department of Energy definition:

"A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."

The CIGRÉ C6.22 Working Group definition:

"Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while is landed."

Both definitions characterize a microgrid as a distribution system where interconnecting loads are supplied by distributed energy generation while monitored and controlled by a controllable entity within a defined electrical boundary. The definitions exclude some important factors necessary to address for planning and building a microgrid such as; the size of the microgrid and the distributed energy resources (DER), what type of technology that should be used, the reliability, environmental aspects and economical aspects.

Microgrids are small-scale power systems that introduce bidirectional power flow, which means that there is a two-way flow in the aspect of current, voltage and power. This makes a microgrid an active distribution network since the generated power in the system is supplied from other sources than only the national grid as in a traditional power system [18]. Furthermore, both definitions present the ability of the microgrids to operate in two different modes:

- Island mode
- Grid-connected mode

2.1.1 Island mode

An isolated microgrid does not have any electrical connection to the overlaying network and will, therefore, operate as a local power system independent of the main grid. During this operation, the microgrid needs to provide power with suitable voltage and frequency control as well as meet the power balance in the microgrid system to feed the local loads. The necessity of high penetration of generation to supply the load and a reliable and good control strategy is major for the microgrid to handle isolated operation. [19]

2.1.2 Grid-connected mode

A microgrid can be operated directly connected to the main grid as one controllable unit. The connection point between the microgrid and the power system is often called the point of common coupling (PCC) and can be seen in Figure 2.1. The PCC is often illustrated as a circuit breaker which is operated to connect and disconnect the microgrid from the main utility grid [18]. If the switch is open, the microgrid operates in island mode. The most common reasons for disconnection of a microgrid are unplanned faults and outages in the main grid or the microgrid. For a reliable and secure transition, a fast responding switch is necessary [1].

The microgrid can contribute the main grid with different services while it is connected [19].

- *The total load demand* - When connected to the main grid, a microgrid can contribute with transferred power to help the main grid meet the total load demand.
- *Active and reactive power generated by the DERs* - The microgrid can contribute with active and reactive power injection through the DERs and support with power factor correction and voltage control at PCC.
- *Voltage and frequency response* - In case of power imbalance in the main grid, the microgrid can contribute with voltage and frequency response to help the main grid encounter power balance.

2.2 The composition of a microgrid

A microgrid is defined as a power system, including different elements within a defined electrical boundary. A general DC microgrid structure is illustrated in Figure 2.1, which includes important components found in a boundary defined microgrid system. An AC microgrid would require less converters for the AC production and DC/AC converters for the DC production units. The principle is still the same. The main elements a microgrid is assembled by are listed as follows:

- Energy generation
- Energy storage
- Loads
- Control and communication

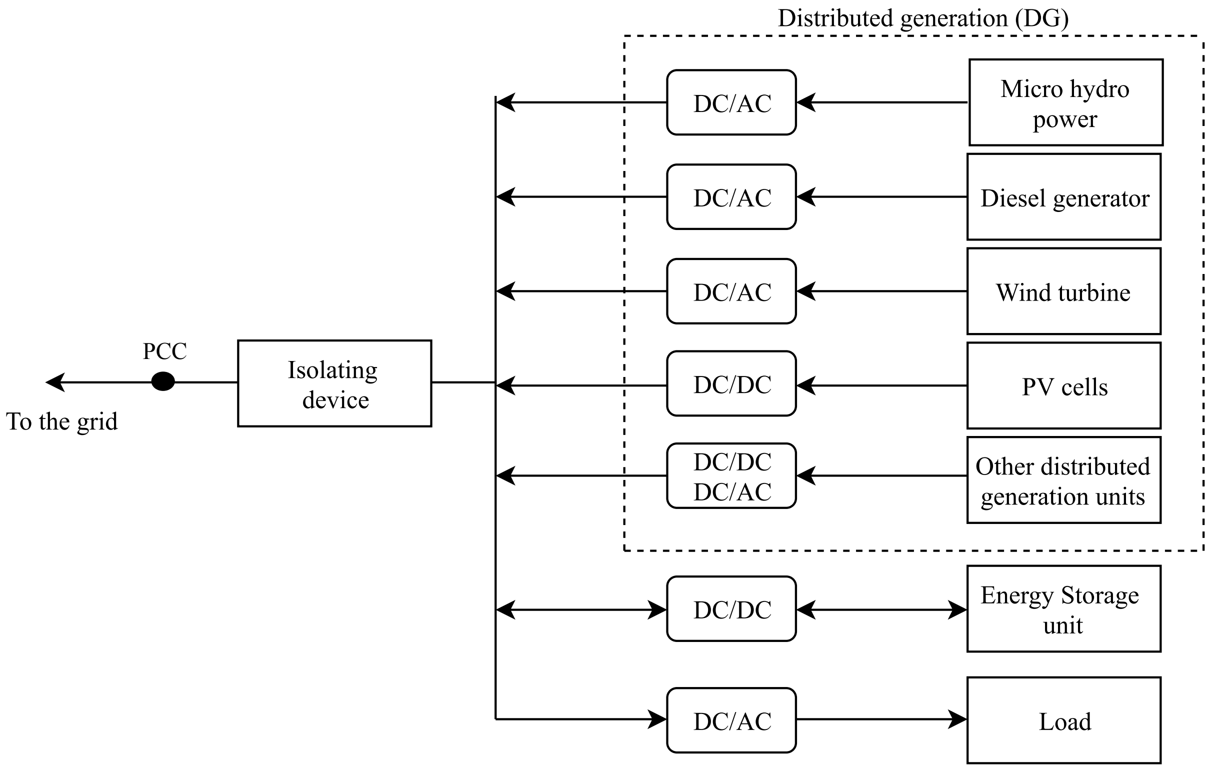


Figure (2.1) General DC microgrid structure [1]

2.2.1 Energy generation

Different aspects lead the energy generation towards more renewable energy generation. Environmental perspectives aiming to reduce climate gas emissions are in focus. Technology related to renewable generation is getting cheaper and more advanced and, therefore, obtain better premises to compete with conventional power plants. A predicted higher energy demand will result in the necessity of expanding the production of energy, leading to a focus on investment [20–22].

The energy generation in traditional power systems are often developed to produce a large amount of power and therefore decentralized located compared to the supplied loads. This type of structure is not suitable for a microgrid system where both the loads and the power sources are placed locally, resulting in non-conventional distributed generation (DG) [18]. A microgrid is greatly depended on DG when it is operated in island mode to meet the load demand in the microgrid.

The most common DERs in a microgrid are wind power, solar power, combined heat and power (CHP), small-scale hydropower and fuel cells [18]. The reliability of these renewable energy resources are highly dependent on weather and availability and can, therefore, result in power imbalance and voltage and frequency problems in a microgrid system if the generation is to low. To handle this problem, conventional generation such as diesel generators can be placed in a microgrid to help during low production hours for the renewable energy resources and/or energy storage systems can be installed to store energy when the penetration of wind and solar is high but the demand is low.

2.2.2 Energy storage

The main function of energy storage in a microgrid system is to store energy when the penetration of renewable energy resources is high and the demand is low, and inject power to the system when the penetration is low and the demand is high. The advantages of installing energy storage are to increase the security of supply, secure consistent power balance, improve the system reliability by performing voltage and frequency control and decrease expenses and peak demand [23–26].

The most discussed energy storage for microgrid system applications are batteries, super capacitors, hydrogen based storage and flywheels [27].

2.2.3 Loads

A typical microgrid consists of locally placed loads to minimize power losses. The loads can be divided into two different load types, 1) prioritized and 2) flexible loads. The prioritized loads need to be supplied at all time. Some examples are hospitals and banks. Flexible customers, which usually are categorized as the normal residential customers and some business customers, can be shedded during necessary times e.g. during faults, blackouts etc. [28, 29]. Furthermore, customers can be divided into passive and active customers. The active customers can also be termed as prosumers, and they produce and deliver energy to the grid. According to NVE, a prosumer in Norway can supply the grid with power below 100 kW [30, 31].

2.2.4 Control and communication in microgrid systems

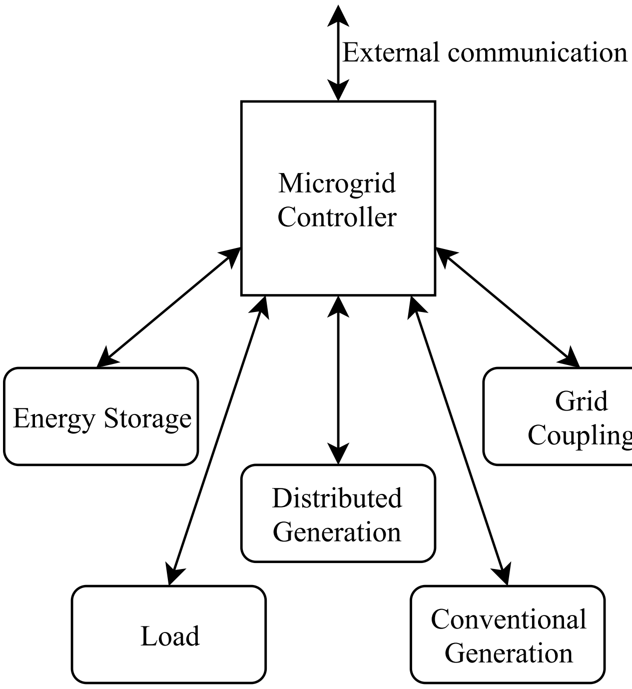
A microgrid with DERs will introduce some new technical challenges which are important to address when planning and designing control and protection schemes for the microgrid system [32]. Some DERs as wind and photovoltaic generation units produce fluctuating power resulting in a more complicated control strategy than the control methods used in the conventional power system [33]. A microgrid control system is defined by IEEE Standard for the Specification of Microgrid Controllers as [34]:

"A system that includes the control functions that define the microgrid as a system that can manage itself, operate autonomously, and connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services; it includes the functions of the microgrid energy management system (MEMS); it is the microgrid controller if implemented in the form of a centralized system."

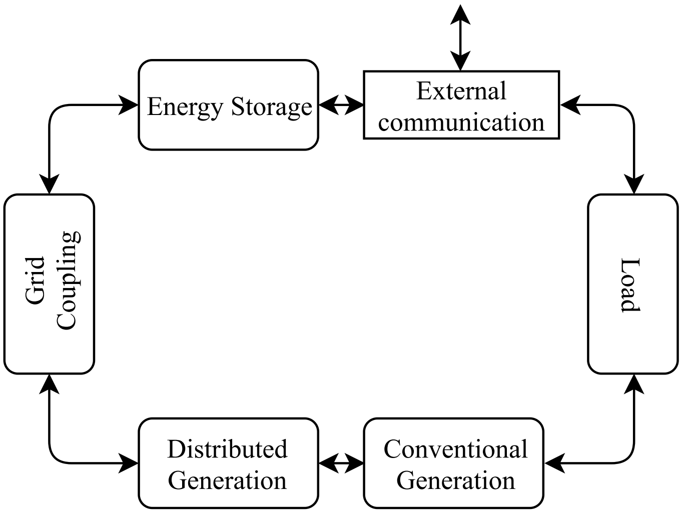
The IEEE definition states that a microgrid control system should be able to;

1. Operate in both modes.
2. Perform automatic transition between the different operating modes.
3. Resynchronise with the main grid again after disconnection.
4. Provide with ancillary services to support the grid.

There are two different approaches for the microgrid control system architecture, centralized and decentralized control. The centralized control approach consists of one central controller with two main functions; 1) communicate with the main grid and the grid operator, and 2) exchange information with other local controllers in the microgrid and process the information. This control architecture leads to all decisions being generated in one centralized controller [33]. Decentralized control contains local control systems for the different devices in the microgrid, making each component independent and the strategy obtains locally generated decisions. Each component controller is connected to each asset in the microgrid to prevent trouble in regards to absence of central control making and lack of information flow. This obtains a chain of information flow between the different peers. [2]. Figure 2.2 illustrates centralized and decentralized control architecture.



(a) Centralized control architecture



(b) Decentralized control architecture

Figure (2.2) Example of centralized and decentralized control architecture, inspired by [2]

2.3 Advantages

An overview of some important advantages regarding integration of microgrids are presented as follows;

- **Security of supply** - A microgrid might provide greater security of supply to its members and especially the critical loads due to the possibility to operate in two operation modes. When a fault or disturbance occur in the main utility grid, the microgrid is able to operate in island mode and supply the loads for a period of time from the DERs and energy storage systems. [35]
- **Reduced power losses** - When microgrids have local energy generation, a greater part of the generation is done close to the loads. This leads to less power loss due to the short travel of energy. Energy produced and consumed at distribution level does for instance never need to be transferred through the transmission system.
- **Reduced environmental impact** - With a focus on using renewable energy sources in the DERs, microgrids and other local energy communities with local generation contribute to that a greater part of the electricity production is renewable.
- **Reduced energy cost** - The DERs in a microgrid can be utilized to provide economic benefit for the members. That can either be in the form of revenue from power sales, reduction of net consumption or reduced network tariff.
- **Ancillary services delivered to the utility grid** - DERs can be utilized to improve the signals in the utility grid and deliver services that will be social economically beneficial. Some important ancillary services are voltage control, congestion management, frequency regulation, peak shaving and harmonic compensation. The relevant services and their features are explained in Section 3.2.
- **Postponed grid investments** - By having local energy production and utilizing the flexibility of storage systems and controllable loads, a microgrid can postpone grid investments. The advantage can especially be significant when the microgrid is established in a remote area with a need for more transmission capacity or replacement of some grid units.

2.4 Disadvantages

Some important disadvantages and problems regarding integration of microgrid systems are presented as follows;

- **Harmonic components** - High penetration of power electronic interference results in an increase of harmonic components in the system. The harmonic components result in current and voltage signals with frequency regions that deviate from the fundamental frequency obtained in a pure sinusoidal waveform.
- **Low inertia in the system** - In [23], this problem is investigated when the microgrid is disconnected from the stiff network. The result illustrates that the microgrid obtains problems when the generation is only based on distributed generation with power electronic interference since the synchronizes coupling between the system and the generators is lost.
- **Bidirectional power flow** - The conventional distribution feeders and transformers are not designed for the bidirectional power flow. A result of chaining the distribution system components might lead to voltage instabilities, fault currents and problems regarding the protection coordination. The protection scheme is also problematic to design for a microgrid that should operate in different modes.
- **Lack of standardization** - Due to the early stage of deployment different problems might arise regarding different aspects as integration problems, modelling and coordination between elements and components not matching the system and therefore unable to carry out the necessary functions. For new and fast growing technologies such as microgrids, the need for standardization is important to prevent failures and ensure safe operations. The work towards microgrid standardization is elaborated in [36].

Chapter 3

Review of power system aspects relevant for microgrid integration

This is a theoretical chapter aiming to enlighten important aspects that will affect the integration of microgrids into the power system. The chapter presents how the power system and the power market in Norway are organized, with the purpose of presenting an overview of the present systems without customization for microgrids. An overview of ancillary services and demand response is given to present thoughts on which role a microgrid can play in a society. The scenarios and features of the microgrid tested in this thesis are based on the obtained knowledge from this chapter.

3.1 The Norwegian power system

In order to develop models for microgrid interaction, an understanding of the interaction and scope of the Norwegian power system is necessary. Thus, it is important to know how the Norwegian power system is structured and assembled. This section will focus on introducing and describing the Norwegian power system with motivation on overview, structure and market. The content might be necessary for further reading and understanding of the focus, goal, scope and direction of this thesis.

3.1.1 The Norwegian power system structure

The Norwegian power system can be structured into three different levels, 1) the transmission system, 2) the regional system and 3) the distribution system. Table 3.1 contains the different voltage levels in the respective grid levels.

Table (3.1) Voltage levels for respective grid systems [8]

Grid level	**Voltage level [kV]**
Transmission system	420, 300 and (132)
Regional system	132, 110, 66, 47 and 33
Distribution system	22, 11, 0.4 and 0.23

The transmission system

The transmission system in Norway represents the highest voltage levels in the grid (ref. Table 3.1), and is mainly constructed as a meshed network. Large production entities are often connected to the transmission system. In Norway, the transmission system is owned by Statnett SF, which is the Norwegian transmission system operator (TSO). Statnett is a state enterprise and owned by the Norwegian government by the Ministry of Petroleum and Energy (OED) [37]. The main task provided by Statnett is to ensure power balance in the power system and by that have the responsibility for the superior management and control of the Norwegian power system [8].

To secure frequency quality, a system operation agreement in the Nordic power system aims to keep the system frequency in the boundary of 50 ± 0.1 Hz [38]. The system administrator (Statnett in Norway) is in charge of fulfilling this responsibility and by that control the primary, secondary and tertiary control in the power system.

The regional and distribution system

The regional system consists of the medium to high voltage levels where 132 kV and 66 kV voltage levels are most commonly used. The primary task of the regional system is to be the transferring connection between the transmission system and the distribution system. Sizable production units and loads as larger industrial consumers are primarily linked to the regional system. The distribution system contains the medium to low voltage levels and transfers the power to the consumers often through radial constructed networks. Some smaller production facilities might be connected to the distribution system [8]. The regional and distribution systems in Norway are divided into different boundary zones based on geographic location and ownership. In Norway there are approximate 123 grid companies termed distribution system operators (DSO) (Statnett is excluded from this number) [39].

3.1.2 The DSOs area of responsibility

The normal company structure for a DSO in Norway is corporation, but there are also DSO companies that are structured as cooperative enterprises and municipal enterprises. The DSO companies have a natural monopoly and responsibility of the operation of the regional and distribution grid located inside their geographical boundary. By the Norwegian energy act §3-3 and §3-4, DSOs are required to connect new customers to the network and supply energy to the consumers inside its geographical boundary [39–41]. The natural monopoly prevents the customers to freely choose between DSO companies, which means that the DSO needs to maintain neutrality and protect the customer [42].

By the Norwegian energy law §4-6 and §4-7 [41], DSO companies with more than 100 000 customers, production companies and electrical energy sales must be corporately distinguished. It means that they need to have independent and separate legal entities. Furthermore, the DSO companies and competitive entities have to be functionally separated, meaning that the management needs to be separated. In 2016, the Norwegian Parliament agreed on changing the law to only require the functional separation for DSO companies with more than 10 000 customers, which will take effect the 1st of January 2021 [43]. The exemption from the functional separation for DSO with less than 10 000 customer must be implemented by a new legislative amendment.

Energy consumers pay a tariff to the DSOs for providing the customers with energy and maintenance of the network. The DSOs revenue is based on a yearly amount established by the Norwegian Water Resources and Energy Directorate (NVE). This income aims to cover the operational costs of the network and reasonable gross and might vary for different DSO responsibility areas [44]. NVE also decide which parts that are going to be included in the tariffs and the minimum share of each part. The network tariff consists of a fixed part and a part based on the energy consumption.

The voltage quality is an important factor in ensuring the quality of the supplied energy and preventing destruction of electrical appliances. The voltage quality can be divided into three main parts. According to [38], these three parts are in Norway; 1) the frequency of the voltage, 2) the root mean square (RMS) value of the voltage and 3) the voltage waveform. The frequency is set and balanced by the TSO while the RMS value and voltage waveform are local measurements measured and operated by the grid owner for the given measuring point (Statnett in the transmission system and the DSO for regional and distribution systems). The DSOs are required to continuously measure the system voltage and report the data to NVE. The allowed variation of the voltage is 10 % of the nominal voltage measured as an average over one minute [45], which is ensured through §3-3 in the Norwegian delivery regulation [46]. In high voltage distribution networks, the voltage deviation should lie within a limit of 7 %, including the step changing of the transformers. The deadband of the step changer in a transformer is roughly 2 %, giving a limit of 5 % in the rest of the high voltage distribution network [47]. Meaning that the maximum variation of the voltage in each bus in the high voltage distribution network is 5 % through one year.

Network investments

It is predicted that a total of 145 billions NOK will be invested in the power grid until 2026 where 28.5 billions are predicted as an investment requirement in the high voltage distribution system until 2023 [14, 15]. Network investments are necessary due to various factors such as; preventing future blackouts, repairing components after damage, replacing old components near the end of their operational lifespan and increasing transmission and equipment capacity to ensure the power supply by expanding and improve the network.

The two reports developed by Vista Analyse and Asplan Viak [48, 49] investigate potential alternatives to network investments and examine possible actions to prevent network investments. Some discussed alternatives to network investments are; local power production, the use of batteries, smart management and efficiency improvements of power transfer. The normal situation regarding the question of network investment is related to possible future developments, especially concerning increasing load demand that might result in capacity problems. This problem might be solved using alternative strategies that introduce better and cheaper solutions than the network investment alone. It is therefore important for a DSO company to analyze all the possible strategies that might help solving the network problems.

The report [49] examines seven different initiatives as alternatives to network investments. Another option is the implementation of distributed generation (DG) and microgrids. A DG and microgrids with DG and energy storage can contribute with active power to the system and help with voltage regulation and therefore support the main distribution system in the case of high demand hours and ease the capacity problems. In [50], microgrids are investigated as an economical alternative to underground cabling, which might be costly for the DSO. In [51], the microgrid impact on medium voltage system regarding optimal network planning is examined and aims to illustrate the possible savings a microgrid can contribute with to the DSO company.

3.1.3 Smart meters and smart meter data hubs

The Norwegian Water Resources and Energy Directorate (NVE) decided in 2011 that the network companies have to install a smart meter at every measurement point within the 1st of January 2019 [52]. The smart meters are able to measure real-time energy consumption down to 15 minutes granularity and can therefore give the customers a better overview of their consumption and enable automatic regulation of the consumption pattern. To obtain more accurate billing, the per hour energy consumption is submitted to the DSO. That enables time of use pricing, and the DSO can use the data to operate the grid more effectively [52].

The data established from the smart meters are secured through a guide about smart meter security, established by NVE [53]. This guide aims to lead the DSOs to handle the data and privacy policy according to Norwegian law. The customer will have jurisdiction over their own smart meter data, but the DSOs have the right to gain access to the data required to calculate the billing of the customer consumption. To obtain an efficient and secure exchange of smart meter data, Statnett is required by NVE to develop a smart meter data hub termed ElHub [54]. The ElHub is a centralized IT system for storing historical metering values and customer data. The implementation of ElHub ensures that all the market participants only have to communicate with one data management entity. DSOs provide daily metering and meter point data to the ElHub, while the power suppliers provide customer data for each metering point. With a centralized data hub, it will be possible for DSOs to reduce customer management costs considerably, and third party access to historical consumption data can effectively be standardized [55].

3.1.4 The Norwegian power system market

The Norwegian power system market consists of the wholesale market, the retail market and different reserve markets. This section describes the markets and how they are managed.

Wholesale market

The wholesale market is open, joint and managed by Nord Pool. Nord Pool is owned by the transmission system operators in the Nordic and Baltic countries and is responsible for both physical and financial trade. The wholesale market consists of the day-ahead market and the intraday market. In the day-ahead market, the spot prices for each hour the following day are decided. Nord Pool operates the day-ahead market for the Nordic countries as well as Estonia, Latvia, Lithuania and the UK. The buyers, mainly power suppliers, reports how much they are willing to pay to meet the demand the following day. The sellers, power producers, report how much energy they can deliver to which price. Nord Pool calculates the prices based on the power demand and supply bids. Different price areas might occur due to the costs of transmission constraints. Norway is divided into five different areas that have different prices when the transmission capacity between them gets constrained. [56]

The intraday market is covering the Nordic, Baltic, UK and German markets. It supplements the day-ahead market to secure the balance between supply and demand in the power market. It is a continuous market where the trading takes place until one hour before the delivery. The market is becoming increasingly important as more unpredictable and non-dispatchable power production, such as wind power plants, are installed. [57]

Reserve markets

Primary, secondary and tertiary reserves are acquired through market solutions to deal with imbalances. Generators, consumers and grid companies can deliver reserve services, where the TSO is the only buyer [58]. The primary reserve market is carried out in both a weekly and a day-ahead auction. The offer is hourly based and must be at least 1 MW [59, 60].

The secondary reserve market is carried out by a weekly auction, where the bids are between 5 and 35 MW. The secondary response is activated evenly between all the providers in the Nordic countries. A common secondary reserve market for the Nordic countries for both buying and activating reserves is under construction. [61, 62]

The tertiary reserve market in Norway is divided into the balancing market (BM) and the reserve option market (ROM). BM is used for up and down adjustments in real time and is based on bids from producers and consumers. The minimum quantity offered must be 25 MW and be delivered for one hour. ROM is developed to make sure that there always are sufficient balancing reserves available. Providers get paid in advance to have capacity available if it is needed. [63, 64]

Retail market

The Norwegian retail market covers end users, mainly households and business consumers, that purchase electricity through a retailer [65]. The energy price in the contracts between the power supplier and the consumers can be set in three different ways. It can be set as a fixed price, which will be valid in a predefined period. One year is a typical period for the contract. The price can also be set as a fixed price that can be changed during the period of the contract. The supplier then have to inform about changes at least 14 days in advance. The last method is to have a floating price that are based on the day-ahead price from the wholesale market. When the electricity price is based on the day-ahead price, the customers normally pay the average day-ahead price for the actual month and an additional payment. When the smart meters are installed, the power supplier also has the opportunity to make real-time pricing contracts [66].

Prosumers

Prosumers can sell their surplus energy to the network companies which decides if they want to buy energy. The prosumers then pay a simplified network tariff for the energy they export. Another possibility for the prosumer is to make an agreement with a retailer to sell the surplus energy. Installation of smart meters and Elhub is necessary to have the possibility to sell power to a retailer. [30]

3.2 Ancillary service

3.2.1 Microgrid as an ancillary service

In a power system, the balance between load and production is essential to maintain a reliable and steady grid. An ancillary service aims to maintain the proper flow and direction of the electrical power in the grid, ensure power balance in the system and help the system to recover from outages and failures [67]. This section describes some important ancillary services that a microgrid can provide to the main grid and will not focus on all possible services the system operators must provide in the power system. The distinction between an ancillary service and a system service is stated as follow according to Eurelectric [68]:

"System services are the services provided by the system operator to all users of the network, while ancillary services are the services supplied by some of the users of the network to the system operator. To provide its system services, the system operator usually buys ancillary services from generators and consumers."

Furthermore, Eurelectric defines an ancillary service as:

"Ancillary Services are those services provided by generation, transmission and control equipment which are necessary to support the transmission of electric power from producer to purchaser. These services are required to ensure that the System Operator meets its responsibilities in relation to the safe, secure and reliable operation of the interconnected power system. The services include both mandatory services and services subject to competition." [68]

Providing ancillary services from DERs might be a helpful strategy to solve power quality problems. In a report submitted by the Oak Ridge national laboratory [4], some essential factors where DERs can play an important role in system stability are highlighted;

1. Local regulation, both regarding voltage and frequency control, is more efficient with local production and is something DERs can provide.
2. Harmonic compensation and network stability require fast responding mechanisms, which DERs with power electronic interference can provide.
3. Backup supply and peak shaving obtain the best result when the power source is nearby, which makes DERs a good source to provide this service.
4. DERs can help to maintain the utility network as a reserve and perform ancillary services for the main grid for different occasions.

In [69], ten different types of ancillary services provided by microgrid DERs are discussed. These may be categorized as in Figure 3.1. An additional ancillary service, congestion management, is included in this thesis. The main categories are active power based services, reactive power based services and reduction of harmonic component based service. The active power based services can be divided into two different sections, which are frequency based and balance based services. Both sections aim to maintain the balance in the system, but focus on different aspects and time duration. The frequency based services are fast responding services that track the frequency to avoid high frequency deviations, while the balance based services obtain system balance by investigating longer time periods. The eleven different ancillary services are discussed briefly in this section.

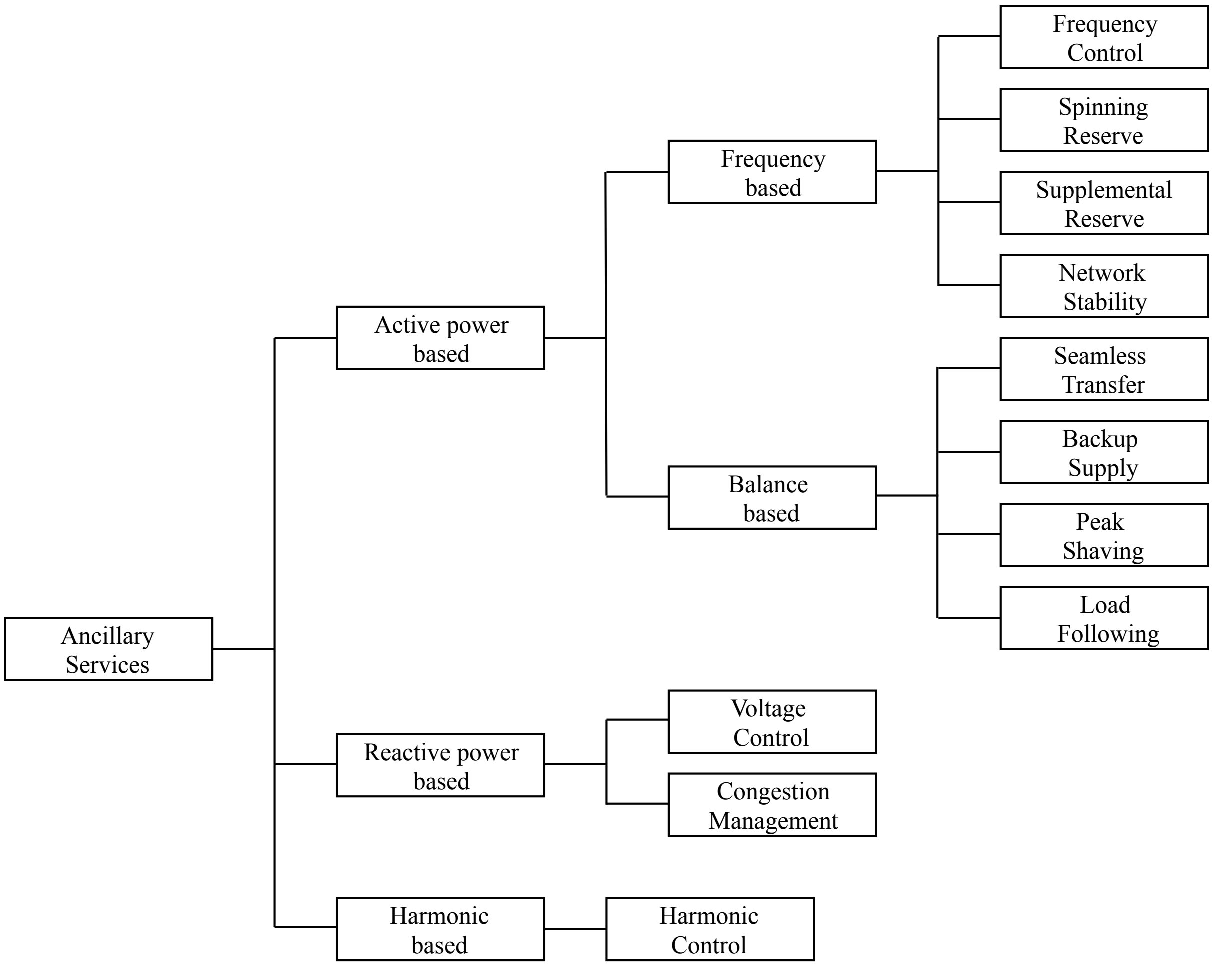
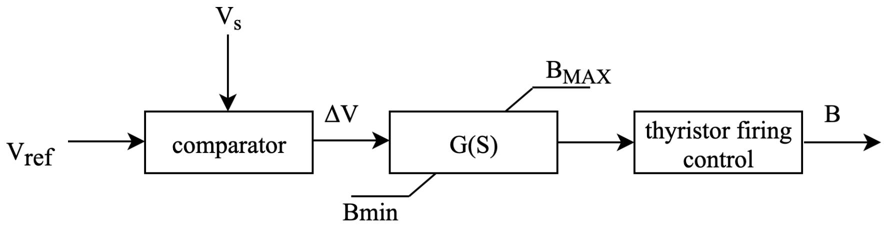


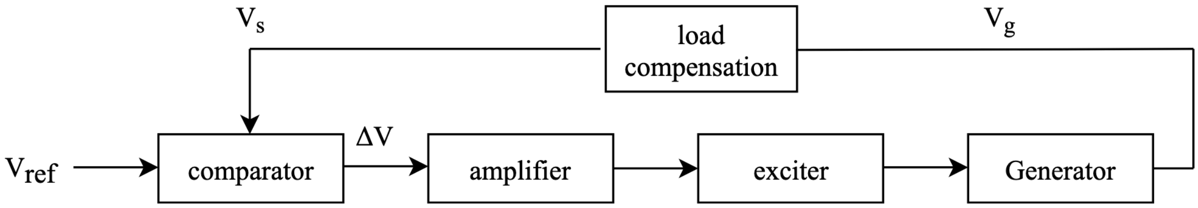
Figure (3.1) Structure of ancillary services

Voltage control

The main task of the voltage control is to maintain the voltage at a bus. Voltage control can be divided into three different levels; 1) primary voltage control, 2) secondary voltage control and 3) tertiary voltage control [70]. The primary voltage control maintains the voltage setpoints at the bus. This control is a local and automatic control provided by control systems such as the automatic voltage regulators (AVRs) and static VAR compensators (SVCs) placed in generating units. Both systems operates as a feedback control loop to compensate for deviations in bus voltage. The systems are illustrated in Figure 3.2 [3]. The secondary voltage control manages the injection of reactive power as a centralized controller, and the tertiary voltage control desire to optimize the reactive power flow across the power system [70].



(a) Simplified feedback control loop for a SVC



(b) Simplified feedback control loop for an AVR

Figure (3.2) Block diagram of feedback control loop for a SVC and an AVR. Inspired by [3]

Three main factors contribute to voltage deviation and create voltage sag and swells. The first one is change in demand requiring more or less power transferred through the system. The second is loads with inductive components which absorb reactive power leading to higher power losses, which again result in voltage drops. The third is due to faults in the utility causing a change in the sending end voltage, which results in a change in the receiving end voltage as well [4].

The voltage control depends on reactive power control, but an active power control can in some cases be used. Figure 3.3 illustrates voltage control in a system scheme. The main function of the controller is to produce and inject reactive power if V_L is smaller than V_g, and to absorb reactive power if the opposite is the case. For microgrid participation, the DERs and energy storage systems can contribute with this voltage support to both the main grid and an isolated microgrid.

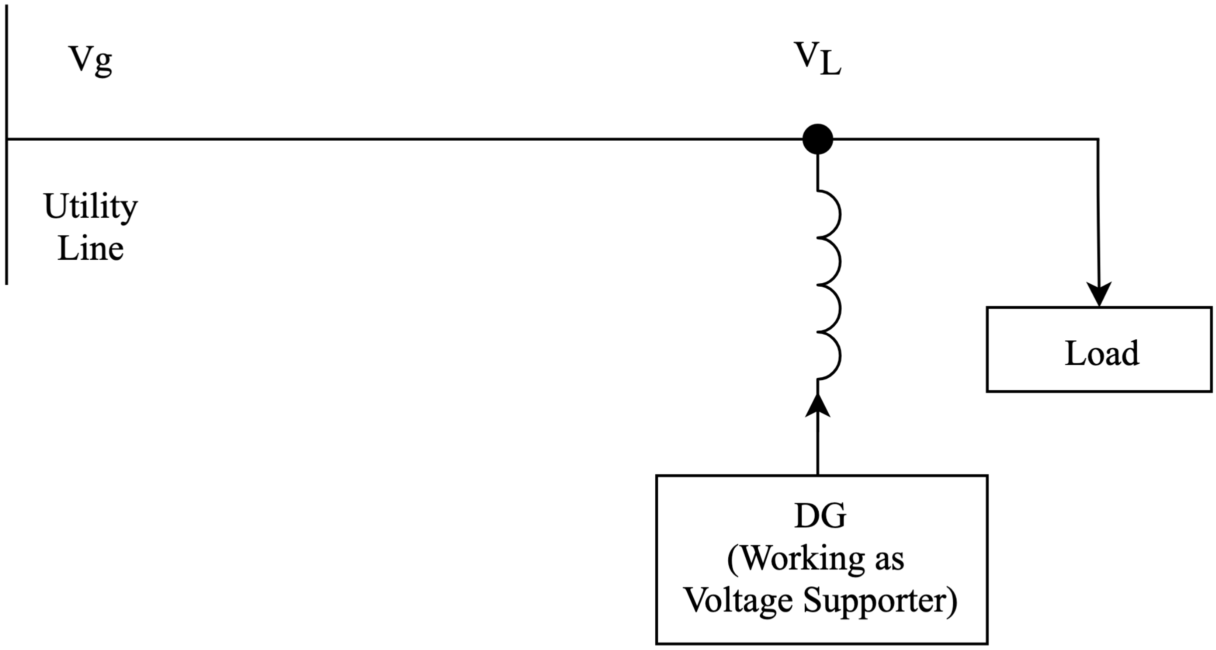


Figure (3.3) Voltage support, the figure is based on a figure from [4]

Congestion management

Congestion can refer to system lines and cables that are unable to transfer the supplied power due to overloading equipment limitations in the system. This might lead to equipment failures and disturbances in the system, and therefore, a fast responding congestion management is important. Reasons for congestion might be the absence of matching system equipment to the needed generation demand in the system, unexpected outages as loss of generation, unexpected high power demand and system equipment failure [71]. Since congestion spans over different problems, congestion management might take the form of different service methods.

The methods can be divided into the cost-free technical methods and the non-cost-free, non-technical methods. The standard methods usually depend on reactive power control and are demand response, load shedding, DGs, generators rescheduling (GR) and nodal pricing schemes. Optimization of grid losses can also be included in congestion management algorithms to establish optimal solutions for the power system [71, 72]. Distributed generation units and energy storage can perform congestion management. One common solution is the changing of generation patterns to local loads to help to reduce the burden on the system parameters.

Frequency regulation

Frequency regulation is based on continuous supervision of the power balance in the power system. The main feature of frequency regulation as an ancillary service is the following of moment-to-moment fluctuation of the system loads [73]. This type of regulation aims to regulate the generator resources based on the fast monitored load fluctuations to maintain the power balance in the system, and therefore keeping the system frequency within acceptable boundaries [74]. This type of ancillary service is fast responding and will respond in seconds.

Typical control strategies for frequency regulation are based on the swing equation presented in equation 3.1 (See [16] for a more detailed explanation on the swing equation). The swing equation illustrates how a change in generated power or load demand causes the speed in a synchronous machine or turbine to react to resist this change. H represents the inertia constant, ω_s is the synchronous speed and P_{gen} and P_{load} represents the generated power and the demanded power in per unit respectively.

$$\frac{2H}{\omega_s}\frac{d\omega_s}{dt} = P_{gen} - P_{load} \tag{3.1}$$

In a microgrid, this ancillary service can be obtained through the governors and automatic generation control units present at the DGs. Control algorithms visualizing virtual inertia can be installed for DGs with power electronic connection. In [16, 75–77], a deeper focus on other control methods that can simulate inertia for frequency regulation are analyzed.

Load following

Load following is often addressed together with frequency regulation since both services aim to track the system load. The main difference between these two types of ancillary services is the time range measurement of the system loads. Whereas the frequency regulation follows the load fluctuation, load following follows the long term load variations in the system [78]. Instead of treating momentarily fluctuations in load profiles, load following focus on ensuring that daily and hourly load demands are meet and by that following a daily load cycle. If both the daily and moment-to-moment variations in load demand are met, the maintenance of a stable power system will be satisfied, and the power system adheres its responsibility and reliability [74].

In a microgrid, load following can contribute with a supplementary task in addition to following the system load. Since most microgrids have a high penetration of storage devices, the storing of spare energy produced by the DERs during low demand hours could contribute as an ancillary service. Some of this energy could be sold to the main grid as a service to help the main grid meet the demand, and the rest can be used locally in the microgrid during high demand hours with low penetration of produced energy from DERs. [79]

Network stability

Network stability has a higher response time than frequency regulation but aims to provide the same service by monitoring the frequency fluctuations and preventing the frequency from deviating outside the desired boundaries. Generation units as DGs with power electronic interference and storage units such as batteries could perform this type of ancillary service due to the fast response these types of equipment can perform. [69]

Spinning reserve

A definition of spinning reserve has been proposed in [80] and says that:

"the spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power"

The definition may be applicable for most power systems, but excludes some factors such as time response and duration. Spinning reserve is an ancillary service that intends to respond quickly to help the power system in case of outages or other imbalance events.

The service is provided by the online generation units (including DERs) with available capacity or resources provided by the demand side in order to respond fast to prevent the system from collapsing. For normal power systems, the spinning reserve should be utilized in less than 10 minutes to correct for the imbalance that happened during a fault in the system [81].

Supplemental reserve

Supplemental reserve intends to perform the same service as a spinning reserve. The main difference between these two types of ancillary services is that supplemental reserve address DRs and generation units that are offline. The utilization time for supplemental reserve can be somewhat higher than for the spinning reserve, but DERs usually have fast responding time [81]. An online generation unit can also contribute as a supplemental reserve.

Peak shaving

Peak shaving is an ancillary service that aspires to reduce the energy demand during peak load hours. The main target is to prevent possible problems in the power system due to high load demand. During peak hours, the energy price is often higher for the consumers than when the demand is low. Peak shaving can encourage consumers to lower their consumption during peak hours to save money on electricity as well as lighten the load on the system. Different approaches can be used for the end consumer to participate in peak shaving such as; turn off non-important loads, automatic thermostat, install storage and solar panels [82]. The best option to perform peak shaving is by using generators. The generators will then turn on and start producing power when the load is higher than the peak price. This strategy makes peak shaving similarly to spinning reserve since both aims to provide active power to prevent system failure [83].

The DERs and storage units present in a microgrid could perform peak shaving. Energy storage systems (ESS) can charge during low demand hours when there is a high penetration of renewable generation, and discharge during peak hours to provide extra power to the grid. [69, 83]

Backup supply

Backup supply is a service provided to the customers where the customer is able to purchase power in the case of utility outages. DGs are very suitable to provide this ancillary service since they usually are locally placed near the loads. The backup supply is able to operate after the operating reserves are returned to regular operation. The typical time frame for the backup supply is half an hour to two hours. [84]

Seamless transfer

Seamless transfer is based on preventing that the switching of a microgrid between the different modes harms the stability of the utility grid. By ensuring a seamless transfer, the DERs in a microgrid can contribute with the wished ancillary service without imposing any instabilities and variation in the power system [85]. To ensure seamless transfer, a proper control strategy is necessary.

Harmonic compensation

A high presence of harmonic components in a power system might lead to different problems. Some of these problems are the deformation of supplied voltage, higher RMS current, resonance, failures in compensation systems and sensitive devices, increased voltage reduction and problems with protection and control systems [86–89]. Online generators, such as DERs, can compensate for harmonics produced by non-linear loads. Harmonic compensation aims to reduce high frequency noise of higher order components, and by that prevent the harmonic components from being present in the utility grid. The normal solution is to use filters that can be located inside DERs with power electronic interference. Active filters are common to use. They prevent harmonic components in the grid by calculating the current drawn by the non-linear load and generate a current equal to the distortion current [5]. Figure 3.4 illustrates how an active filter reduces harmonic currents in the main grid. Other used filters are passive filters and hybrid filters [16].

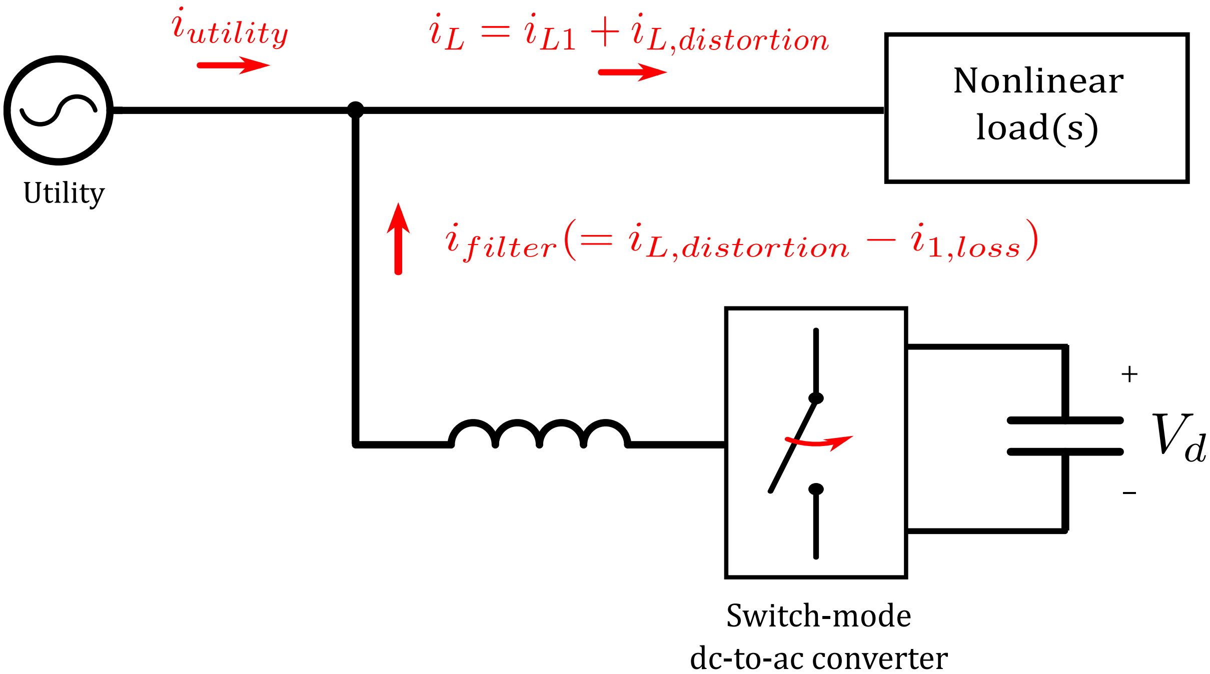


Figure (3.4) One-line diagram of an active filter [5]

3.2.2 Features of ancillary service

The different ancillary services discussed have various features. The beneficial effects of these ancillary services might differ for the different operators. Oak Ridge national laboratory has conducted a study regarding this topic [4], and the result is illustrated in Table 3.2. The pattern indicates that the services providing frequency balancing, supplementary reserve, spinning reserve and network stability benefits the utility the most, while more customer related services as backup supply, load following and peak shaving benefit the DER owner (microgrid) the most. Seamless transfer is expected to benefit the microgrid owner the most since this service is related to control methods in a microgrid. Voltage control, frequency regulation and harmonic control are services that benefit the utility and the microgrid approximately equally. Both voltage control and harmonic compensation will improve the power quality by regulation of the bus voltage and prevent harmonic current from flowing through the utility. Frequency regulation tracks the load to maintain the frequency in the system. This service will also benefit the DER owner since the microgrid can be considered as a load. Congestion management is not discussed in this report, but is becoming one of the main services to overcome congestion issues. It can be expected to have a large impact on the grid owner, and therefore also the microgrid owner [71,72]. In [90] the impact of distributed generation on congestion management is investigated. It concludes that the power transferred through lines can be reduced with optimal placing of DERs. That can be a desirable solution to relieve the congestion on lines with capacity problems.

Table (3.2) Overview over ancillary services and most beneficial impact based on [4]

Ancillary service	**Most impact on**
Frequency Regulation	Both DER owner and utility operator
Spinning Reserve	The utility (TSO)
Supplemental Reserve	The utility (TSO)
Network Stability	The utility (TSO)
Seamless Transfer	The DER owner
Backup Supply	The DER owner
Peak Shaving	The DER owner
Load Following	The DER owner
Voltage Control	Both DER owner and utility operator
Congestion Management	Both DER owner and utility operator
Harmonic Control	Both DER owner and utility operator

3.2.3 Important ancillary services for DSO companies

There are only some of these ancillary services that are important for a DSO to maintain a reliable network operation. Table 3.3 summaries the main accountable for the service and which control method that is most commonly used to provide the service. From this table, four main services are distinctive for the DSO to provide. The main service a DSO need to provide is voltage control. The maintenance of the voltage quality is essential to ensure the quality of the supplied voltage. Voltage problems often appear during two different situations. The first situation is during high peak hours, when a high amount of power transferred over the lines and cables results in a high voltage drop, especially for buses in a radial network. The second situation appears when there is low demand, and a production unit present in the distribution system results in an elevation of the voltage in the nearby nodes. Harmonic control and voltage control aim to ensure the quality of the supplied power and will therefore affect the DSO. Peak shaving is a service that easier can be implemented by the DSO company when all the customers have smart meters installed. Smart meters provide real time data of the consumption, which facilitate higher customer participation. This can be utilized to operate the grid more efficient by implementation of such demand response programs. The last service is congestion management which is important to ensure a secure operation and prevent failures and outages of devices in the power system. This problem is often related to the planning of network investment and it is therefore important to address congestion with a valuable planning phase to find the optimal solution to the problem before conduction with network investments.

Table (3.3) The accountable for providing with the system service [9]

Ancillary service	**The main accountable (TSO/DSO)**	**Control method**
Frequency Control	TSO	Active power
Spinning Reserve	TSO	Active power
Supplemental Reserve	TSO	Active power
Network Stability	TSO	Active power
Seamless Transfer	-	Controller
Backup Supply	TSO	Active power
Peak Shaving	TSO and DSO	Active power
Load Following	TSO	Active power
Voltage Control	TSO and DSO	Reactive power
Congestion Management	TSO and DSO	Reactive power
Harmonic Control	TSO and DSO	Current

3.3 Demand response and market participation

3.3.1 Demand response

Demand response can be used to change demand curves to obtain economic gain, better flexibility and to postpone reinforcements in a grid. It should be implemented in a way where every part involved benefit when it is used. The article in [6] defines DR as follows:

"Demand Response can be defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. Further, DR can also be defined as the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

Demand response is especially interesting considering microgrids because they not only include loads, but also generation units and storage units. The ability for storage units to both use and supply electric power allows the microgrid to represent both a significantly bigger and smaller load than the normal consumption pattern. Demand response might be important for a microgrid to exploit its advantages to ensure economic benefits for its members and to have a better possibility to deliver services to the utility [91].

In response to price signals, there are three main actions customers can perform. The customers can reduce electricity consumption when the electricity price is high, which involves a temporary lack of comfort. The price is normally highest during load peak hours. The second option is load shifting. The total energy consumption remains the same, but the customer changes some peak hour activities to off-peak hours to obtain lesser costs related to the activities. The third action is to use on-site generation. By utilizing on-site generation during peak hours, the utility may experience significant change in electricity pattern, while the electricity users retain the same usage pattern. [6]

There are different types of demand response, which can be seen in Figure 3.5. They can roughly be divided into incentive-based programs (IBP) and priced based programs (PBP). IBP are again divided into classical programs and marked based programs (MBP).

In classical programs, the customers get paid a predefined price when the system operator either asks the customers to reduce their load, or can remotely shut down equipment on short notice. In MBP, the customers offer demand response actions in a market. In PBP, the customers control their demand based on the costs of using electricity. Some programs that are relevant in Norway, and can be interesting from a microgrid point of view are explained later in this section. [6]

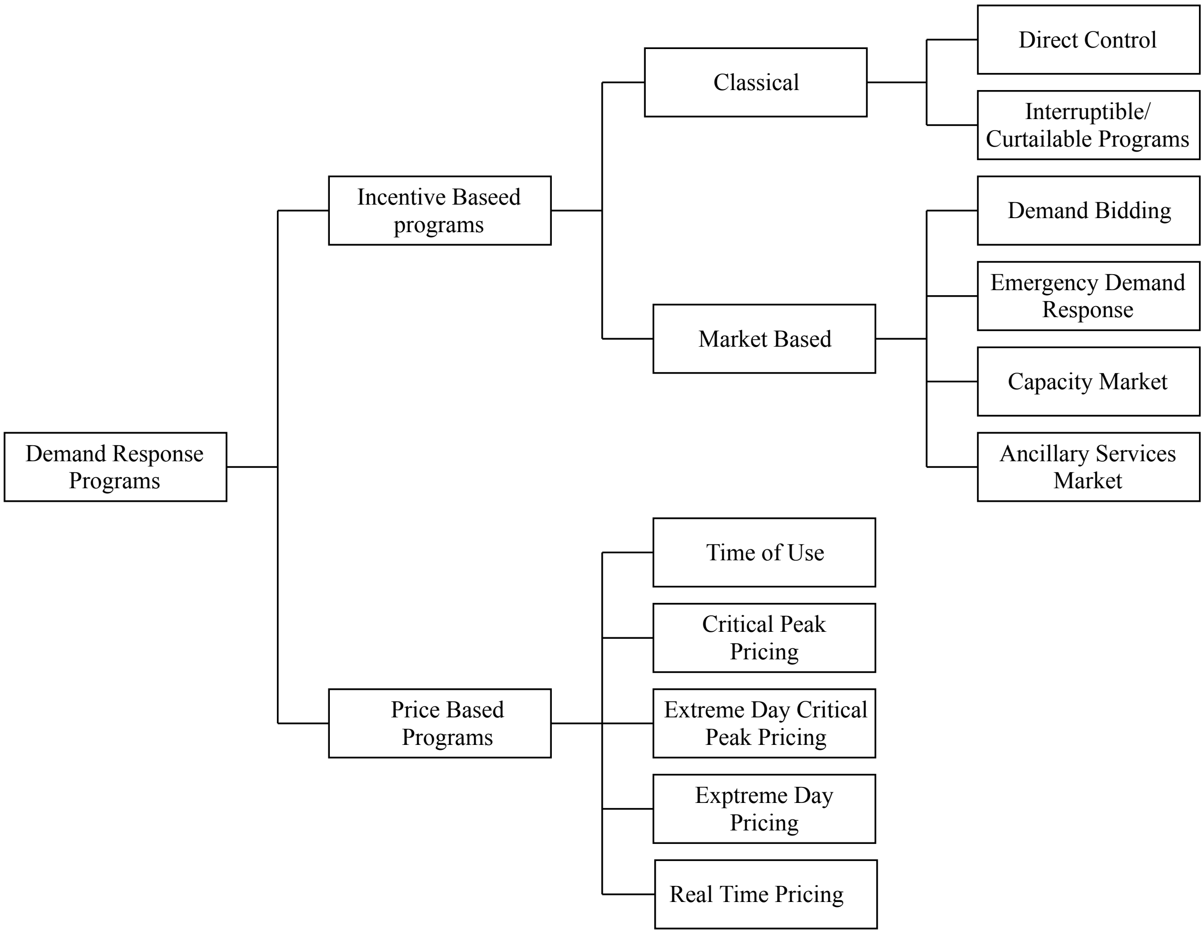


Figure (3.5) Overview of demand response programs [6]

Possible price based programs in Norway

Price based programs are easy to implement. There is no need to develop new market solutions to use those programs since the customers respond to variations of electricity prices for their own benefit [92]. The different programs mentioned in Figure 3.5 will be based on the decided network tariff model decided by the DSO and the electrical energy price model in the contract between the power supplier and the customers.

To better represent the costs for the DSOs because of energy consumption patterns, and to facilitate more demand response in the Norwegian power grid, there will be changes in the design of the network tariffs. How the design is going to be is not yet decided. In addition to the customer-specific fixed part and the energy consumption part of the tariff, it is expected to include one or more parts based on the use of electrical power. Those parts can be based on a subscription of electrical power, measured electrical power and time of use [92]. The two first alternatives decide the price by the maximum power demand or the maximum power used, while the last part decides the price by how much energy that is consumed at which parts of the day. [93, 94]

Possible market based programs in Norway

In [95], Universal Smart Energy Framework (USEF) argues that a market based model should be used to exploit the flexibility. That is because PBP can give insufficient economic incentives to change controllable loads. Tariffs also do not consider local needs and are unfair because the costs are divided between all the users regardless of whether they participate with demand response or not. There are different options considering developing a market suited for demand response. Enfo consulting proposes and describes in [92] three different flexibility marked models that can be implemented into the Norwegian power market system. The proposed models are described below.

1. *Bilateral agreements*

   Bilateral agreements are long term contracts between the DSO and the customer (aggregator or end-user) regarding how much available flexibility the customer will have during a period. Development of a market place for bilateral agreements are not complex or challenging, and is a natural first phase when developing flexibility market models.

2. *Integration in existing markets*

   It is possible to integrate the flexibility market into the existing reserve markets. Then, both the TSO and the DSOs are going to be buyers. The market needs to be customized to fit the DSO as well. The bids have to be area specific, so the competition is going to be between the TSO and the local DSO. The bids need the opportunity to be smaller than in the reserve markets today. The DSO also needs to buy options earlier than a week in advance to use the flexibility market to postpone grid investments. This market form force cooperation between the TSO and DSOs, but can be complex to develop. Some big industrial customers already operate in the current reserve markets.

   A second option is to integrate the flexibility market into the wholesale market. Here, area-specific bids need to be possible to place in the market. This market will ensure less price volatility for the DSO but does not provide sufficient long term planning possibilities for the DSO. Therefore, it is recommended to combine this market form with another flexibility market.

3. *Separate flexibility markets*

   In a new local flexibility market separated from the existing markets, the DSO will be the only buyer. The market can be developed to satisfy all the requirements for the DSO and is less complex than a joint market for the TSO and the DSOs. The challenges are that one would have to develop a new system with new price links and that there is no competition in the market for the DSO.

3.3.2 Aggregation

In a power system, aggregation means to gather different units with different characteristics and constraints to a portfolio with less constraints. An aggregator can control loads, storage units and production units on behalf of a customer to exploit the flexibility potential of the units. By aggregating different customers together, an aggregator can offer more flexibility services to stakeholders. Customers do not need to manage demand response activities themselves when they have an agreement with an aggregator. [92]

It is not clarified which part in the Norwegian power system that is going to take the role as an aggregator. There are three main types of aggregator roles that are discussed to be used for demand response in Europe. The types are; 1) integrated, 2) independent and 3) aggregator controlled by a system operator. In [96], NordREG describe different solutions for the three main types as follows. Integrated aggregators can be existing power suppliers or new and similar units that manage the flexibility for the customers. A contract between the customer and the aggregator and open competition between aggregators will secure the economic benefit for the customers. An independent aggregator manages the flexibility without operating as a power supplier for the customer. There are different possibilities of the division of responsibilities and roles between the aggregator and the power supplier. Because there are well-functioning and competitive retail markets in the Nordic countries, NordREG recommends to use integrated aggregators in the Nordic countries and concludes that it is not necessary with an independent aggregator. The reason to use an aggregator controlled by a system operator is in situations with high importance of reliability and if a market based model gives to big disadvantages for the system operator. [92]

Aggregation is necessary in a microgrid to exploit the demand response potential and to make it possible to participate in future flexibility markets. The higher level of observability and control in a microgrid compared to a conventional distribution network provide optimal conditions for effective aggregation of the resources in the microgrid [91]. If a microgrid is going to be presented as one unit in the electrical power market, it is not possible to have competition between different integrated aggregators for the units within the microgrid. All the units have to be controlled by the same aggregator. If an integrated aggregator solution is used, aggregators have to compete against each other to get the control responsibility for the whole microgrid.

3.3.3 Potential of demand response in Norway

Norway has a high flexibility potential and has the biggest potential in the Nordic countries. The reasons are the large electrical power consuming industries with high demand response potential, the high penetration of electrical heating and electric water heating in households and commercial building in Norway. Performing demand response for industry customers can have a high marginal cost, since it might disturb the production. Considering heating and water heating in households and commercial buildings, it is possible to perform demand response with no or little lack of comfort [92, 97]. [97] points out, based on the TSOs action plans, an estimation of the demand response potential in the Nordic countries. On the medium term the potential is expected to be around 10 000 to 12 000 MW, where 5 000 MW is expected to be in Norway. Approximately half of the potential is allocated at industry customers.

Demand response activities in Norway

There are several projects in Norway where demand response solutions are tested. [98] has examined 17 different activities. They are divided into already implemented activities, science activities and demonstration activities. Already implemented activities are solutions that are already in use, while demonstration activities are activities where some specific solutions are tested on some customers. It is easy to see results from those two types of activities since they are tested on real customers.

There are multiple activities where a DSO company tests the implementation on a part of the network tariff which is based on the consumed power from the households. Besides, the DSOs gives the customers a way to visualize their consumption pattern through the implementation of the smart meters. Additionally, there is one activity where the customers can control their own loads from a mobile phone application. The results illustrated that for most of the project, the total consumption decreased when the customers obtained an awareness of their own energy consumption. Thus, the results revealed that the engagement was higher in the beginning of the project, whereas it decreased later on in the project. None of the DSO companies could see any clear result related to the customer change during the hours the customers used some specific loads. The project discovered that the customers had problems regarding separating between energy and power.

Some large commercial buildings and industries have already implemented a consumed power part of their network tariff. Different energy suppliers also provide solutions to control the demand in their buildings to lower the energy costs. One type of solution is to offer aggregator services to provide flexibility for the buildings and industries into the reserve market. Some suppliers that offer aggregator services believes from obtained experience that todays market forms prevent new investments, development of new technology and services for flexibility reasons. The reason is that the market is designed for producers and not consumers, and a lack of market where flexibility can be offered as an electrical power service.

The conclusion illustrated that by including a new network tariff, the influence is greater when an automatic controller performing the demand response is present compared to the situation where the demand response is performed manually by the consumers.

Statnett has performed a similarly project where they can control the loads in 40 large institutions in the north of Norway. The projects have illustrated the potential of using large loads in primary and secondary control. The control of large loads can in general also provide with a better utilization of the local power grid.

Chapter 4

Interaction between microgrid and DSO

This chapter aims to answer some questions regarding how a possible interaction between the DSO company and a microgrid might unfold in Norway and problems that may occur. Different important aspects need to be investigated and clarified before a possible interaction can take place. This chapter is divided into two parts, where the first part address the regulatory problems related to the integration of microgrids and the second part suggests a simple possible strategy for how interaction between a DSO company and a microgrid might be unfolded.

4.1 Regulation

Microgrids and renewable distributed energy sources are predicted to take a larger role in the future power system in Norway [99]. These types of energy sources need to be connected to the main distribution network and therefore contribute to the overall distribution system. In chapter 3 a diversity of important ancillary services that could be provided from DERs and energy storage devices were discussed. From a DSO point of view, the most important services are voltage control to ensure that the voltage supplied to the end customers is within the acceptable limits, congestion management and decreased costs because of interruptions. The possibility to run the microgrid in island mode when there are faults make the last mentioned service achievable. For the DSO, a microgrid and DERs can contribute as an asset and help with different problems regarding congestion and voltage. To perform these type of services, a standard regulation arrangement must ensure a secure operation where all the needed requirements are met.

When discussing the interaction, different important aspects need to be clarified. Some of these questions are not fully clarified in any regulations and have not been addressed in any great extent. Some important questions which will be elaborated in this section are listed as follows;

- What is the role of the DSO regarding the microgrid?
- Who owns the microgrid?

- What type of microgrid?
- What can be required from the microgrid?
- How to communicate?
- What problems might arise regarding regulation?

One of the most important aspects that needs to be addressed before planning and discussing the developments of an agreement and regulation for interaction between a DSO and a microgrid, is the question about the owner. Different types of firms as production companies, DSO companies, property developers, property owners and compositions of different stakeholders can be all potentially become owners of a microgrid.

A report constructed by Thema consulting for NVE discusses some problems the integration of local energy communities (LEC) will meet regarding regulations in the Norwegian power system [35]. This study has been investigating 30 Norwegian LEC projects where 8 of the projects are owned by a DSO company, while the rest are owned by a property developer. In the paper written by Ton and Smith regarding the microgrid initiative, different important aspects related to microgrid and microgrid development are discussed [100]. One important factor is the stakeholders that can be included in the microgrid planning, development and operation. Different types of microgrid projects can motivate different types of stakeholders to participate. The same is mentioned in the report by Thema consulting.

The listed questions will be answered based on the microgrid owner. The microgrid owners will be divided into three different categories; 1) DSO owned microgrid, 2) microgrids owned by sales-oriented companies and 3) microgrids owned by different stakeholders.

The microgrid will be discussed and seen as one unit in this thesis. Distributed generation alone will be seen as a part of a microgrid and not discussed as an own theme. The microgrid will be assumed to include generation units, energy storage units and loads, and can participate in the retail market for selling and buying energy. Another assumption is that the microgrid mainly operates in grid-connected mode, but can also disconnect from the grid if necessary.

4.1.1 DSO owned microgrids

A microgrid can be seen as a small power system including network operation, and is therefore required to obtain a network operator. There are two different situations for a microgrid to be owned by a DSO company; 1) owned by the regional DSO, which owns the network outside of the microgrid as well or 2) establishing of a new DSO company that only operates and owns the network within the microgrid boundary. The last case will most likely happen if the owner not is a network company and, therefore, fall under the next category. This section will focus on an established DSO company owning and operating a microgrid.

The most common reason for a DSO company to invest in and own a microgrid is related to reducing the total network investments and avoid congestion. This can either be related to remote areas or just an expected increased demand in the system. In [35], it was seen that the LEC-relevant projects owned by DSO companies that aimed to postpone the network investments often seek to lower the peak capacity demand. This was conducted through the use of the network flexibility by either implement flexible loads as a form of demand response, install local production and storage units and by creating local flexibility markets. The results will reduce the downstream loads in radial meshed networks and by that relieve the network component and extend their lifetime. This result might also ensure that possible future investments are reduced by implementing cheaper solutions.

The benefit of DSO owned microgrids is the knowledge a DSO company has regarding how to operate a distribution system. The DSO company will through the owned distribution system have the area license for voltage levels higher than 230 V, ensuring the DSO company to have distribution network installations on their specific area [101]. The DSO company will also have a trading license as a network operator and be familiar with the given requirements included in this license [101].

Regulatory barriers and solutions

For a well established DSO company with other network activities and customers, some regulatory questions and problems will arise. Some of these problems are listed and explained as follows;

- Owning and operating production units
- Operating the microgrid during island mode
- Network tariffs
- Data management

Owning and operating production units

A DSO company that owns production units and energy storage will contradict §4-7 (and §4-6 for DSO with more than 100 000 customers) of the Norwegian energy law. A DSO has monopoly of the network operation within a given area and needs to maintain neutrality to protect the customers. A situation where a DSO operates and regulates generation units as well as participates in the retail market will go against these regulations.

There are different solutions a DSO company can implement to solve some of the regulatory problems. To fulfill the Norwegian energy act, a third party actor can obtain the ownership of the generation units in the microgrid. This will enable the DSO to enter an agreement with the third party where factors as ancillary services could be in the main focus of the agreement. Another likely scenario is to use aggregators to obtain customer flexibility. In the winter package developed by EU, a proposal of changing the network operators right to own storage units in the future is discussed [102]. This will enable the DSO companies to exploit the flexibility in the network and easier provide ancillary services as voltage regulation and congestion management. In [103], four different ownership strategies are discussed regarding energy storage; 1) 100% prosumer owned energy storage, 2) a 50/50 ownership between the prosumer and DSO, 3) 100% DSO ownership of the energy storage and 4) DSO invest 50% while the prosumer owns the rest.

Operating the microgrid during island mode

The second problem will be related to operating the microgrid during island mode. During island mode, the microgrid is operated as a separate network and the DSO will then have to operate two separated networks and ensure the quality of supply in both. For the customers connected to the microgrid, island operation also prevents the customers from choosing their supplier freely.

The problem regarding operating the microgrid during island mode will most likely require a good strategy plan from NVE where a standard related to regulatory questions for temporary islanded operations must be clarified. One possible solution is to obtain a form of an agreement with a third party or obtain a solution where the microgrid has an own microgrid operator, which should maintain the operation during island mode [35]. To ensure that the customers are cared for in the right matter, it might be necessary to enter an agreement with the customers who renounce the opportunity to choose the supplier during island mode freely.

Tariffs

The report from Thema discusses that new tariffs might be required for this new situation where the network can operate in different modes. Different tariffs could, in theory, be applied to different groups. NVE is the main accountable for deciding the tariffs in the network, and a standard for determining the tariffs might be required.

Data management

Active distribution systems with a high penetration of transmitted information and integration of various ancillary services will require a higher interaction between the DSO and TSO and a good strategy for data handling. The interaction between the DSO and TSO will require a comprehensive coordination scheme that must ensure their responsibilities towards third parties and the system operators role towards each other [35, 102]. They will need to obtain a regulatory standard for maintaining and operating customer data, ensure that the privacy policy is according to the law and ensure that the right actor treats the correct data.

4.1.2 Microgrids owned by sales-oriented companies

Sale-oriented companies that might be interested in owning a microgrid can be production companies, property developers or property owners. The main motivation for such an owner is to attract customers, be involved in a new market form and increase income.

If a new legislative is to be established, which acquit companies with less than 10 000 customer from the discussed functional separation, the role of the microgrid owner can be defined in different matters. In Norway, the different DSO companies are divided into four different groups [39].

1. Large distribution grid companies: more than 30 000 customer.
2. Medium size distribution grid companies: between 7 000 and 30 000 customer.
3. Small distribution grid companies: less than the median distribution operator company in the local distribution system.
4. Not ordinary distribution grid companies

A microgrid system alone generally contains both demand customer and power production through distributed generation and energy storage. Thus, making a typical microgrid fall under the definition as a *not ordinary distribution grid company* which is defined as a

DSO with some network operation but mainly operates with other activities as power production or electricity trading [39]. Together with the new discussed legislative, the microgrid owner might be a small DSO company.

Regulatory problems

Some different barriers this group of owners encounter and need to solve are listed and discussed as follows;

- Who should operate the network?
- Network tariffs
- Islanded operation
- Communication with nearby DSO
- What is the market for trading and selling energy?
- Data management

Who should operate the network?

This owner group will most likely lack expertise regarding network operation. If the microgrid include less than 10 000 customers and the legislative approves, independent operation of the microgrid will be possible for the microgrid owner. The first problem the microgrid owner will encounter is the area and trading license that needs to be obtained for operating a network. This license will require more obligations and an administrative burden to the microgrid owner [35]. Another solution strategy is to get a third part, such as a DSO company, to provide with the operation of the microgrid network

The Germany microgrid project *Wildpoldsried microgrid* [104] operates as a topological power plant meaning that the microgrid includes both production units and customers while it can be regulated as a conventional power plant. Some goals through this project are to investigate possible restrictions and requirements given by the network operator and legal regulatory framework conditions for the realization of the project. A challenging encounter in this project is the lack of standardized products and solutions independent of the producer. This project illustrates three different operation strategies this owner group can adopt; 1) operate for own profit, 2) aggregator operates for profit for a given group and 3) the DSO obtain the responsibility for the network operation. The main findings are that this strategy will require a well established agreement between the participants, and that some problems regarding the information flow between regulating and not-regulating units might occur.

Network tariffs and islanded operation

The problems regarding tariffs and islanded operation will be similar to the problems described in Section 4.1.1. The question will embrace what the right tariff must be in the microgrid with the knowledge of what the tariffs in the nearby areas are. The problem can be related to who the microgrid customers are supposed to pay the network tariff to. If a clear boundary is drawn between the DSO area and the microgrid area and the network operation in the microgrid is conducted by others than the local DSO, the tariffs will most likely be paid to the microgrid operator. For a situation where the DSO company maintains the network operation in the microgrid is this problem less clear. Equal as for the DSO owned microgrid, a microgrid will during island operation prevent the customer from choosing their supplier freely, and an agreement with the customers will be required.

Communication with nearby DSO

A clarified boundary between the microgrid and the nearby DSO needs to be drawn to obtain an area with a trading license. Thus, the microgrid owner will be required to have interaction with the nearby DSO owners. If the microgrid is going to be connected to the main grid, the same rules will apply for the microgrid owner as for other production units owners. Thus, a form of network tariff must be paid to the DSO company for the use of the network connection.

A report developed by *Energi Norge* [105], address the problem regarding the connection point between the network of the DSO and the production unit, which is the microgrid in this setting. The DSO company will through §3-4 be required to connect the microgrid to the system, but the regulations state that new production units can only be connected to the network when it is operationally safe and if there is sufficient network capacity for the entire production. This means that if the network capacity is poor, the microgrid owner will be required to pay an investment contribution (anleggsbidrag) to the DSO company before the network connection can happen. The report emphasizes the importance of the DSO company to obtain an overall assessment of the need for network investments before the planned developments are to begin. The investment contribution applies a first come, first served principle. That means that as the DSO is required to connect the microgrid and the generation units as long as the network capacity is within acceptable limits. The investment contribution can not be given to units that are already connected, but it can be required for planned production. There are some possible outcomes [105];

1. *The developer does not accept the investment contribution* - The reason might be that the developer does not wish to pay the construction contribution. The most likely reason is if the project is not profitable. The obligation of connection for the DSO company will not apply.
2. *The developer accept the investment contribution and the planned production is implemented* - The project is realized, the investment contribution is paid and the DSO company will be required to report to NVE.
3. *The planned production is not implemented* - The DSO company can ensure their claims and require investment contributions from the developers who have entered a binding agreement. This will apply even if the development is not implemented, and will only apply for the accrued costs.

Another temporary opportunity for connection is the *temporary conditional connection*. This is often related to situations where the DSO awaits capacity expansions in the network [105]. This is only a temporary solution and can not be utilized as an alternative to network investments. This strategy excludes the opportunity for the DSO and the microgrid to write an agreement for the connection to only apply for the worst hours situation where the network capacity is poor.

Market, trading and selling energy

Microgrids will be required to obtain a trading license needed for companies that sell, trade and have production of energy [41, 106]. This license include the billing of electricity and balancing responsibilities. The producer needs to meet the imbalances in the balancing market for their customers and exchange the needed information for billing purposes. If the microgrid is to provide generation to local market platforms a market place license will be required [106]. Each generation unit is required to have an asset license and trading licence.

One problem can be to place the microgrid generation into a market form directly. They are usually capable to produce more power than the limit of a prosumer. On the other hand, the production is normally insufficient to participate in the wholesale electricity market. In [35], this is addressed as a major barrier for implementing of systems such as microgrids.

Data management

The same regulatory problems as in the previous case will apply for this type of microgrid owner too. The main difference might be related to the experience of handling customer data. The microgrid owner will be required to maintain a good interaction with the nearby DSO to enable a good coordination scheme if the microgrid is connected to the grid. One question regarding who that should handle the AMS data could arise if the microgrid owner outsource the microgrid operation to the DSO company.

4.1.3 Microgrid owned by a collection of different stakeholders

This last section will look at the microgrid as a project with multiple stakeholders that cooperate in planning, building and operating the microgrid system. The motivational aspects might be research projects, stakeholders with a common goal of implementing more renewable energy resources and zero emission environments or different companies that invest in a microgrid project together to solve different problems. An example of the last case might be a DSO investing in a microgrid together with a property developer. The motivation of the DSO might be to reduce network investments and avoid congestion, while the property developer aims to increase income.

This type of ownership will meet the same regulatory barriers as the sales-oriented owners and the possible agreements between the DSO and the microgrid owner might be similar as in the last case. The main difference is that the local DSO often is a part of the project and participate with investments. This situation will in multiple settings make communication, division of roles and the agreement settlements easier. In [100], multiple of ongoing microgrid projects under the U.S Department of Energy (DOE) and its Smart Grid R&D Programs including different stakeholders are displayed. Multiple of these projects are motivated by multiple stakeholders. The goal for the Smart Grid R&D Programs is to optimize the grid operations and implement demand response and customer participation.

Simris grid in Sweden is an example of a microgrid with different stakeholders [107]. The project is based on investigating the interaction between different DER technologies, customers and energy storage units. Research related to technical and operational aspects of a microgrid is performed. The local DSO company, E.ON, obtain the role as the grid operator and have invested 50 % of the investment costs for the project. The microgrid is not able to be a fully stand-alone system, but runs in island mode for one week every fifth week.

4.2 Possible interaction strategy

The previous section addressed the regulatory problems related to the integration of microgrids in the Norwegian power systems. This section will suggest a possible interaction strategy between a DSO and a microgrid under the assumption that the microgrid owner or the production units in the microgrid is not the DSO company. The main motivations for a DSO company to participate in a microgrid project are to reduce network investments, increase the network capacity and avoid congestion in the network. If a microgrid project is to be established, the planning phase would be crucial for all the participants. Since the connection of the microgrid also influences the nearby systems, the planning phase is very important for the DSO. There are some different directions the interaction could take based on the DSOs participation and wanted outcomes.

A possible interaction strategy could be related to using the microgrid as an alternative to network investments. If a DSO company has predicted a high investment cost regarding future network investments, an interaction with a microgrid could perhaps reduce this investment cost. One strategy for the DSO is to invest in the microgrid from the beginning of the project and become a stakeholder to the microgrid project. The DSO could then function as the microgrid operator and take responsibility for all the network operations inside of the microgrid as well as inside of their own area. The agreement could then include that the microgrid should contribute with ancillary services as voltage regulation during high demand hours or that the microgrid should perform different demand response programs. This agreement could also liberate the microgrid owner from paying network tariffs.

If the DSO company is not investing in the microgrid project, the DSO could engage to an interaction. The DSO could make agreements with the microgrid owner where the microgrid could function as an ancillary service to the distribution grid. By providing necessary services from the microgrid to the DSO, they both could benefit from. The agreement could include different benefits for the microgrid if the microgrid is to support the distribution system. Some of these benefits could be that the microgrid does not have to pay the whole or parts of the network tariffs or a possible investment contribution. The agreements could also include some possible network operation requirements for the DSO company.

For the rest of this thesis, the interaction will be presented through the simulation model proposed in Chapter 5 and 6. The interaction will mainly be illustrated as different types of ancillary services the microgrid could provide to the distribution system.

Chapter 5

Model construction

This chapter aims to provide an overview of how the system model is constructed. The focus will be on the explanation of the theoretical method behind the construction of the different aspects of the model and how this will be implemented in the demo system. Necessary limitations and assumptions will be explained, and the tools used to develop the system model will be introduced.

5.1 Python

Python is the chosen programming language used to construct algorithms for solving different problems regarding the model in this thesis. The main reasons for using Python is; 1) Python is an open source programming language and therefore freely available and distributable to everybody making the codes used in this thesis reusable and 2) Python is a friendly programming language which is easy to understand and learn.

5.1.1 Pandapower

Pandapower is used in this thesis for the development and usage of the test system. Pandapower is a package available in the Python environment and is an open source tool for power system modeling. It is built on the data analysis library pandas and the power system analysis toolbox PYPOWER. Furthermore, Pandapower obtains the possibility to model any power system network, and it can perform a static analysis of a balanced power system. In this thesis, Pandapower is the chosen modeling tool due to the easiness of parametrizing electric models of lines, loads, switches and production units. It is also desired to use open source code that can freely be modified, customized and reused [108].

5.2 The distribution network model

The network to be addressed in this master's thesis is based on a 33-bus distribution network from Baran & Wu [109, 110]. The original network is a partially meshed network and constructed based on minimizing power losses and obtain load balancing. The distributed network modeled for this thesis is constructed as presented in Figure 5.1. The meshed part from the original 33-bus network is removed to make a fully radial system network more equal to a Norwegian distribution system. Thereby obtain three radials where the main radial goes form bus 1 to 22. Some of the bus numbers are changed to achieve a systematical network, making the main radial to consist of 22 buses. The model is composed in Pyhton through the installed package Pandapower.

The system will be illustrated as a weak distribution network and might differ from an actual distribution network. The reason for building the network as a weak network is to be able to illustrate the problems and analyze how different situations might improve the problems in the modeled network. The goal is to analyze how days with different weather might influence the system voltage and lines and explore the impact of the microgrid on the system.

The case for this thesis can be elaborated as a part of a planning phase for a DSO company. Some possible different situations can be; that the lines in the distribution network are old and near the end of their lifetime, an expected increase in demand requiring more available capacity in the distribution system or planned development of a microgrid. All these situations will require the DSO company to investigate the most optimal solution for the company and its customers to ensure safe and secure operation. One alternative to grid investment can be the implementation of a microgrid system that can perform ancillary services to the distribution system when it is required. This model will be investigating the effect a microgrid including DERs and loads have on the weak distribution system.

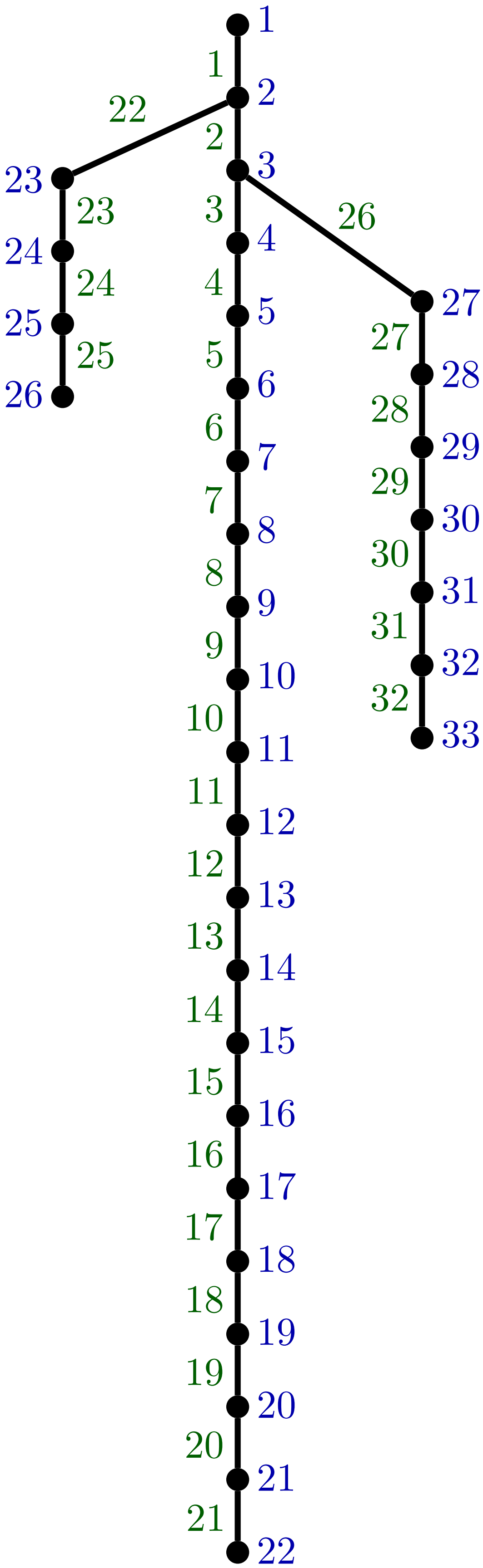


Figure (5.1) 33-bus radial distributed network, the buses are labeled in blue and the lines in green

5.3 The microgrid model

The microgrid that is implemented in the model is illustrated in Figure 5.2 as how the authors imagine that it can geographically appear. Figure 5.3 presents how it is constructed in Pandapower. It is a small network including loads, critical loads, wind generation, photovoltaic generation, and batteries. The network is organized as in Table 5.1. The system consists of 20 000 PV cells, which can be presumed to be installed on the different loads but is illustrated through one bus in the network. The microgrid system furthermore consists of 10 wind turbines and one battery storage system. The different generation units are explained more in the next sections. The loads are systematically divided into normal loads and critical loads, but for this model, separation of these two different loads will not be considered in any large extent. Since the microgrid is supposed to deliver services to the main distribution system, the maximum installed generation capacity is higher than the expected maximum power demand in the microgrid.

Figure (5.2) Sketched model of the microgrid

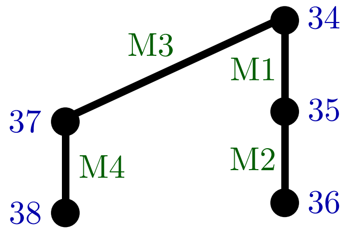


Figure (5.3) Model of the constructed microgrid network, the buses are labeled in blue and the lines in green

Table (5.1) Overview over symbols used to generate PV output power data [10].

Bus	Bus type	Explanation
34	Connection bus	Bus connecting the microgrid to the main distribution system. A battery is connected to this bus for some strategies.
35	Generation bus	Wind turbine generation.
36	Generation bus	PV generation.
37	Load bus	200 residential loads.
38	Critical load bus	Critical loads illustrated as two hospital buildings.

5.4 Construction of model data

The data profiles will illustrate a 24-hour situation based on different days in 2018. The situation will illustrate some different possible weather profiles that might occur during a year. The development of load data, wind generation data and photovoltaic generation data is based on weather measurements in Mære in Nord-Trøndelag, Norway. The situations are;

1. *4th of June 2018* - A day with normal temperatures for the spring and fall seasons with high penetration of generation.
2. *7th of June 2018* - A day with normal temperatures for the spring and fall seasons with low penetration of generation.
3. *1st of March 2018* - A cold day with high penetration of generation.

The first case aims to present a good day, whereas the two other cases will illustrate two different worst case scenarios. The data for the analyzed days can be seen in Appendix A.2, Table A.3, A.4 and A.5. Be aware that the average wind speed for June 4 and 7 have been slightly modified by switching the last four hours with four hours earlier. The reason is to get the problem hours to appear earlier in the day to easier see the effect of the different methods. The next sections in this chapter will demonstrate calculation methods and construction of the different data used in the network system model.

5.4.1 Assumptions

When constructing model data, some assumptions are necessary. The assumptions and estimates are as follows;

- Since the model only analyzes three different scenario days and not yearly profiles, it is estimated that the hour with the highest voltage during a year on bus 22 is 22 kV. This estimation would most likely not be the case in a real distribution system, but the prediction would be accepted in this model. Since the model aims to illustrate the effects of the different services and only investigates three different days, the actual lowest voltage during a year on bus 22 is not calculated. This estimation would result in a lower voltage limit than 20.9 kV.
- The planning phase of the microgrid will be excluded in this presentation of the model. Therefore, economic perspectives and predicted weather change will be excluded.
- When constructing the PV and wind data profiles, methods introducing small estimations are used. The algorithms exclude important factors as the optimal placement of the generation units and the PV angling. It is therefore estimated that the generation units are able to produce the highest possible power based on the weather data for that specific hour.
- The weather data is collected as average hourly measurements, resulting in profiles estimated as hour profiles.
- Since only three days are used for making the scenarios is it hard to tell if the chosen wind turbines and PV panels are optimal for the measuring site and if the site is suitable for wind and solar power. This would be necessary to investigate during a planning phase of development of a microgrid.
- The load data will only be estimated based on high load demand for weekdays, and might not be the most accurate data to use for all the situations.

5.4.2 Construction of PV generation data

The fill factor power method

The construction of PV generation data is based on a paper represented by Jones and Underwood [10]. The paper presents an efficient model of how to calculate the output power of PV panels based on the fill factor ratio. The purpose is to establish a model to generate PV data based on module parameters obtained in data sheets and without the use of experimentally obtained data. The diode model is one of the most commonly used mathematical models to achieve the behavior of PV cells, and express the current-voltage characteristic (I-V curve) with the current through the diode, the photocurrent, and the current through the resistance. The fill factor power model, on the contrary, is a simpler model and calculates the maximum power output based on the relationship between the irradiance and the temperature from the diode model with the short circuit current and open circuit voltage. From this, the maximum output power of one single module can be obtained as in equation 5.1, where the fill factor can be obtained as in equation 5.2. Table

5.2 gives an overview of the meaning of the symbols with units used to generate the PV output power.

$$P_{out} = FF \cdot I_{SC} \cdot \frac{E}{E_0} \cdot V_{OC} \cdot \frac{ln(k_1 E)}{ln(k_1 E_0)} \cdot \frac{T_0}{T_{cell}} \tag{5.1}$$

$$FF = \frac{P_{mpp}}{I_{SC} \cdot V_{OC}} \tag{5.2}$$

Table (5.2) Overview over symbols used to generate PV output power data [10].

Symbols	**Meaning**	**Unit**
V_{mpp}	Maximum power point voltage	V
I_{mpp}	Maximum power point current	A
P_{mpp}	Maximum power point power	W
V_{OC}	Open circuit voltage	V
I_{SC}	Short circuit current	A
I_0	Diode saturated current	A
E	Measured irradiance	W/m^2
E_0	Standard irradiance	W/m^2
FF	Fill factor	
C_{FF}	Fill factor model constant	Km^2
T_0	Standard module temperature	K
T_{cell}	Measured cell temperature	K
T_{air}	Measured temperature in the air	°C
K	Constant	A/(W/m^2)
k_1	Constant term	m^2/W
η_{inv}	Inverter efficiency	
$NOCT$	Nominal operating cell temperature	°C
N_m	Number of modules	
A	Area module	m^2

The AC output power from the PV array can be calculated as in equation 5.3 when the fill factor model is used.

$$P_{out,AC} = P_{out} \cdot N_m \cdot \eta_{inv} \tag{5.3}$$

Other important values to be obtained for calculating output power is the temperature of the photovoltaic cell T_{cell}, which can be calculated based on equation 5.4. T_{air} and E is based on local measurements of temperature and irradiation.

$$T_{cell} = T_{air} + \frac{NOCT - 20}{800} \cdot E + 273.15 \tag{5.4}$$

The constant term k_1 can be calculated as a fraction of the constant K and the diode saturated current I_0. The diode saturated current can be expressed from the saturated current density which is $I_0/(cellarea)$ given as $10^{-12}/(cellarea)$ [A/m^2]. The constant K

is a fraction of the short circuit current I_{SC} and the standard irradiance E_0, giving K equal to I_{SC}/E_0.

Development of photovoltaic data

The construction of PV generation data is based on values of temperature and global radiation at the measuring point, Mære in Nord-Trøndelag. The PV module data is based on Mitsubishi Electric photovoltaic module for a 255 Wp, and the data sheet can be seen in [11]. Table 5.3 summarizes the constants and calculated data for parameters used to express the output power. Since the fill factor model best predicts power output values for PV cells during clear and overcast weather, shading, scattered and transient cloud cover are neglected. This thesis will not cover the optimal placement of the PV panels and neglect the optimal placing and angling of the panels. Based on the fill factor model production profiles for PV generation is obtained and the calculation has been conducted in Python.

Table (5.3) Data for constant parameters based on Mitsubishi Electric Photovoltaic Module [11].

Symbol	**Value**
V_{mpp}	31.2 V
I_{mpp}	8.18 A
P_{mpp}	255 W
V_{OC}	37.8 V
I_{SC}	8.89 A
I_0	$1.6 \cdot 10^{-12}$
E_0	1000 W/m^2
FF	0.7595
T_0	298.15 K (based on T_0 = 25°C)
K	0.00889 A/(W/m^2)
k_1	$555625 \cdot 10^4$
η_{inv}	0.9
$NOCT$	45.7°C
N_m	20000
A	1.6 m^2

5.4.3 Construction of wind generation data

Mathematical method for calculating the output power of a wind turbine

A mathematical method to construct output power generated from wind turbines is discussed in the book *Renewable and efficient electric power systems* by G. M. Masters [7]. The power in the wind is calculated as in equation 5.5, where ρ represent the air density in [kg/m^3], A is the cross-section area through which the wind passes in [m^2] and v is the speed of the wind in [m/s].

$$P_{out} = \frac{1}{2}\rho A v^3 \tag{5.5}$$

The kinetic energy extracted by the wind turbine can be calculated as in equation 5.6. The wind speed right after the wind turbine must deviate from zero if the upstream wind speed of the turbine is different from zero. That results in a difference in the extracted power from the wind turbine compared to the kinetic energy in the wind. C_p is often featured as the efficiency of the rotor and illustrates the amount of power the wind turbine is able to extract. The efficiency of the rotor is based on the deviation in the wind speed before and after the wind turbine.

$$P_{out} = \frac{1}{2}\rho A v^3 C_p \tag{5.6}$$

The wind speed applied to calculate the output power of the wind turbine is based on the height of the wind turbine. The wind speed at any height can be calculated by using a reference height and speed. The expression is shown in equation 5.7 where v_0 and H_0 represents the reference values of the wind speed and height, H represent the height of the turbine and v is the wind speed at the wind turbine height. The friction coefficient α is based on the terrain characteristic for the given area and Table 5.4 summaries the different variations in the friction coefficient.

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha} \tag{5.7}$$

Table (5.4) Friction coefficient for various terrain characteristics [7].

Terrain characteristics	**Friction coefficient α**
Smooth hard ground, calm water	0.10
Tall grass in level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

A wind turbine power curve illustrates the output power based on wind speed. The power curve is categorized into four different zones shown in Figure 5.4. In the first zone, the wind speed is to low to overcome the friction to drive the train of the turbine. V_C is the cut-in speed which is the minimum needed speed to start the generator. The second zone is located between the cut-in speed and the rated wind speed, where the turbine aims to maximize the output based on the wind speed. The rated power speed V_R idealizes the power curve and gives the rated output power for the wind turbine. The third zone is between the rated wind speed and the cut-out speed V_F, and the turbine sheds the wind in this zone to obtain rated output power. The cut-out speed illustrated the maximum wind speed where the wind speed is too high and might danger the wind turbine. The machine will shut down which indicates the fourth zone.

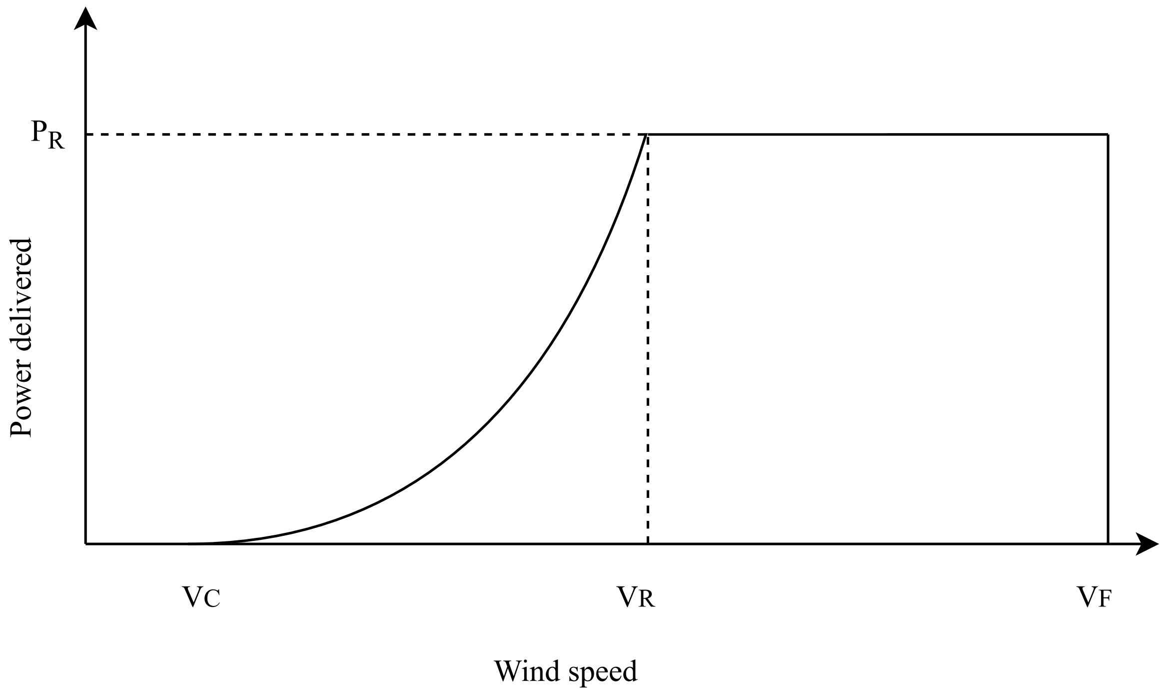


Figure (5.4) Example of idealized power curve [7]

Wind turbine

The modeling of wind turbine output power is based on the hourly average wind speed at 2 m height for the measuring point. The generation of wind speed at rotor hub height is based on equation 5.7 and conducted in Python. Through measuring of wind speed at different heights, a wind turbine from ATB Riva Calzoni named WTG ATB 500.54 [12] is found to be the best match for the wind speed characteristic at the measuring point. The reason is based on the relatively low cut-in speed (V_C) and rated wind speed (V_R) for this wind turbine, which will result in higher obtained output power and fits well to the weather conditions at the measuring point for the investigated days. A summary of the most important data for the ATB 500.54 wind turbine is shown in Table 5.5.

Table (5.5) Wind turbine data [12].

Parameter	**Value**	**Unit**
V_C	3	m/s
V_R	10	m/s
V_F	25	m/s
P_R	500	kW
Rotor bub height	50	m
Number of turbines	10	-

The output power based on wind speed is estimated with the help of the power curve to the wind turbine, shown in Figure 5.5. The estimation is done with linear interpolation and the algorithm can be seen in Algorithm 1. The wind speed is estimated for a wooded countryside terrain characteristic, giving $\alpha = 0.25$, for better representing the weather at the measuring point.

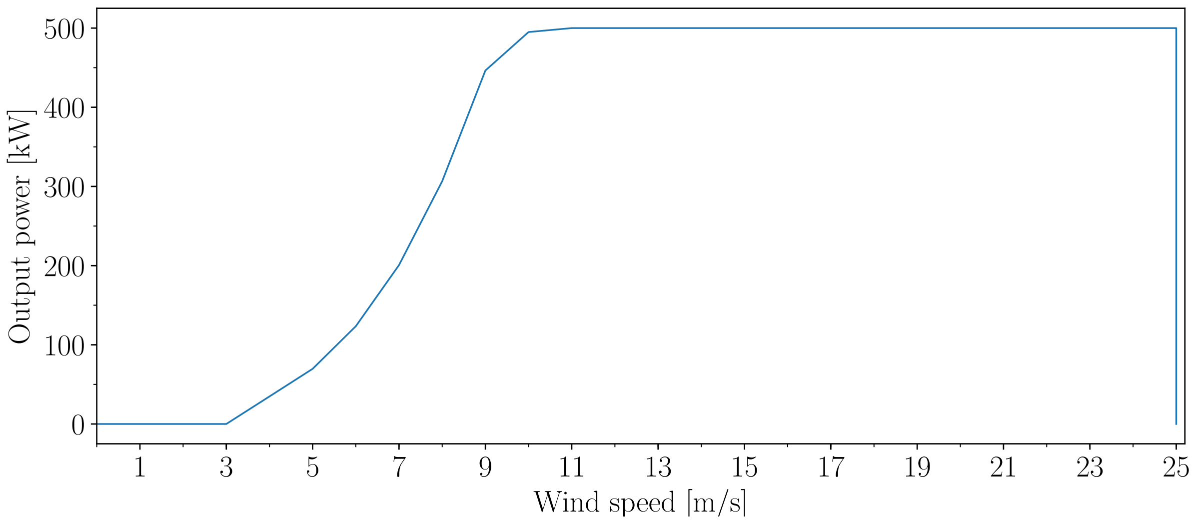


Figure (5.5) The power curve for the WTG ATB 500.54 wind turbine

Algorithm: Linear interpolation algorithm

```
for hour in the range of 24 hours do
    update velocity (v) for turbine height based on reference velocity and height
    if v[hour] ≤ V_C or v[hour] > V_F then
        output power of hour = 0
    else if v[hour] > V_R and v[hour] ≤ V_F then
        output power of hour = rated power
    else
        #Linear interpolation based on values for velocity and output power from the
         wind turbine power curve
        V_a = rounded down of v[hour]
        V_b = rounded up of v[hour]
        output power of hour = power for value a + (power for value b - power for
         value a) · ((v[hour] - V_a)/(V_b - V_a))
    end
end
```

5.4.4 Construction of energy storage

Energy storage type and characteristics

The energy storage system in the model is illustrated through a battery energy storage system (BESS). The chosen BESS has a capacity of 2 MWh and a rated charging and discharging power of 1 MW. In the model is the battery built to be able to have a state of charge (SoC) equal to 0 % and 100 %. Thus, the battery will be able to be fully charged and fully discharged. This illustrates a representation of a BESS of 3.33 MWh where the

SoC should be between 20 % and 80 % in a normal operation. The choices of size and type of storage system are justified below.

A BESS was chosen because it is predicted to be a good economical alternative to other grid investments in many cases in the distribution system in Norway [111]. Batteries are easily scalable, and manufacturers such as Tesla with the Powerpack already offers solutions that can be implemented in the distribution system or microgrids [112]. The lithium-ion battery technology, also used in the Tesla Powerpack, is a promising technology to use in distribution level microgrids. To avoid degradation of the durability for lithium-ion batteries, they should not be fully charged or discharged [113]. The state of charge limitations are therefore set.

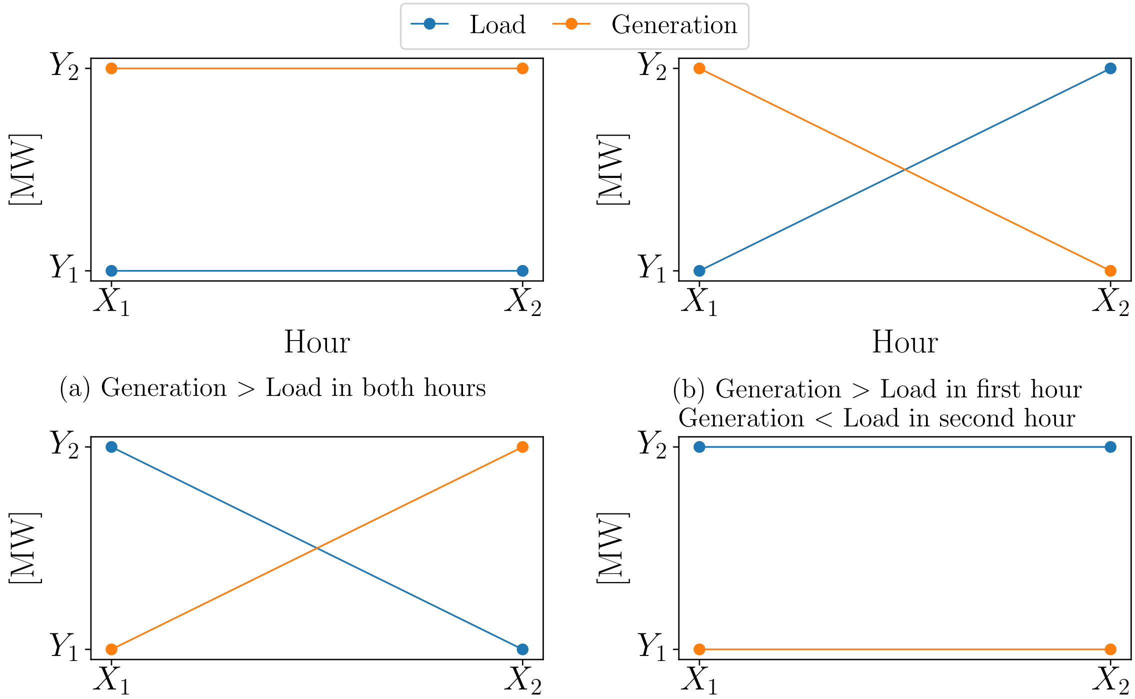
The efficiency of the modelled battery used in this thesis is set to be 100 %, and the actual efficiency obtained by a BESS is therefore neglected. This assumption is made since the model only aims to illustrate the effects from the different strategies. However, the Tesla Powerwall obtain a round trip efficiency of 90 % [114], which is a typical battery efficiency.

The capacity and the rated power of the BESS are chosen big enough to represent a significant part of the load and the energy generated in the microgrid. At the same time, the BESS is small enough to prevent the impression of unlimited flexibility. Some already exciting and relevant grid scaled BESSs are taken into account when the size was decided. The biggest battery that is projected in the Norwegian grid is placed at Skagerak Arena in Skien. The battery obtains a capacity of approximately 1 MWh and 800 kW, and aims to supply the load peaks due to floodlighting during the football games. At other periods, the battery system is going to ensure optimal utilizing of PV generation units [115, 116]. The currently biggest battery storage system in the Nordic countries is at Fortum's Järvenpää power plant. It has a capacity of 1 MWh and a rated power of 2 MW [117]. There is also a similar project in Finland where a battery storing system thrice the size is going to support a wind power plant [118]. Both in Samoa and the Philippines, Tesla Powerpacks are used to create a microgrid to respectively help the island to be fossil fuel-free and to stop outages. In Samoa, the capacity of the BESS is 6 MWh with a rated power of 1.4 MW, while the capacity is 2 MWh with a rated power of 2 MW for the BESS in the Philipines [119, 120].

Method for estimating energy storage

Since the step length of the model is one hour, the battery will obtain some inaccuracies. This inaccuracies can occur when the battery is operated based on the difference between the generation and the load in the microgrid, and the modeled values are produced as continuous curves. The battery will between two hours endure one of four different cases illustrated in Figure 5.6. To take this into account, and by that avoid some inaccuracies, the trapezoid method is applied. The algorithm can be seen in Algorithm 2. The algorithm will first locate which case between two hours that applies and then compute the step length based on the case and difference in generation and load between the two hours. To decide how much the charge and discharge step is, is the area of the effect calculated. The battery will charge and discharge based on the charge and discharge step and the SoC in the battery.

Later in the thesis the battery algorithm is altered to simplify the modelling of the demand response programs. The algorithms used for the batteries modelled for the demand response programs are presented in Section 6.4.



(a) Generation > Load in both hours

(b) Generation > Load in first hour
Generation < Load in second hour

(c) Generation < Load in first hour
Generation > Load in second hour

(d) Generation < Load in both hours

Figure (5.6) The four different battery cases

Algorithm: Energy storage algorithm

d = generation - load

if *Case a* **then**

  Charge time = 1 [hour]

  Charge step = abs($0.5 \cdot Chargetime \cdot (d_{next} + d_{prev})$) [MWh]

else if *Case b* **then**

  Charge time = $d_{prev}/(d_{prev} - d_{next})$ [hour]

  Discharge time = 1 - $Chargetime$ [hour]

  Charge step = abs($0.5 \cdot Chargetime \cdot d_{prev}$) [MWh]

  Discharge step = abs($0.5 \cdot Dischargetime \cdot d_{next}$) [MWh]

else if *Case c* **then**

  Discharge time = $d_{prev}/(d_{prev} - d_{next})$ [hour]

  Charge time = 1 - $Dischargetime$ [hour]

  Charge step = abs($0.5 \cdot Chargetime \cdot d_{prev}$) [MWh]

  Discharge step = abs($0.5 \cdot Dischargetime \cdot d_{next}$) [MWh]

else

  (Case d)

  Discharge time = 1 [hour]

  Discharge step = abs($0.5 \cdot Dischargetime \cdot (d_{next} + d_{prev})$) [MWh]

end

5.4.5 Construction of load data

The load data is based on FASIT-profiles for average profiles for different types of customers. The data for high load demand during weekdays for some important load customers can be obtained in Appendix A.1. The calculation of average load profiles are based on equation 5.8 where A and B are parameters from the FASIT-profiles and T_{air} is the air temperature in [$^{\circ}$ C]. The total reactive load is estimated based on $cos(\phi) = 0.98$ for all the loads.

$$P_{load} = A \cdot T_{air} + B \tag{5.8}$$

Loads are placed different places in the network to obtain a system with large consumers such as industrial, offices, hospital buildings and retail customers at the start of the radial network and more residential and school customers with some industrial consumers further down in the radial. This solution is chosen to make a system with a high amount of load and to ensure some voltage problems in the buses furthest away.

5.4.6 Construction of line data

Overhead lines from the Pandapower standard library compatible with 50 Hz system are used to model the network. Three different aluminum overhead lines with different cross-sectional areas for 20 kV are chosen. The lines are distributed in the network considering the expected power flow on each line, where the lines closest to the external grid have the largest cross-section area and therefore the highest current capacity. Line parameters from the standard library can be found in [121]. The line types that are used in the model together with the most important parameters are presented in Table 5.6.

Table (5.6) Overhead lines used in the model

Line type	r **[Ω/km]**	x **[Ω/km]**	c **[nF/km]**	i_{max} **[kA]**
149-AL1/24-ST1A	0.194	0.337	10.5	0.47
94-AL1/15-ST1A	0.306	0.35	10	0.35
48-AL1/8-ST1A	0.5939	0.372	9.5	0.21

5.4.7 Regulation

Active and reactive power losses

The traditional structure of the Norwegian power system explained in Section 3.1.1 requires long lines and cables for transferring power from the production units to the customers. All lines and cables have a resistance and a reactance leading to power losses and voltage drops along the lines and cables. The sum of AC active and reactive power losses along the system lines can be described as in equation 5.9 and equation 5.10. The equation illustrates that the power losses are proportional with the square of the current and therefore inverse proportional with the square of the voltage. N represents the number of branches in the system, I_k is the branch current, R_k is the resistance and X_k is the reactance of the k_{th} line or cable.

$$P_{loss} = \sum_{k=1}^{N} |I_k|^2 \cdot R_k \tag{5.9}$$

$$Q_{loss} = \sum_{k=1}^{N} |I_k|^2 \cdot X_k \tag{5.10}$$

Voltage drop

Furthermore, the voltage drop over a line can be expressed as in equation 5.11, where V_s and V_r stands for the sending end voltage and receiving end voltage respectively, $\overline{I}$ illustrates the line current between the sending and receiving bus, R is the line resistance and X is the line reactance.

$$\Delta V_{loss} = |V_s - V_r| = \overline{I} \cdot (R + jX) \tag{5.11}$$

The current in the line can be expressed as in equation 5.12. P_r is the receiving end active power and Q_r is the receiving end reactive power. This equation is based on the expression for the apparent power at the receiving end seen in equation 5.13.

$$\overline{I} = \frac{P_r - jQ_r}{V_r} \tag{5.12}$$

$$S_r = P_r + jQ_r = V_r \cdot \overline{I}^* \tag{5.13}$$

The assembling of equation 5.12 and equation 5.11 gives the new formula for the voltage loss over a line equal to the expression obtained in equation 5.14.

$$\Delta V_{loss} = \frac{RP_r + XQ_r}{V_r} - j\frac{RQ_r - XP_r}{V_r} \tag{5.14}$$

If the signs of P and Q are equal, the imaginary part of equation 5.14 will become small compared to the real part of the expression since the two imaginary parts will obtain obtain different signs. Therefore, the expression can be simplified as in equation 5.15 [122]. In [47], this assumption is illustrated through an investigation where equation 5.14 and equation 5.15 have been plotted together when Q and P obtain the same sign and when they have the opposite sign. The conclusion illustrated that the simplification was most accurate when P and Q obtained the same sign and the accuracy decreased when the active power production increases.

$$\Delta V_{loss} = \frac{RP_r + XQ_r}{V_r} \tag{5.15}$$

The change in voltage per unit can be expressed as in equation 5.16 where the V_N is the nominal voltage in the system.

$$\Delta V_{loss,pu} = \frac{RP_r + XQ_r}{V_N \cdot V_r} \tag{5.16}$$

Equation 5.16 illustrates that the change in voltage due to the active power produced from a DG can be expressed as in equation 5.17, while the change in voltage due to the reactive power produced for a DG can be expressed as in equation 5.18.

$$\Delta V_{loss,pu,active} = \frac{R \cdot P_r}{V_N \cdot V_r} \tag{5.17}$$

$$\Delta V_{loss,pu,reactive} = \frac{X \cdot Q_r}{V_N \cdot V_r} \tag{5.18}$$

The influence the reactive power has on the voltage can be examined through the R/X ratio for the lines and cables in the system. Low R/X ratio will result in a higher impact on the voltage. Overhead lines usually have lower R/X ratio than underground cables meaning that overhead lines have a bigger potential regarding voltage regulation when using reactive power than cables [15]. This effect can be seen in Figure 5.7. The figure illustrates three different R/X scenarios, R/X = 0.5, R/X = 2 and R/X = 1. The blue line illustrates a situation with some active power production at the end bus, and the orange line illustrates the situation where all the active power has been shifted to reactive power. By comparing the lines for each R/X ratio it is clear that the reactive power influences the voltage in greater extent for low values of R/X, while the active power is more influential to the voltage profile for high R/X ratios.

Figure 5.7 is based on a receiving end load with equal active and reactive demand. This is not typically the case for normal network loads, where the active power demand usually is higher than the reactive power demand. Thus, the equal importance between active and reactive power for R/X = 1.

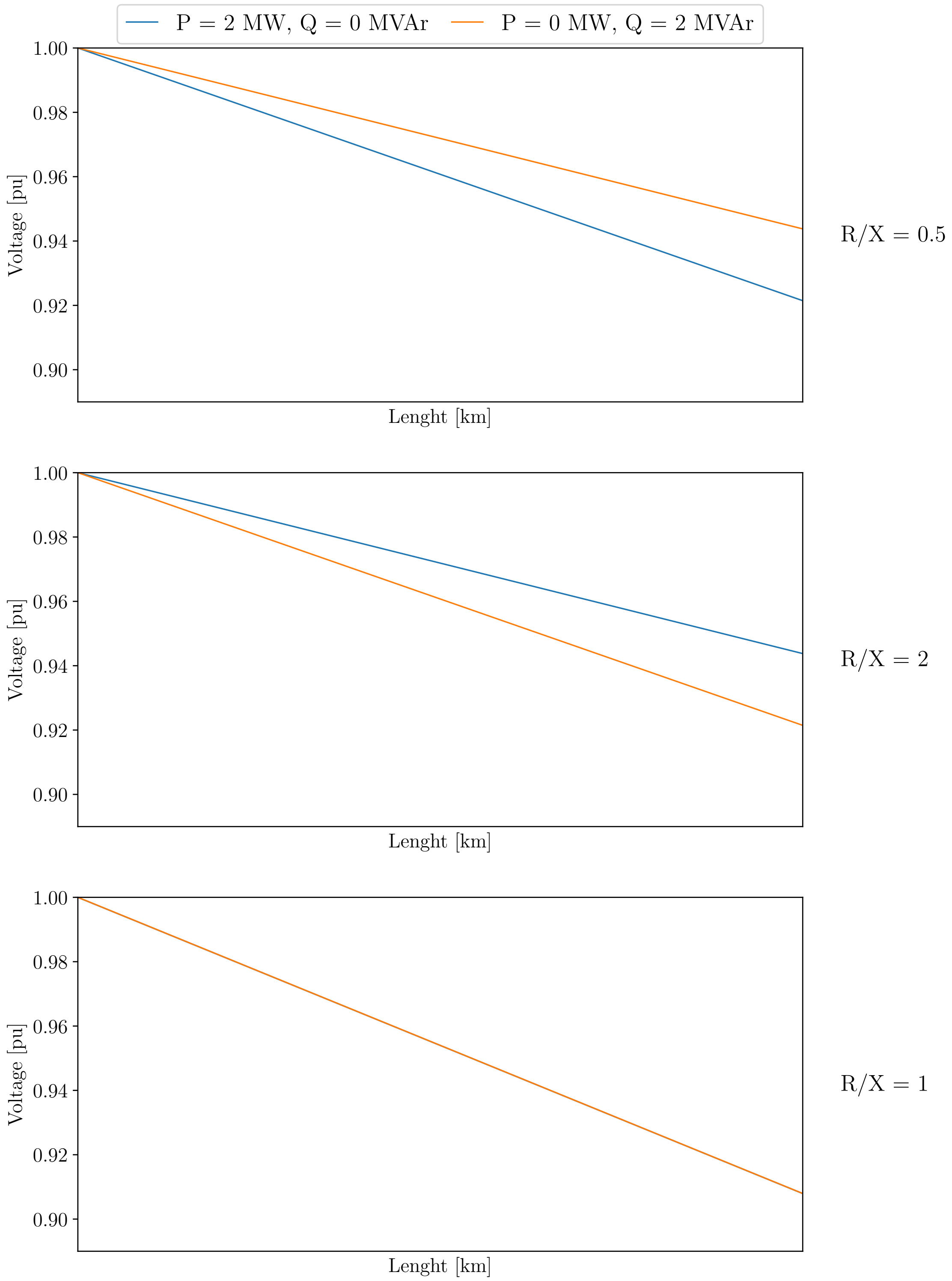


Figure (5.7) The change in voltage based on R/X ratio and the amount of produced active and reactive power

Voltage regulation

In Section 3.2, voltage control as an ancillary service is explained. Different methods aim to ensure voltage control by consuming or generate reactive power. In this master's thesis, voltage regulation with reactive power compensation will be presented. Voltage regulation is based on measurement of the change in voltage magnitude between the sending end bus and receiving end bus. The expression for the percentage voltage regulation of a line can be seen in equation 5.19. Voltage regulation aims to provide the system with reactive power compensation to ensure that the voltage is equal to a voltage setpoint on the given bus [122]. This can be ensured by either deliver reactive power to the system or absorb reactive power from the system to either increase or decrease the voltage.

$$\%regulation = \frac{|V_s| - |V_r|}{|V_r|} \cdot 100\% \tag{5.19}$$

A voltage regulator can function in different manners. One strategy is to monitor all the bus voltages in the system. By this, examine if some voltages in the system surpasses or falls below the voltage limit of that bus. The voltage limit of the bus is decided based on the wanted outcome which is keeping the voltage deviation at a bus within the required 5 % range. This means that the difference between the lowest voltage at high load and highest voltage at low load at any of the buses must be less than 5 %. If some of the voltages go outside of this boundary, the voltage regulator will react with the goal of restoring the voltages. The setpoint voltage for the voltage regulator can be calculated based on different wanted outcomes for the voltage profiles in the network. Thus, the setpoint voltage for the voltage regulator can be calculated with the purpose to obtain any wanted outcomes for the system voltages.

The use of reactive power to restore the voltage can have some negative effects on the system as well. A system obtaining high R/X ratio will, as seen in Figure 5.7, be more sensitive to active power regulation than reactive, meaning that the active power will contribute with more regarding the change in voltage than the reactive power. A higher amount of reactive power will result in both higher active and reactive power losses over the lines due to the increased current, see equation 5.9 and 5.10. Thus, the placement of the regulator is important to make the power travel the shortest possible way. Another problem that might occur regarding reactive power compensation is if the total amount of reactive power injected to the system is higher than the total reactive power demand. This will require the substation between the transmission system and the distribution system to transfer reactive power from the distribution system to the transmission system. As the substation sets the slack bus voltage, the tap changer on the transformer in the substation will work against the voltage regulator to always keep the slack bus voltage equal to the nominal voltage while the voltage regulator will inject more reactive power to keep the setpoint voltage at the regulator bus. This will result in more reactive power than what is really necessary and create a *vicious circle* where two regulating units work against each other. Both the active and reactive power losses will increase if the voltage regulator needs to absorb reactive power to lower the system voltage. This is because more power must be transferred between the transmission system and distribution system.

This master's thesis will only investigate a weak distribution network where some of the system voltages will fall under the voltage limit at 20.9 kV in the fictive 22 kV system. This is based on the 5 % rule telling that the voltage change on a bus must stay within 5

% throughout the year. The algorithm for the constructed voltage regulator can be seen in Figure B.1. The setpoint voltage on the battery bus is set based on minimizing the difference between the highest voltage at bus 22, 22 kV, and the lowest obtained voltage at bus 22, for voltage profiles below the limit. This is done in order to obtain results when the regulator most likely will need to contribute with maximum effect. The maximum voltage change the regulator can contribute regarding reactive power compensation is based on equation 5.18. Due to some small errors regarding equation 5.16, especially when the active and reactive power obtain the opposite sign, which will be for multiple of the regulation hours, the setpoint voltage is tuned to always ensure that the right amount of reactive power is delivered to the system based on the computed highest negative change in voltage. Chapter 6 elaborate more regarding the voltage regulator for the different voltage regulation cases in the model.

Four quadrant operation

A microgrid can be operated in all the four quadrants of a PQ diagram. When the microgrid is connected to the main grid, the power flow between the two systems can also be in all four quadrants. For this model situation, the microgrid will only produce active power when no voltage regulation actions are used, making the microgrid operate in the two first quadrants of the PQ diagram. When voltage regulation actions are implemented, the microgrid will be able to operate in all four quadrants of the PQ diagram. The quadrant of operation is decided by the amount of reactive and active power produced in the microgrid and discharged from the battery compared to the load in the microgrid and the charged power from the battery. Figure 5.8 illustrates the different quadrant operations for a microgrid. The four different operations are as follows;

1. When the microgrid consumes more active and reactive power than it produces, the operation will be in the first quadrant. The microgrid only appears as a load for the main grid.
2. The operation is in the second quadrant when the microgrid produces more active power than it consumes, but consumes more reactive power than it produces. A typical example is when there is a lot of generation in the microgrid, and there is not performed any voltage regulation actions. The only reactive power flow in the microgrid is a result of different loads consuming reactive power.
3. When the microgrid produces both more active and reactive power than it consumes, the operation is in the third quadrant. This can be the case if the microgrid converts some, but not all, of the active power produced into reactive power for voltage regulation purpose.
4. The operation is in the fourth quadrant when the microgrid produces more reactive power than it consumes, but consumes more active power than it produces. One example where this can be the operation case is if the microgrid converts all the active power generated into reactive power for voltage regulation purpose.

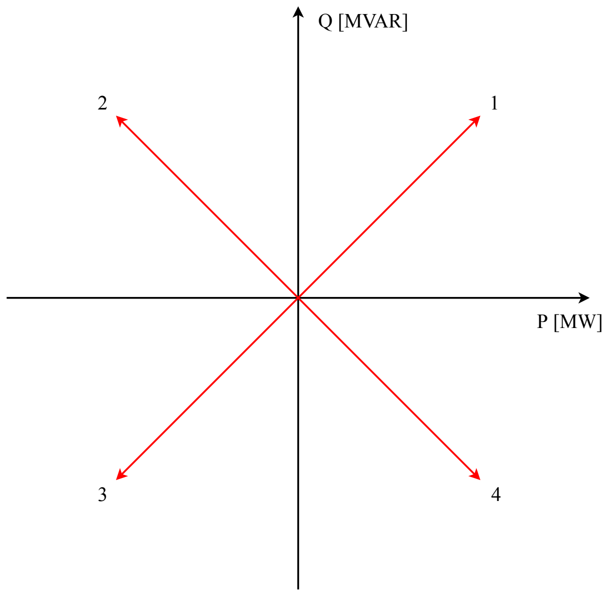


Figure (5.8) PQ curve illustrating the different operation cases for a microgrid

5.4.8 Demand response model constructions

Heat loss calculation in households

It is assumed that equation 5.8 calculates P_{load} when the indoor temperature is held constant. In demand response calculations, the heat loads and therefore the temperatures in the households can be changed. The calculation of household loads in those cases is done based on the first law of thermodynamics, presented in equation 5.20. The law states that the change in internal energy in a system has to be equal to the sum of heat and work delivered to or drawn from the system [123]. Here U, q and w, represent the internal energy, heat and work respectively.

$$dU = dq + dw \tag{5.20}$$

Equation 5.21 is based on equation 5.20 and shows the relationship between the difference of the internal energy and the load of the households with and without demand response. P_{load} is the original load without any demand response. $P_{new\ load}$ is the load with demand response and $\Delta E_{heat\ loss}$ is how much more or less the heat loss changes with different indoor temperatures compared to the reference temperature. The loads are calculated to be constant within each hour.

$$\Delta E = P_{new\ load} - P_{load} - \Delta E_{heat\ loss} \tag{5.21}$$

The different parts of equation 5.21 are described as follows;

- ΔE
  The calculation of the changes in the internal energy is based on the definition of the specific heat capacity. The specific heat capacity with constant volume only depends on the change in heat and is given by equation 5.22, where q_v is the specific amount of heat in [kJ/kg] and T is temperature in [K] [123].

$$C_v = \frac{q_v}{T} \tag{5.22}$$

ΔE for each hour can therefore be expressed as in equation 5.23. T_{end} represent the temperature in the end of the hour, $T_{beginning}$ is the temperature in the beginning of the hour and ρ is the density of air. $3600 \cdot 1000$ is in the denominator to change the unit from kJ to MWh. V is the volume of the household.

$$\Delta E = \frac{(T_{end} - T_{beginning}) \cdot C_v \cdot \rho \cdot V}{3600 \cdot 1000} \tag{5.23}$$

The different constants used in equation 5.23 is $C_v = 0.718$ [kJ/kg*K] and $\rho = 1.20$ [kg/m^3] both at 22°C. The parameters are chosen at 22°C because the temperature is used as the wanted reference indoor temperature in the analysis.

- $P_{new\ load}$
  $P_{new\ load}$ represent the load of the household during demand response actions, and the indoor temperature will, therefore, vary during the day and night.
- P_{load}
  P_{load} is the original load of the household, calculated in equation 5.8, when the indoor temperature is held constant at the wanted reference temperature during the whole day.
- $\Delta E_{heat\ loss}$
  $\Delta E_{heat\ loss}$ is the difference between the heat loss for the new temperatures during the hour compared to the reference temperature. The factor A in equation 5.8 is used as the heat loss for one household per difference in outdoor and indoor temperature. The usage of the factor A is justified by the fact that it is the temperature dependent part of the load equation.

  The heat loss for the new temperatures is calculated using the average temperature during the hour. For the average calculation, it is assumed that the temperature increases or decreases linearly during the hour. The $\Delta E_{heat\ loss}$ is given in equation 5.24.

$$\Delta E_{heat\ loss} = -A \cdot \left(\frac{T_{beginning} + T_{end}}{2} - T_{ref} \right) \tag{5.24}$$

Equation 5.25 is the final equation developed from Equation 5.21, used to calculate $P_{new\ load}$, $T_{beginning}$ or T_{end}, in the household demand response calculations when one of them is unknown.

$$\frac{(T_{end} - T_{beginning}) \cdot C_v \cdot \delta \cdot V}{3600 \cdot 1000} = P_{new\ load} - P_{load} + A \cdot \left(\frac{T_{beginning} + T_{end}}{2} - T_{ref} \right) \tag{5.25}$$

It is assumed that the indoor temperature without any lack of comfort is in a range of 3 °C with 22 °C as the reference temperature. It is also assumed that the indoor temperature can increase between every temperature in the given temperature rage of 22 ±1.5 °C within an hour by increasing the heating loads. Equation 5.24 decides how much the temperature can decrease within an hour due to heat loss.

Calculation of the volume to one household

Equation 5.23 is dependent on the volume of each household. To obtain realistic values for the heat loss due to the change in heat load, a conclusion from Sweco is used [124]. Sweco concluded that 67 % of the total heating loads could be shifted from two hours in the morning, without resulting in any lack of comfort for the consumers in Sweden. The tests were done when the outdoor temperature was between -10 and -15 °C. [125] states that approximately 65 % of the household loads are air heating loads.

By using equation 5.25, the volume used in the further analysis is calculated. The outdoor temperature used is -12.5 °C. The volume of the households is calculated using a $P_{new\ load}$ that is 67 % $\cdot$ 65 % $\approx$ 40 % of the P_{load} and a temperature change from 23.5 to 22 °C from 07:00 to 08:00. Using a roof height of 2.5 m gives an household area of 1867 m^2. The area is way higher than the average household area, but it will give a realistic heat loss behavior for the further calculation and analysis.

Price data collection

The electricity price that is used in the price dependent analysis is the day-ahead prices from the wholesale market. Historical data is collected from Nord Pool for the analyzed days, and can be found in [126]. The day-ahead prices reflect real time electricity pricing for the customers.

Chapter 6

Development of test cases

Chapter 5 explained the general process of the model construction. This chapter will explain the different strategies that are to be explored with this model. The model will be tested for three different days with three different placings of the microgrid. Six different strategies are developed, which gives a total of 54 cases with a microgrid connected to the modeled distribution system. The placement of the microgrid will be chosen somewhat randomly to give an illustrative effect on how the placing affects the distribution system. The placement is decided based on investigating the impact when the microgrid is high in the distribution system, in the middle of the distribution system and at the end of the feeder. The three different microgrid placements will be on bus 10, 15 and 20. Chapter 7 will present and discuss the results based on the described strategies in this chapter.

6.1 Base case

The base case aims to illustrate the different situations without the microgrid connected to the main distribution network. This case presents the weak distribution network situation and discloses any problems that might occur for the different situations. Only a simple power flow calculation will be conducted in this case. The load demand in the network and the voltage profiles for the eight buses furthers away from the slack bus (see Figure 5.1 for the illustration of the 33-bus network) will be presented. The base case is used as a comparison to the developed and tested strategies to show the possible impacts of integrating a microgrid to the distribution system.

The investigated voltage profiles will be compared to the voltage critical limit, explained in Chapter 5, at bus 22.

6.2 The microgrid is connected with distributed generation

This integration of the microgrid will illustrate the different situations when the microgrid is connected to the main distribution network. The only interaction between the microgrid and the distribution operator will be the connection and thus a power flow between the microgrid and the distribution network is obtained. The microgrid will only contribute with active power to the utility for situations where the total production exceeds the total demand in the microgrid. This integration will be divided into two different strategies as listed below;

1. The microgrid is connected without a battery
2. The microgrid is connected with a battery

6.2.1 Strategy 1: The microgrid is connected without a battery

The first strategy aims to investigate the performance of the system when the microgrid is connected to the main distribution system, but with no battery connected to the microgrid. This situation will examine how distributed generation without a regulation strategy can influence the network. This strategy will also investigate how the loads in the microgrid might affect the power flow in the system and the system components. The microgrid will be moved between the three mentioned buses in the distribution system. Another important aspect, highly relevant to the microgrid placement, is the voltage profiles in the microgrid which will be dependent on the voltage profiles in the distribution system. A power flow calculation will be conducted for all the three days with the different microgrid placements and the voltage profiles for the eight buses furthers away from the slack bus and the the total generation and load in the microgrid will be presented.

An important factor in this strategy is that the active power generation from the microgrid DERs only influence the distribution system passively. Thus, the microgrid do not perform any active support to the distribution system.

6.2.2 Strategy 2: The microgrid is connected with a battery

The second strategy will include a battery as an energy storage unit in the microgrid. The battery will not follow any special regulation and aims to only follow the load demand in the microgrid. This means that when there is a surplus of distributed generation compared to the load demand in the microgrid, the battery will store energy until the battery is full or the situation changes. When the load demand exceeds the generation in the microgrid, the battery will discharge until the battery is empty or the situation changes. The algorithm for calculating the charging and discharging step can be found in Algorithm 2. This case aims to examine the same parameters as the case without energy storage, but include how the battery might affect the system. The battery strategy might influence the voltages in the utility compared to the strategy without battery for situations where the battery will charge and discharge. The battery is set to have a state of charge equal to 40 % in the beginning of the analyzed day. The same type of results as for the strategy without the battery will be presented including an illustration of the battery behavior.

Assumptions

The assumptions made in the modelling of the battery are listed as follows;

- The battery is able to be fully charged and discharged. Thus, the battery is able to obtain a SoC equal to 0 % and 100 %.
- The possible battery efficiency is set to 100 %.
- The battery begins with a SoC equal to 40 % in the beginning of each day and new placement of the microgrid.
- The battery will not take the distribution system situation into account. Thus, the battery will only follow the load and production in the microgrid and, therefore, not perform any active service to the distribution system.

6.3 Voltage regulation

These scenarios investigate the system when the microgrid supports the main distribution system with voltage regulation. The voltage regulation will only perform reactive power compensation and not active power compensation although this is a common possible strategy. The voltage regulation is based on the theory explained in Section 5.4.7 and the algorithm for the regulation can be seen in Figure B.1. The voltage algorithm functions in an incremental manner by first computing a power flow simulation of the system without regulation to examine if the system voltage exceeds or fall under the 5 % voltage limit for a distribution system. If the network complies with the voltage limits, the algorithm will proceed to the next hour. If no regulation is needed, a power flow simulation of that hour will be conducted equally to the case with a microgrid connected to the utility including the battery that follows the microgrid behavior. If the network does not comply with the voltage limit, the voltage regulation will regulate with the available reactive power for that hour. The algorithm is built incrementally as described to be able to illustrate a situation where the voltage regulation is able to regulate at any instant. There are two different voltage regulation strategies that will be investigated;

1. Voltage regulation with battery
2. Voltage regulation with battery and the distributed generation

6.3.1 Strategy 3: Voltage regulation with only battery

The voltage regulation with battery is composed to function as an automatic control system with a feedback loop. This enables the battery to regulate at any instant. The battery is presumed to be able to regulate with the same amount of reactive power as it can charge and discharge active power. That gives a maximum reactive power discharge from the battery of 1 MVAr. When the battery regulates by delivering reactive power, the battery will first use the stored capacity before charging active power from the main grid, meaning that the battery will function as a load when it stores active power. Since the system has a step size of one hour, it will be presumed that the battery can store active power while releasing reactive power. A simplification is used, where the battery has the ability to supply reactive power at the rated value in the same hour when it consumes active power at the rated value. When regulation is not needed, the battery will follow the same algorithm as in the battery case in Section 6.2.2. A power flow calculation will be conducted for each hour for all the different days with the different placements of the microgrid, and a representation of the eight furthest down voltage profiles will be conducted.

Assumption

The assumptions made in the modelling of the voltage regulation strategy for battery regulation are listed as follows;

- The voltage regulator will only contribute with reactive power compensation. Active power compensation is also possible, but is not utilized even though the strategy would be preferable for some cases. This is to fully obtain the effect reactive power compensation can have on the system.
- The voltage regulation strategy is based on minimizing the voltage difference between the nominal voltage of 22 kV (the highest set voltage on bus 22) with the voltage on bus 22, if the voltage falls below the critical limit. Furthermore, the regulator will use the necessary reactive power to minimize the difference in voltage.
- The voltage regulator is able to regulate with the same amount of reactive power as the battery can discharge with active. Meaning that the battery can regulate with 1 MVAr.
- The battery is able to be fully charged and discharged. Thus, the battery is able to obtain a SoC equal to 0 % and 100 %.
- The battery begins with a SoC equal to 40 % in the beginning of each day and new placement of the microgrid.
- The possible battery efficiency is set to 100 %.

6.3.2 Strategy 4: Voltage regulation on all the distributed generation including the battery

The battery will follow the same algorithm and operation as in the last case where voltage regulation is performed with only battery capacity. The main difference between this case and the previous is that if the algorithm finds it necessary to regulate with more reactive power, the system will use the generated active power from the DERs to deliver reactive power compensation as well. This strategy aims to investigate how the voltages in the system will respond to more delivered reactive power. The automatic control system will investigate if the active power produced from the DERs can be used based on equation 5.18 to regulate with more reactive power to the system. The same representations as in the previous case will be conducted.

Assumptions

The same battery assumptions as for the case elaborated in Section 6.3.1 applies for this strategy. The other assumptions made in the modelling of the voltage regulation strategy using all the units are listed as follows;

- The voltage regulator is able to fully shift the active power into reactive power if the regulator finds it necessary.
- The voltage regulator strategy is based on minimizing the voltage difference between the nominal voltage of 22 kV (the highest set voltage on bus 22) with the voltage on bus 22, if the voltage falls below the critical limit. Furthermore, the voltage regulator will use the necessary reactive power to minimize the difference in voltage.

6.4 Demand response

These types of integration aims to investigate how the microgrid can affect the rest of the grid when different demand response strategies are implemented. Two different demand response strategies are performed, where the microgrid responds to price signals for its own gain. In the strategies, both operation of the microgrid battery and shifting of the household loads for heating purposes are implemented. Subsequently, it is observed how the microgrid then appears as one load, seen from the utility point of view. Furthermore, an analysis is conducted to investigate how this new appearance affects the voltage of the buses and the loading of the lines in the rest of the grid. The microgrid is assumed to be represented as one customer. The implemented strategies are listed as follows;

1. Price based program
2. Peak shaving program

6.4.1 Strategy 5: Price based program

This strategy is based on the electric energy price following the per hour spot price from the wholesale market. There is not implemented a new network tariff affecting the prices. Therefore, this strategy will not take the total load and generation in the microgrid into account.

Algorithm for the battery

The battery response actions are decided using a dynamic programming approach including both optimal substructure and overlapping subproblems. Figure 6.1 illustrates the algorithm, where the operation of the battery is constant through one hour. The battery will in a price based strategy charge and discharge at rated power to maximize the profit, if the capacity limits allow it. Therefore, the charging and discharging power are set to always be 1 MW from the battery point of view. The state of charge can then vary between three states in each time step when both the initial and final state are chosen to be 50 %. Each element illustrated by S in the figure represents the different states the battery can achieve in each hour. The states represent the state of charge and also contain the maximum amount of surplus the microgrid can obtain when it ends up in that certain state during that hour. The algorithm iterates through every hour. The highest surplus for each state and the path between states to get there are updated for every hour. The efficiency of the battery is taken into account in the surplus calculation. In the Figure 6.1, P is the electricity price in the hour between the states and n is the battery efficiency. It is assumed that the energy discharged from the battery is sold at the same price as the buying price if the microgrid gets a surplus of generated energy. The S in the figure represent the different state of charges the battery can achieve in the each hour.

The battery efficiency is assumed to be 95 % for both the discharging and charging process. That will give a round trip efficiency of 90.25 % which is close to the efficiency of the Tesla Powerwall according to its data sheet [114].

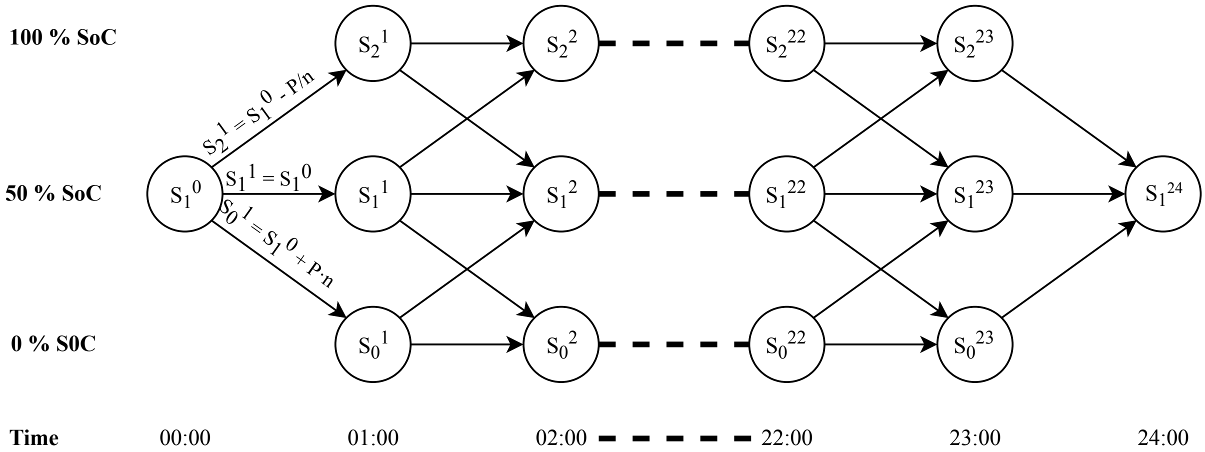


Figure (6.1) Algorithm for operation of battery with real time pricing program

Algorithm for the households

The demand response actions from the households are decided using the same approach as for the battery. Figure 6.2 illustrates this algorithm. The three different states, S, represent the allowed temperatures during the hours. ΔE is the difference in household load to achieve the new temperature compared to the load the same hour when there is no demand response. Because of the maximum possible amount of heat loss during one hour, the temperature might not be able to jump down from T_{max} to T_{min} in just one hour by only reducing the load of the households. Therefore, the algorithm can use more temperature stages than three in the decision process. The results in this thesis are made by using 17 stages. As for the battery algorithm, the optimal temperature path for each stage is updated for each hour, and the optimal temperature path that begins and ends at T_{ref} is used for the calculation of demand response loads.

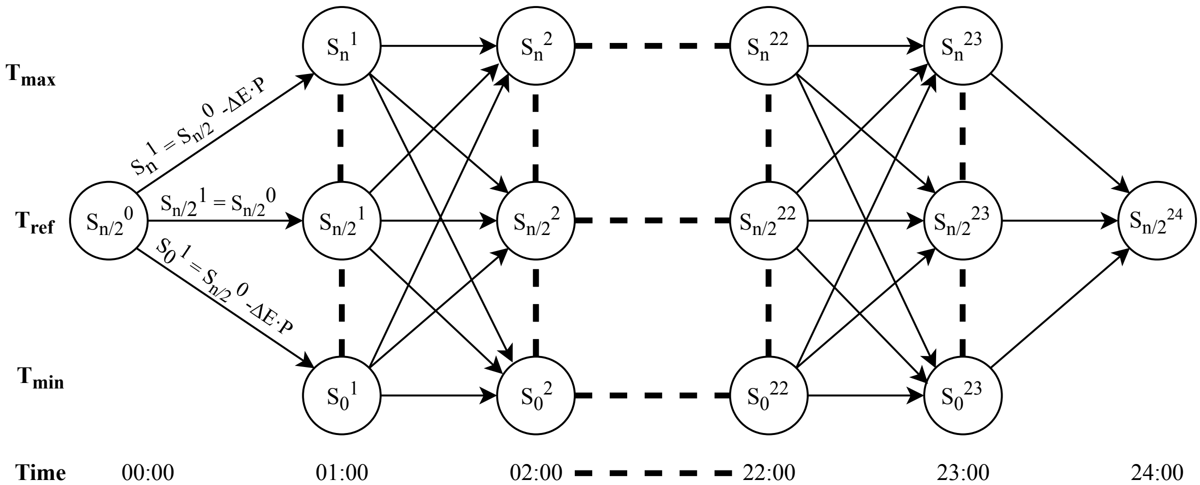


Figure (6.2) Algorithm for operation of households with real time pricing program

Assumptions

The assumptions made in the development of the real time pricing program are listed as follows;

- The price from the day-ahead market is assumed to alone represent the electricity price for the customers if real time pricing is implemented.
- Both the discharging and the charging process of the battery are assumed to have an efficiency of 95 %.
- The efficiency of the battery is used for price and revenue calculations, but is neglected for load calculations. It is assumed that the efficiency does not have any significant impact on how the effects from the different operations of the battery appears.
- The battery is assumed to have an initial SoC of 50 %.
- The temperature range in a household without any lack of comfort is assumed to be 3 °C.
- The average ideal indoor temperature for the household customers is assumed to be 22 °C.

6.4.2 Strategy 6: Peak shaving program

This strategy aims to lower the total demand peak in the microgrid. The motivation behind this strategy can be that measured electric power is implemented in the network tariff, but that time of use is not implemented. The measured electric power part can be implemented in different ways. It can for instance be based on the highest load peaks during a month. One other option is to calculate the power part of the tariff based on the highest load peak on every day. The last alternative encourages to reduce the load peaks every day. Since the microgrid is represented as one customer, the total load in the microgrid is the sum of all loads and generation in the microgrid, where generation counts as negative load.

Algorithm for the battery

The algorithm for peak shaving operation by the battery is based on the simplified optimization scheme presented in [127]. The flow chart of the algorithm that is developed in this thesis can be seen in Figure B.2. The battery goes through an iteration with lower and lower shaving level, where it ensures that the total load in the microgrid every hour is lower than the shaving level. The state of charge limits decide whether it is possible to reach the shaving level in the iteration or not. The total load is lowered by discharging the battery. In order to lower the load peaks as much as possible, the battery tries to reach its maximum capacity prior to the peaks by charging. As a simplification, the state of charge limits are here set to 0 % and 100 %, and will therefore represent the percentage of the available capacity in the battery. After the last peak, the initial state of charge will be reached. If this is not possible, a decided final state of charge limit might also work as a constraint for the peak shaving.

Algorithm for the households

The algorithm developed for peak shaving operation by the households in the microgrid is based on the same approach as for the battery. The flow chart of the algorithm can be seen in Figure B.3. The total load in the microgrid is changed by adjusting the loads for heating purposes. The indoor temperature always have to be within the range. Therefore, the indoor temperature is the limitation for which shaving level that is possible to reach. In order to lower the load peaks as much as possible, the households try to reach their maximum allowed temperature prior to the peaks.

Assumptions

The assumptions made in the development of the peak shaving scenario are listed as follows;

- It is assumed that there will be an incentive for the microgrid to perform peak shaving in all the days, regardless whether there are high peaks or not.
- The efficiency of the battery is neglected for load calculations. It is assumed that the efficiency do not have any significant impact on how the effects from the different operations of the battery appears.
- The battery is assumed to have an initial SoC of 40 %.
- The temperature range in a household without any lack of comfort is assumed to be 3 °C.
- The average ideal indoor temperature for the household customers is assumed to be 22 °C.

6.5 Line congestion

Longer periods of higher loading on a line might cause overheating and failure of the line. Thus, as a way to differentiate between the different strategies and visualize how the strategies affects the lines, the line loading percentages will be analyzed. The loading percentage of two lines are analyzed, and the chosen lines are line 4 and 13. They are chosen because they are placed in different parts of the grid, and can therefore experience different affects based on the placement of the microgrid.

6.6 Strategy names

As this thesis involves multiple strategies and cases, naming the different strategies can be necessary to avoid misunderstandings and inappropriate explanations. Table 6.1 includes the different names with an explanation of which strategy the name belongs to. The names of the strategies will be used consistently during the representation and discussion of the result in Chapter 7.

Table (6.1) Simplified naming of the different cases

Strategy/Case name	**Description**
Base case	The base case illustrates the representation of the 33-bus network without any microgrid connected.
Generation	The case where the microgrid is connected to the utility, but without any battery. All the produced active power from the microgrid will be used at that instant.
Battery	The case where the microgrid is connected to the utility, but with battery functionality following the production and demand in the microgrid. The battery will follow an algorithm based on storing energy when the production is higher than the demand and release energy for the opposite case.
Battery regulation	The case where the microgrid battery contributes with voltage regulation by delivering reactive power.
All regulation	The case where the microgrid battery and all the generation units can contribute with voltage regulation by delivering reactive power.
PBP	The case where the battery and the households in the microgrid are operated in response to real time pricing price signals.
Peak shaving	The case where the battery and the households in the microgrid are operated to get the total load peak in the as low as possible.

Chapter 7

Analysis of results

This chapter will present the results based on the three different days. The results will be presented based on day, strategy and then the placement of the microgrid. The results for each day will therefore first be explained before comparisons between strategies will be discussed in the end. Appendix C include some additional information about the conducted simulations that might be interesting to obtain a brighter view.

7.1 Day 1: 4th of June

7.1.1 Base case

Figure 7.1 shows the load demand curve in the 33-bus distribution system for the 4th of June. The first demand peaks appear around hour 9 and 11 before the demand slowly decreases until hour 24. Figure 7.2 illustrates how this demand affects the bus voltage for the buses on the radial placed furthest away from the slack bus. Some of the bus voltages have already around hour 7 dropped under the lowest set criterion. The limit is constructed based on the 5 % rule and is 20.9 kV for bus 22 when the highest voltage during a year is assumed to be 22 kV at bus 22. For an easier comparison, this critical limit will apply for all the eight compared buses, even though bus 15 to 21 will have slightly different critical limits. The critical limit can be illustrated as the dotted black line in Figure 7.2. The temperature during this day illustrates a normal day in the spring or fall in Norway and is therefore not the worst case the distribution system might encounter during a year. The voltages on all the seven buses furthest away fall below the critical limit during this day. The maximum change in voltage compared to the nominal voltage in the system happens at hour 20 and is $\Delta V_{max} = 0.0632$ pu $= 1.39$ kV. That gives a voltage equal to 20.61 kV. This is not an acceptable operation and some changes to the system are required.

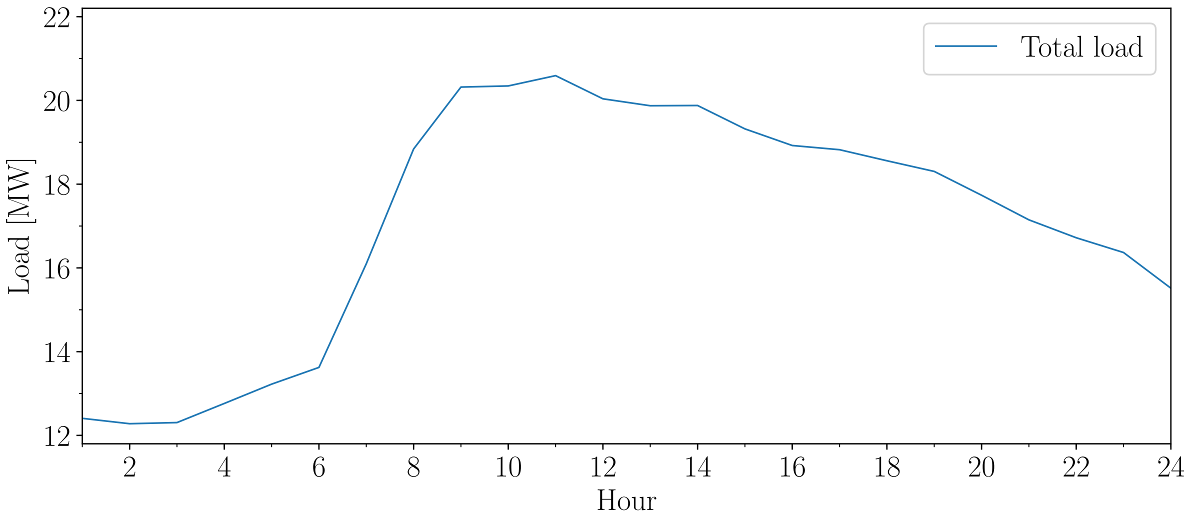


Figure (7.1) Base case: Active load profiles in the 33-bus network on the 4th of June

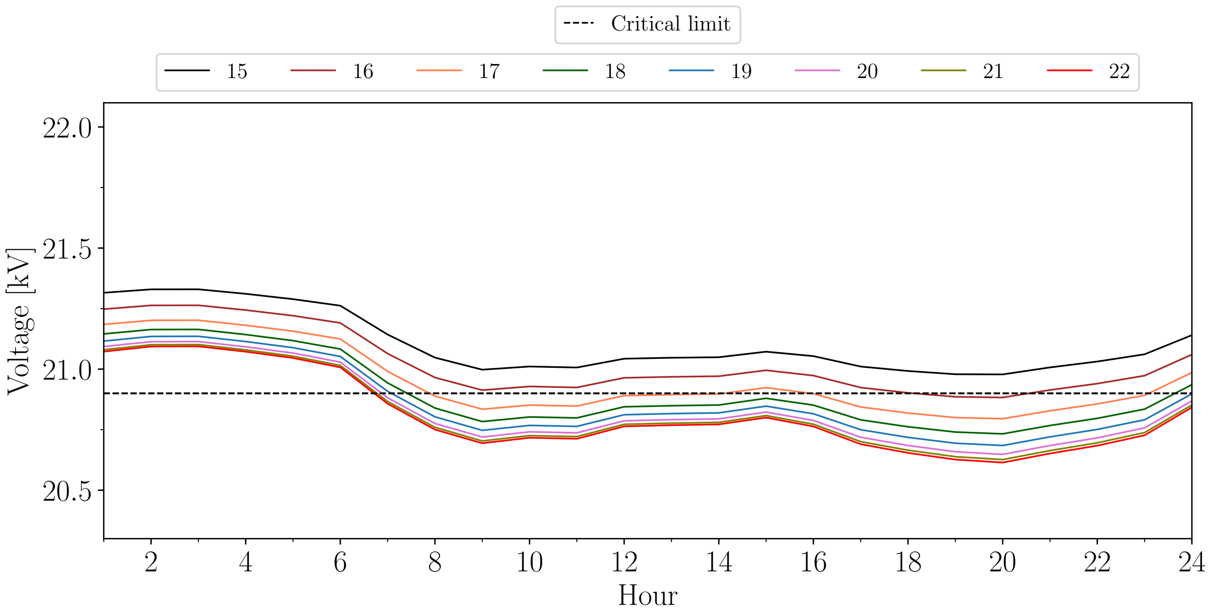
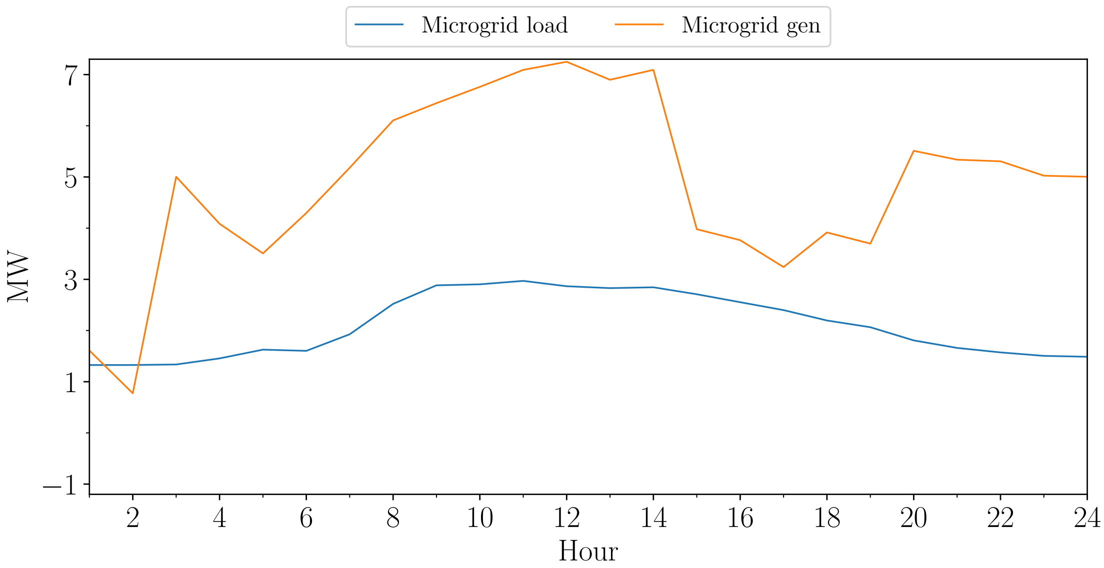


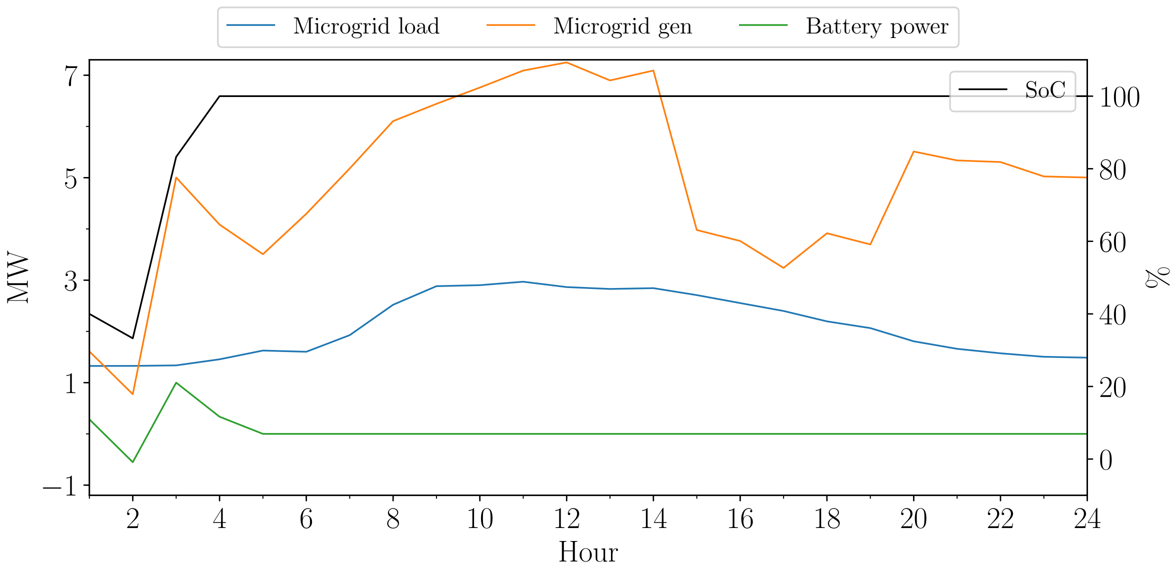
Figure (7.2) Base case: Voltage profiles for the most vulnerable buses on the 4th of June

7.1.2 Connection of microgrid and voltage regulation

Figure 7.3 displays the total load and production in the microgrid for this day. In Figure 7.3b, the SoC (black) of the battery and the battery power (green) are included. The battery power values are negative for discharging and positive for charging. In this case, there is only one hour where the demand exceeds the production in the microgrid and the battery discharges. It results in only one hour where the distribution system experiences the microgrid as a load. For the rest of the hours, the microgrid is seen as a generator from the distribution system point of view. The battery stores energy after that hour and is full for the rest of the day. Since the battery only is required to discharge and charge once based on this situation, the battery will be able to contribute with stored capacity for reactive power compensation.



(a) Without battery



(b) With battery

Figure (7.3) Load, generation and battery in the microgrid on the 4th of June

7.1.2.1 Microgrid connected to bus 10

Connection without voltage regulation

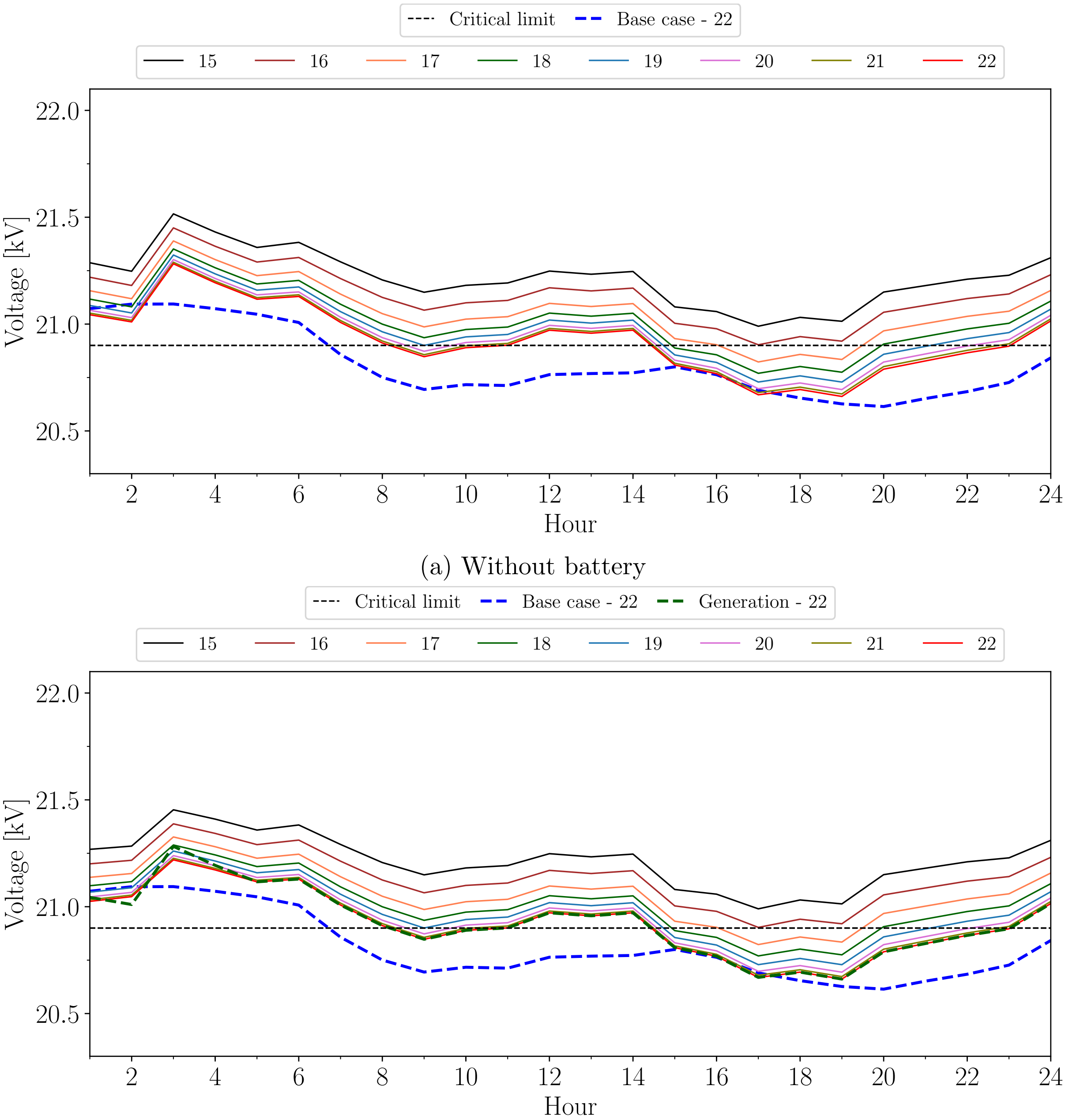
The first case to investigate is when the microgrid is connected to bus 10 in the main distribution network (see Figure 5.1 for illustration of the microgrid). Bus 10 is located relatively high on the main feeder in the distribution system. Figure 7.4 illustrates the voltage profiles for the most vulnerable buses in the main distribution system when the microgrid operates with and without battery, but without any active regulation strategy. The microgrid will, therefore, only contribute with active power during hours where the total production exceeds the total demand in the microgrid. Since the microgrid only discharges a small amount of power during one hour where the voltages are within the critical limit, the effect regarding the worst hours of the two Figures 7.4a and 7.4b will be equal. Thus, the voltage profiles for both the strategies, with and without battery, will be identical since the battery is not in use after it is fully charged in hour 4. The effect can be illustrated through the dotted green line in Figure 7.4b, which follows the voltage profile for bus 22 for the generation strategy.

The dotted blue line in Figure 7.4 illustrates the voltage on bus 22 for the base case. The voltages are worsened for the first two hours where the load in the microgrid surpasses the total production from the DERs, and the utility experiences a higher total demand in the system. This effect is a result of the distribution system experiencing the microgrid as an additional load in the network. It can be seen between hour 16 and 17 that the voltage profiles drop slightly compared to the base case. This hour experiences a small drop in generation, requiring the distribution network to transfer more power from the slack bus compared to the previous hours where the penetration of active power is higher. For the other hours, the connection of the microgrid will improve the voltage profiles, since more local production of active power is present. Thus, the distribution system will experience the microgrid as a generation unit and not a load. This effect illustrates that the contribution of active power produced closer to the loads helps the voltages drastically for hours with high production. Whereas, for hours where the demand exceeds the production in the microgrid and the production is low, the voltages are worsened compared to the base case.

Table 7.1 summarizes the percentage increase in voltage on bus 22 for the battery strategy compared to the base case. Four different hours are represented. That is the hour with the highest increase, the hour with the lowest increase, the new worst hour and the worst hour in the base case. The best effect happens for hour 12 when one of the highest penetration of active power production happens.

Table (7.1) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	12	1	19	20
% Increase, battery	1.001	-0.226	0.168	0.848



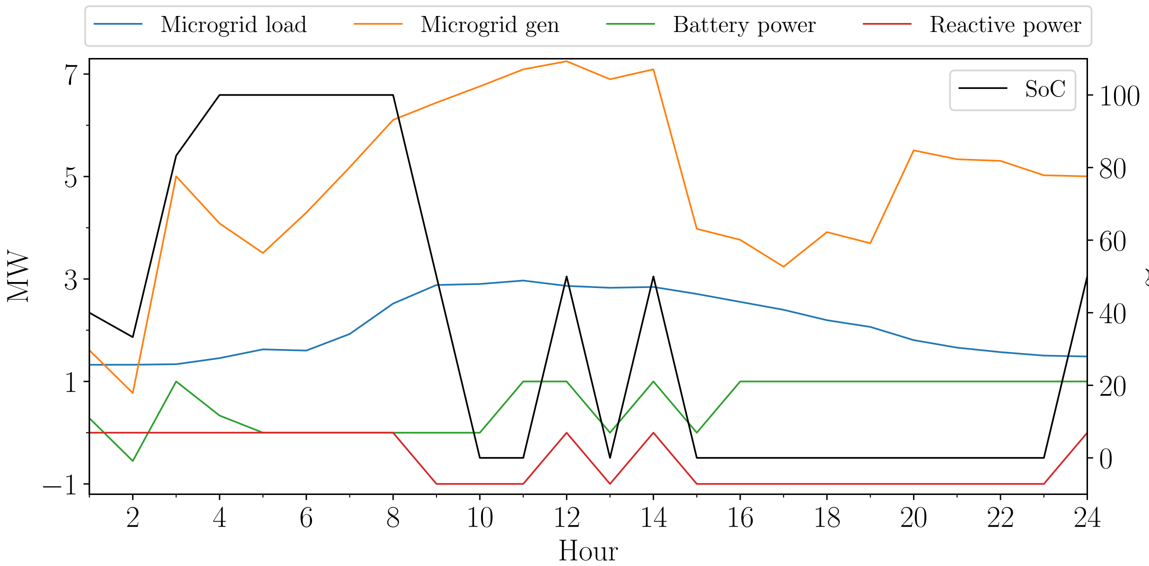
(a) Without battery

(b) With battery

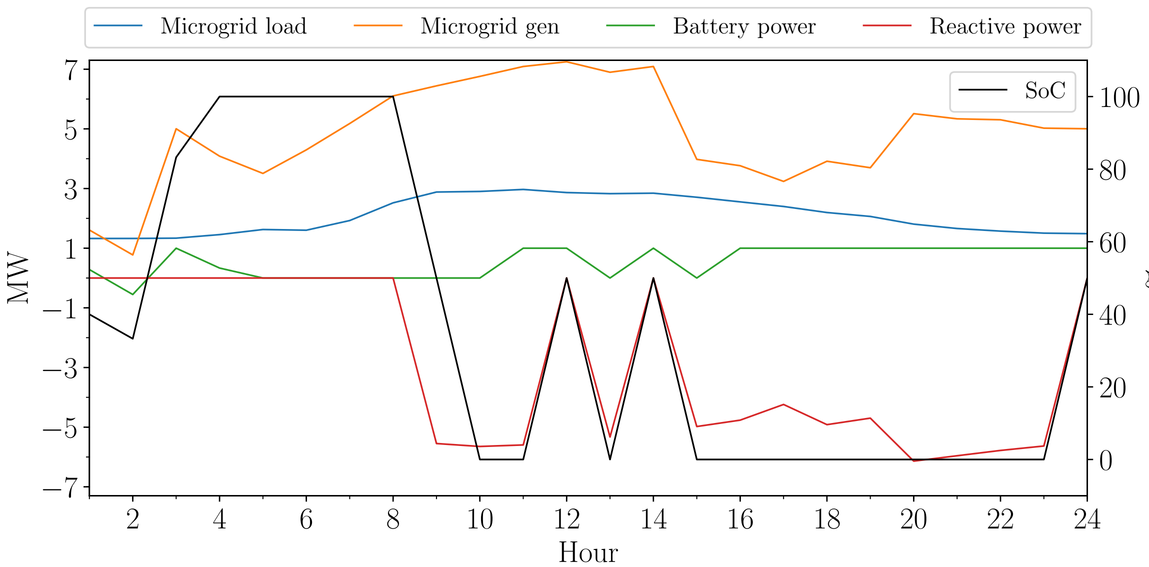
Figure (7.4) Voltage profiles for the most vulnerable buses with microgrid connected to bus 10 on the 4th of June

Connection with voltage regulation

When introducing voltage regulation to the system, the battery will operate as in Figure 7.5. The figures shows that the battery contributes with voltage regulation for hour 9 to 11, hour 13 and hour 15 to 23. Some of the regulation hours can be directly expected based on the voltage profiles obtained in Figure 7.4. The amount of reactive power contributing during the regulation hours can be seen as the red line in the figures, where negative contribution means that the battery releases reactive power to the system.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.5) Load, generation and battery in the microgrid with the microgrid connected to bus 10 on the 4th of June

Figure 7.6a illustrates the voltage profiles for the battery regulation strategy. Figure 7.6b illustrates the voltage profiles for the all regulation strategy. The voltage profiles for bus 22 from the previous cases are added into the plots for an easier comparison between the strategies. Both the voltage regulation algorithms are able to recover the voltages for hour 9 to 11. The production from the DERs during these hours are high, and for hour 9 and 10 the regulator is able to draw the reactive power directly from stored capacity in the battery without needing to store any active power from the main utility.

Since the strategy follows the battery algorithm during hours with no regulation, the battery will begin to store energy at hour 12. By investigating Figure 7.6b, it can be observed that the voltage drops during this hour since some of the produced power will be consumed by the battery, resulting in the voltage barely staying over the critical limit. For hour 13, the battery algorithm wants to store more active power, making the voltage fall below the critical limit. The voltage regulators will therefore contribute with reactive power compensation for this hour to restore the voltage. The regulators are able to perform the voltage regulation with the stored capacity from hour 12. After hour 13, the same effect is seen and the voltage regulators will again act from hour 15 to 23. The result illustrates the difficulty with this type of battery algorithm. A smarter strategy would be to postpone the charging to an hour where the voltages are kept within an acceptable limit. Another strategy could be for the battery to charge with lesser power each hour to preserve the voltage profiles.

Figure 7.6b shows that the voltage profiles for both regulation strategies start dropping when the battery needs to charge active power to perform voltage regulation. Thus, the system will see the battery as an active load consuming active power. By investigating Figure 7.6b, it can be seen that the all regulation strategy will result in better voltage profiles than the other tested strategies.

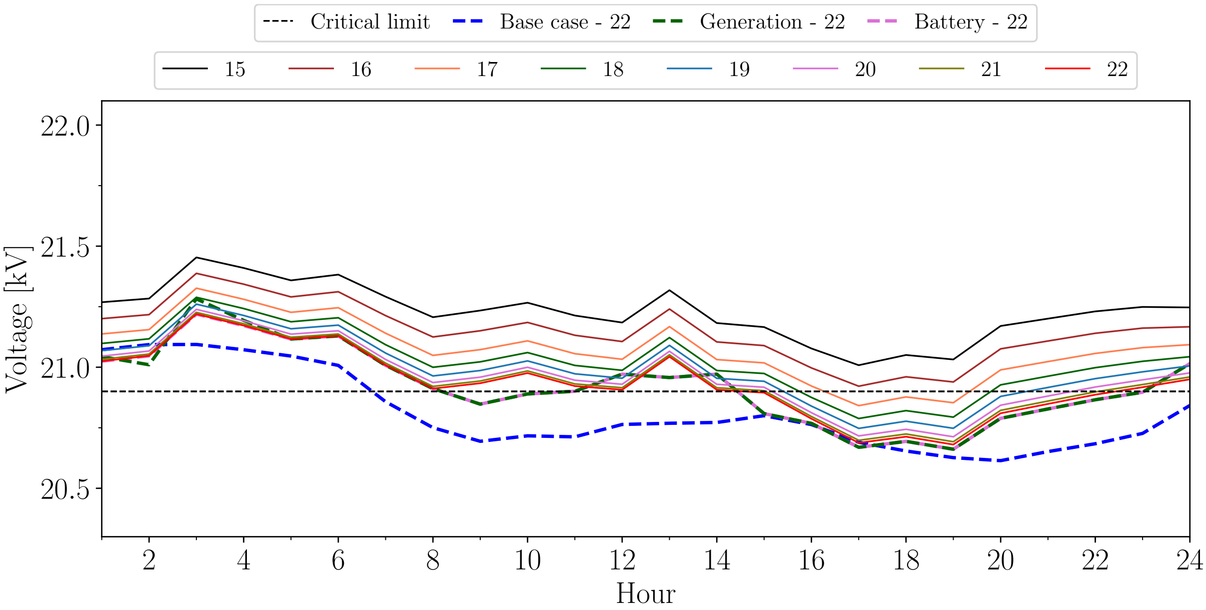
Table 7.2 and Table 7.3 illustrate the percentage increase in voltage at bus 22 for the worst hour in the base case, the new worst hour for the voltage regulation case, the regulated hour with the best effect and the regulated hour with the poorest effect for both the regulation strategies compared to the base case voltage. The tables illustrate that with high penetration of produced active power, the all regulation strategy will contribute with the highest effect.

Table (7.2) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

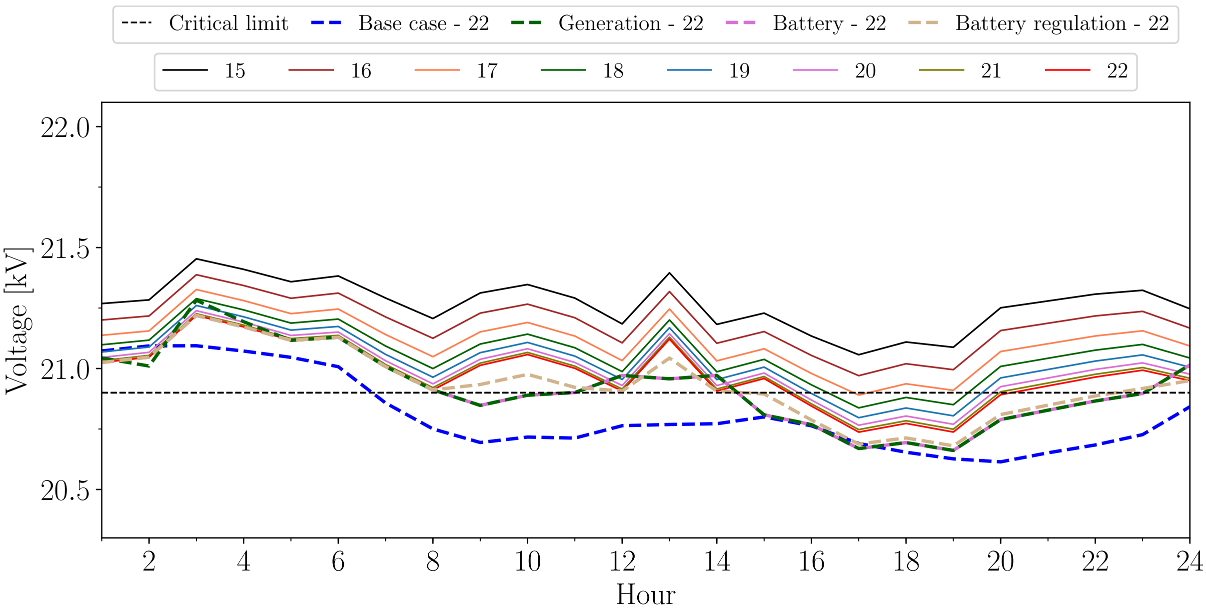
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	13	17	19	20
% Increase, battery regulation	1.322	-0.101	0.262	0.949

Table (7.3) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst hour**	**Base case worst hour**
Hour	13	17	19	20
% Increase, all regulation	1.700	0.227	0.537	1.346



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.6) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 10 on the 4th of June

7.1.2.2 Microgrid connected to bus 15

Connection without voltage regulation

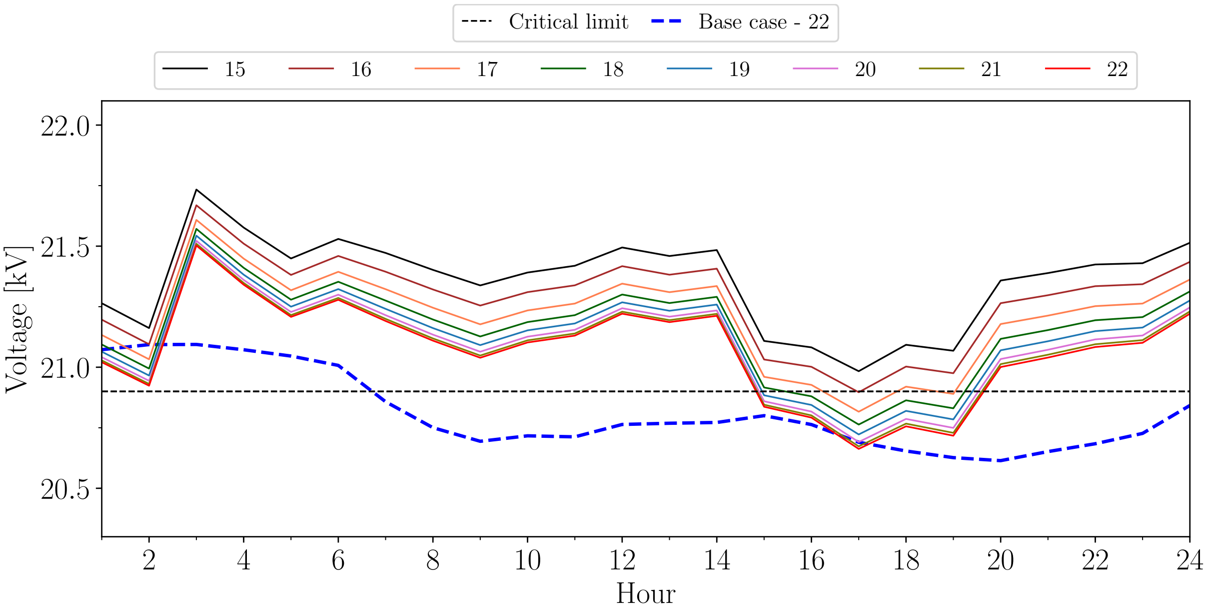
The microgrid is now placed on bus 15 in the main distribution system. Figure 7.7a and Figure 7.7b illustrate the voltage profiles for the eight buses furthest down in the main radial with no battery connected and with the battery connected respectively. As seen for the situation where the microgrid is placed at bus 10, the voltage profiles for these two cases are equal after hour 4 where the battery will be fully charged and is not discharged again during this day. It can be observed for hour 2 that the voltage profiles for the generation strategy will drop compared to the voltage profiles for the battery strategy. Since the battery has a SoC equal to 40 % in the beginning of the day, the battery is able to contribute with active power to the system when the demand exceeds the production. This will result in better voltage profiles.

With this microgrid placement, the system obtains voltages below the critical limit for hour 15 to 19. By comparing Figure 7.7b with Figure 7.4b, it can be observed that the microgrid connection at bus 15 is a better placement for the voltage profiles in the distribution system. This effect is a result of shorter travelled power from the microgrid to the buses far down in the main radial, resulting in decreased power losses.

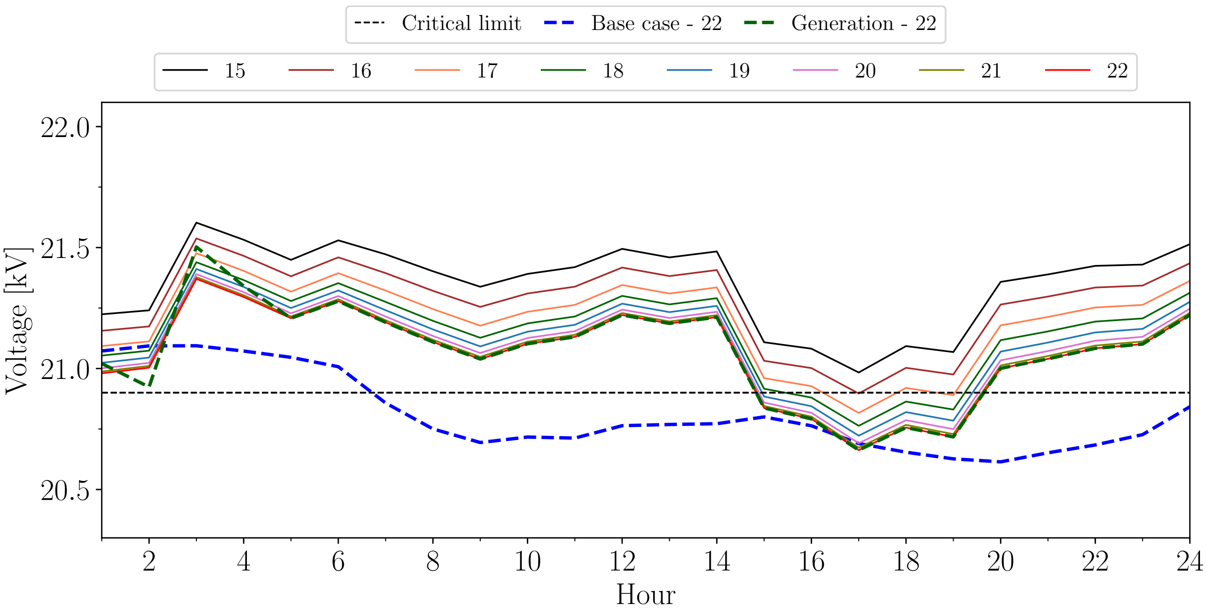
Table 7.4 contains the percentage increase in voltage on bus 22 for the battery strategy compared to the base case for the worst hour in the base case, the worst hour in this case, the hour with the best effect regarding the contribution of active power and the hour with the poorest effect. The best hour is hour 12 as expected since the battery is fully stored and the penetration of produced active power is high.

Table (7.4) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	12	1	17	20
% Increase, battery	2.203	-0.438	-0.133	1.875



(a) Without battery

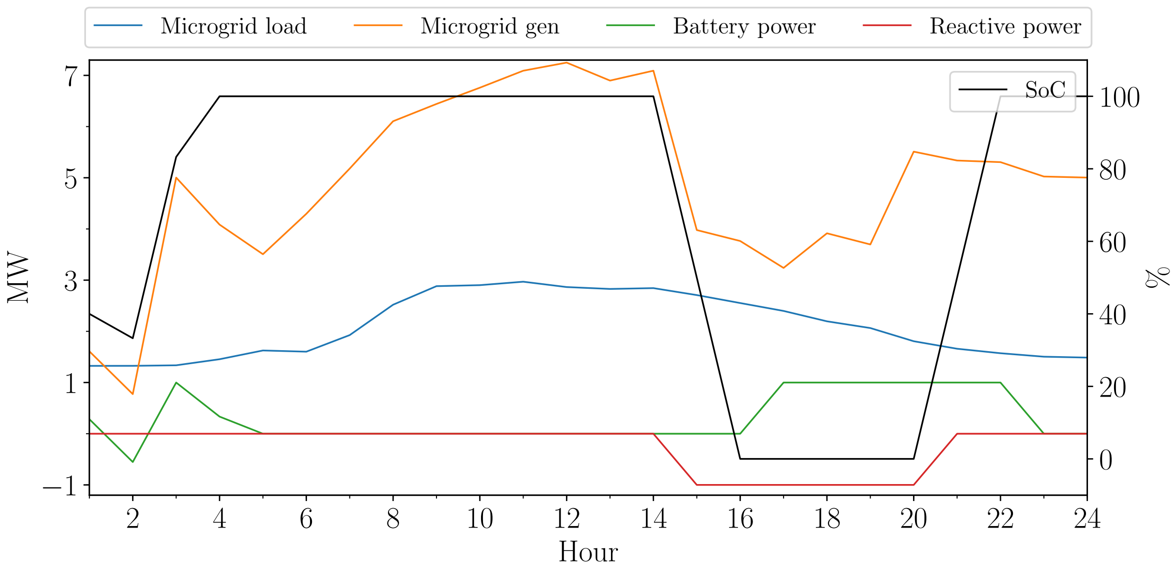


(b) With battery

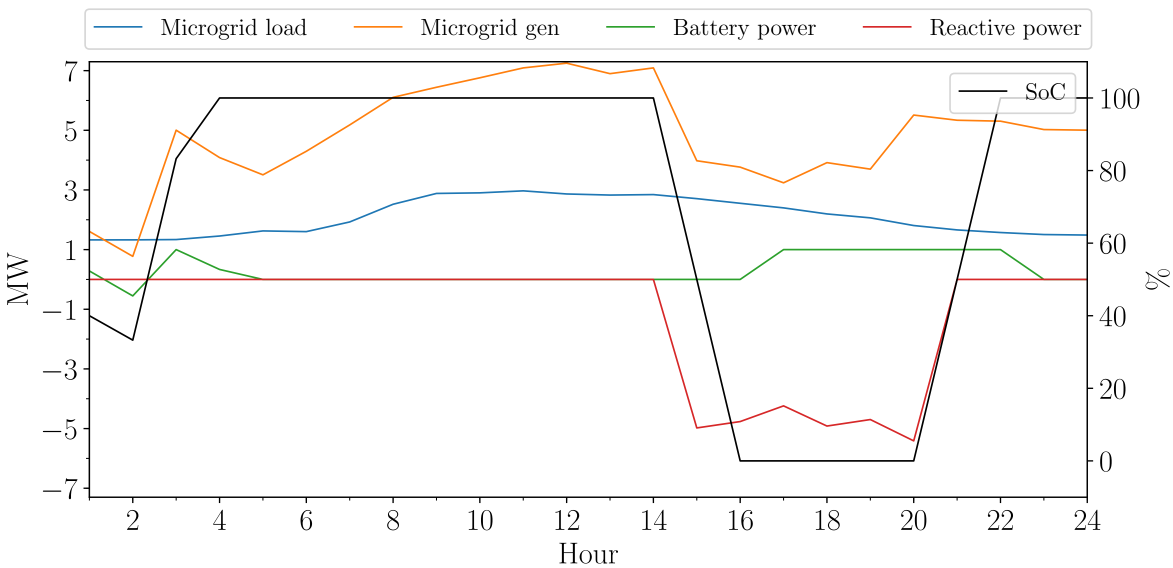
Figure (7.7) Voltage profiles for the most vulnerable buses with microgrid connected to bus 15 on the 4th of June

Connection with voltage regulation

Figure 7.8a and Figure 7.8b illustrate the battery operation during this placement of the microgrid for the strategies with battery regulation and all regulation respectively. The figures disclose that the system will perform voltage regulation from hour 15 to 20.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.8) Load, generation and battery in the microgrid with the microgrid connected to bus 15 on the 4th of June

Figure 7.9 discloses that both algorithms for the voltage regulation are able to restore the voltage in the utility for hour 15 and 16 and for hour 20. The rest of the hours with regulation are not restored. It can be observed from Figure 7.8 that during hour 15 and 16, the voltage regulators are able to regulate with stored capacity. The total production in the microgrid is increased in hour 20 compared to the previous regulation hours, resulting in more compensated active or reactive power based on the type of regulation strategy. The effect of the regulation is poorer during the rest of the regulation hours. This is due to two different reasons. First, the battery needs to draw active power from the system. Thus, the system will see the battery as an active load. Second, these are the hours where the total production in the microgrids drops compared to the previous hours.

From Figure 7.8, the same effect as for the case with the connection point at bus 10 can be observed. During hour 20, the voltage will drop below the critical limit when the battery algorithm tries to store active power, resulting in the voltage regulators to react and regulate for that hour. For the next two hours, the battery will store active power, and it can be observed that the voltage profiles drop compared to the strategy without regulation. This effect can be seen in Figure 7.9b by comparing the voltage profiles with the profile for bus 22 from the strategy without regulation (green and orchid dotted overlapping lines). The voltages for these two hours are kept above the critical limit, but the battery strategy is not optimal for this case either.

An interesting factor with this microgrid placement is that both regulation strategies give approximately the same outcome for the voltage profiles. This effect can be seen in Figure 7.9b by comparing the voltage profiles with the tan colored dotted line representing the battery regulation strategy. The all regulation strategy gives slightly better results than the battery regulation strategy and the battery regulation strategy. This can be seen by comparing the percentage increase in Table C.3 and Table C.4 or in the smaller Tables 7.4, 7.5 and 7.6.

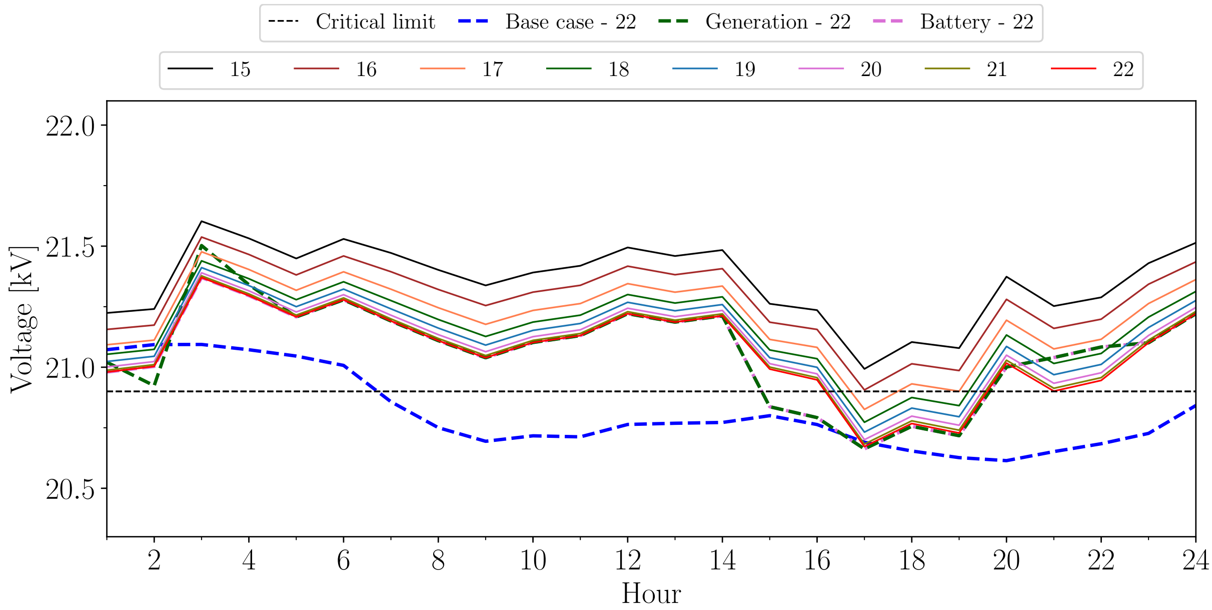
Table 7.5 and Table 7.6 contain the increase in voltage for bus 22 compared to the base case for the worst hour in the base case, the worst hour for this case and the hours with the highest and lowest increase for both the regulation strategies.

Table (7.5) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

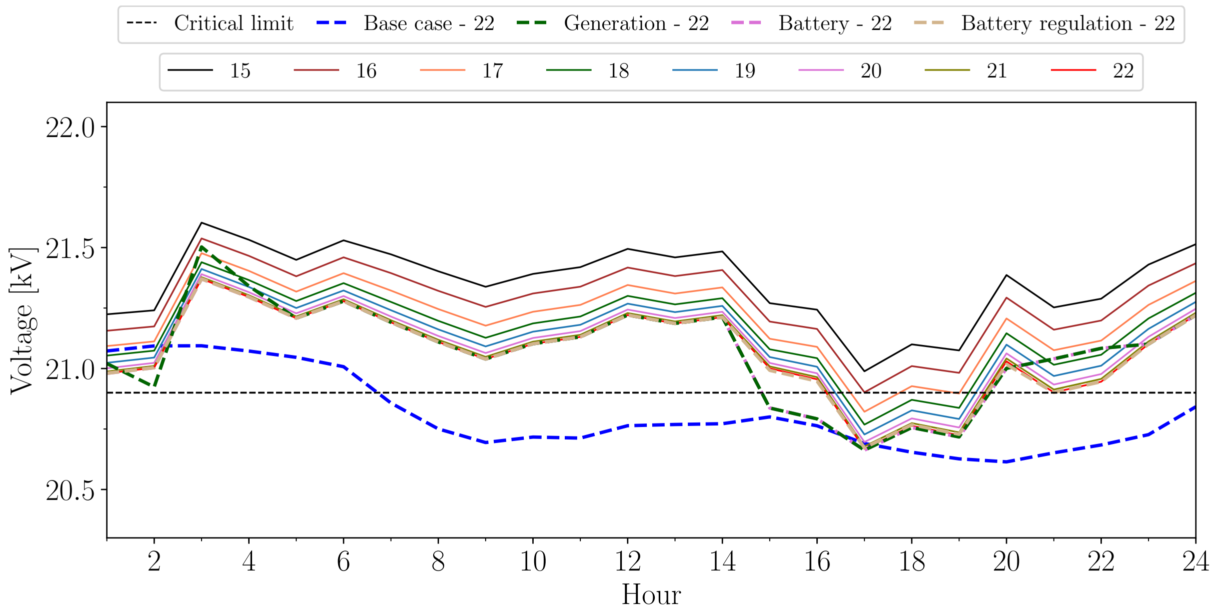
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	20	17	17	20
% Increase, battery regulation	1.953	-0.087	-0.087	1.953

Table (7.6) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	20	17	17	20
% Increase, all regulation	2.015	-0.109	-0.109	2.015



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.9) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 15 on the 4th of June

7.1.2.3 Microgrid connected to bus 20

Connection without voltage regulation

In this case, the microgrid is connected to bus 20, which is located far down in the main radial of the system. Figure 7.3 with the microgrid load, generation and battery profiles applies for this situation as well. Figures 7.10a and 7.10b illustrate the voltage profiles for the eight buses furthest down in the main radial with the microgrid connected to the system for the case without and with battery respectively. The figures deviate during the same hours as in the two previous cases. The deviation happens for the first four hours due to discharging of the battery when the load in the microgrid exceeds the production, and charging when the situation is changed.

A comparison between the voltage on bus 22 for the strategy with and without battery in Figure 7.10b illustrates some different aspects for the first hours. For hour 1, the voltage profile for the battery strategy is slightly under the critical limit, while for the strategy without battery, the voltage profiles are above. This result can be explained based on the generation-load curve in Figure 7.3. The demand is slightly lower than the production during the first hour, causing the battery to start storing energy. When the microgrid is placed on this bus, the resulting effect is that the bus voltage drops below the limit. The reason is the higher amount of power that needs to be transferred a longer distance to meet the demand. It results in more losses compared to the generation strategy and the other microgrid placement cases.

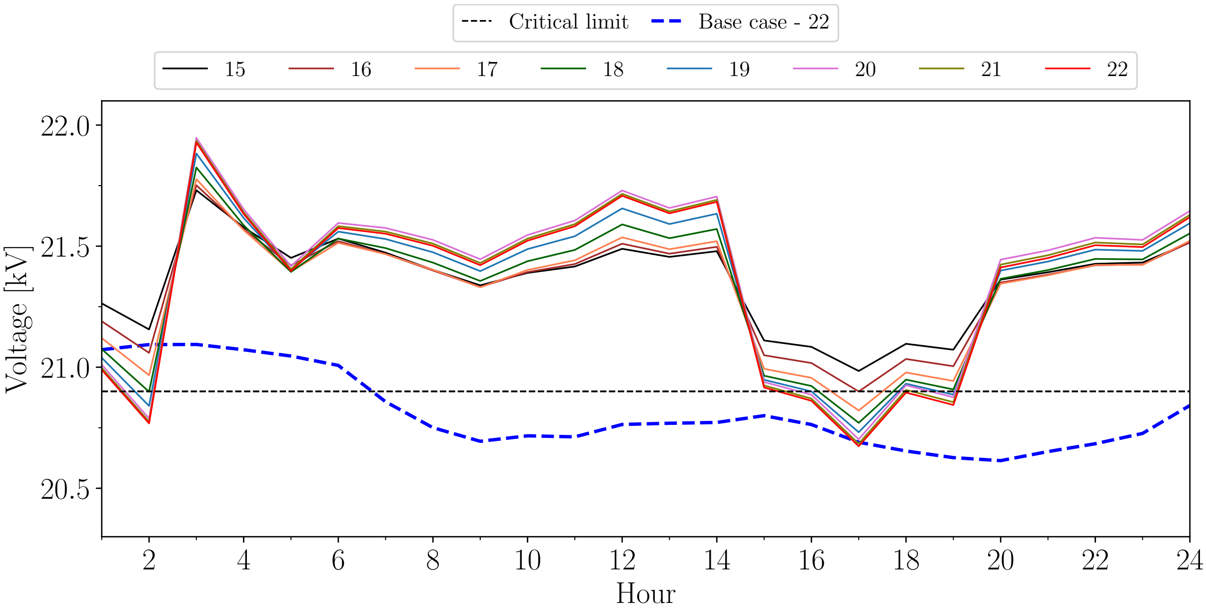
In hour 2, the demand is higher than the production. The battery will release active power to the network and thereby obtain better voltage profiles compared to the generation strategy. For the generation strategy, the distribution system sees the microgrid as a load. Therefore more active power is supplied from the slack bus, resulting in higher power losses and voltages drops over the lines.

The production from the DERs and the battery are able to restore the voltage for all the hours except hour 1 and hour 15 to 19.

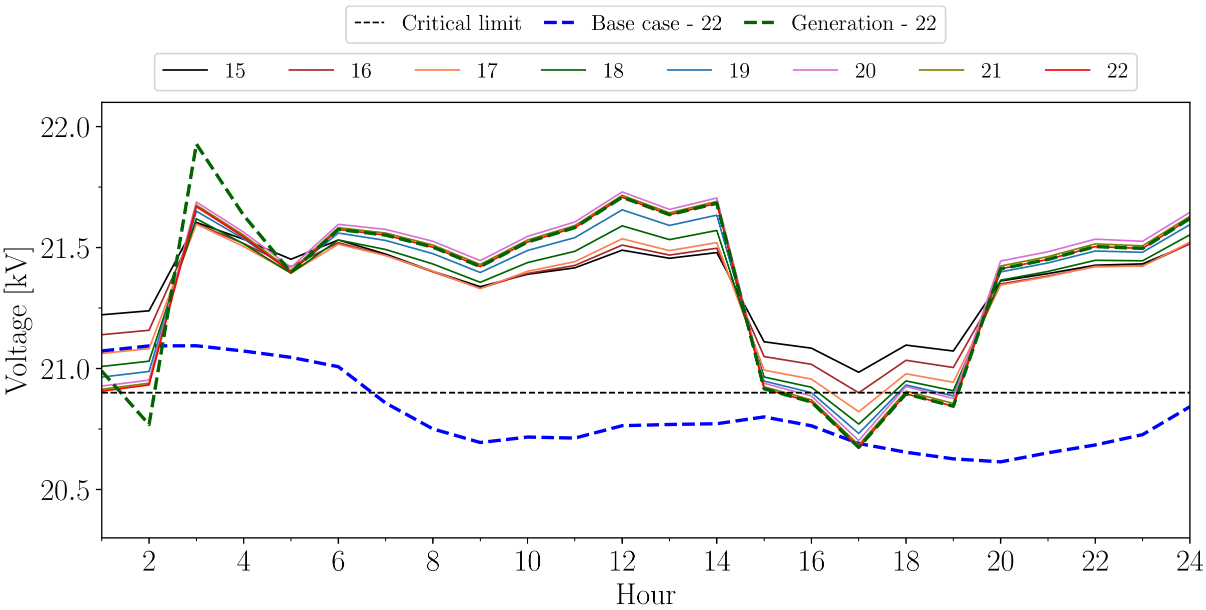
Table 7.7 contains the increase in voltage on bus 22 for the battery strategy compared to the base case for the worst base case hour, for the new worst hour during this strategy and the hour with the highest and lowest increase.

Table (7.7) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	12	1	17	20
% Increase, battery	4.548	-0.788	-0.079	3.870



(a) Without battery

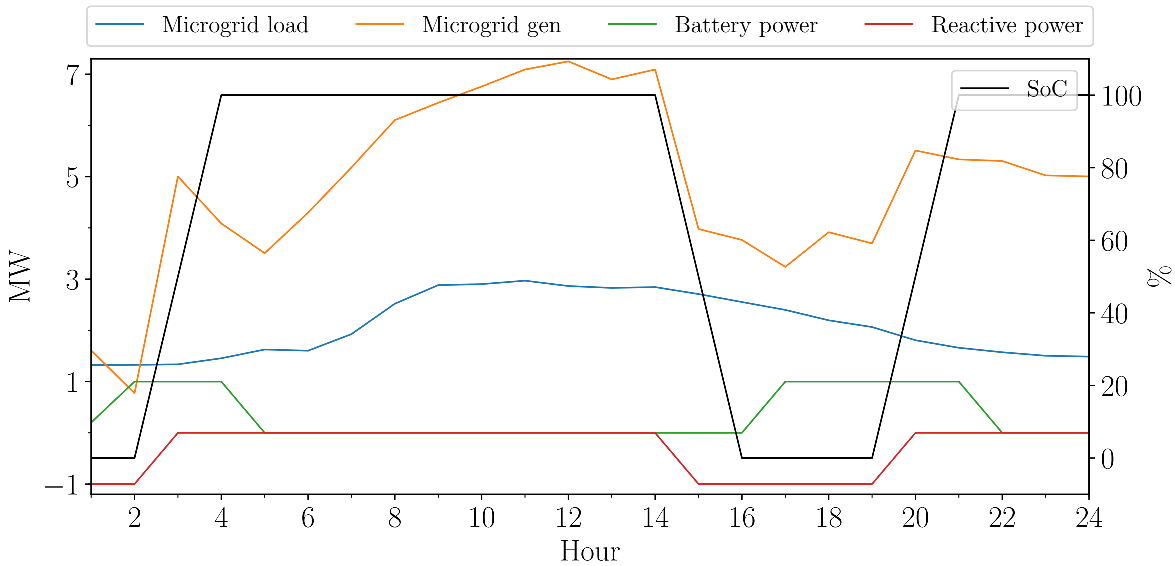


(b) With battery

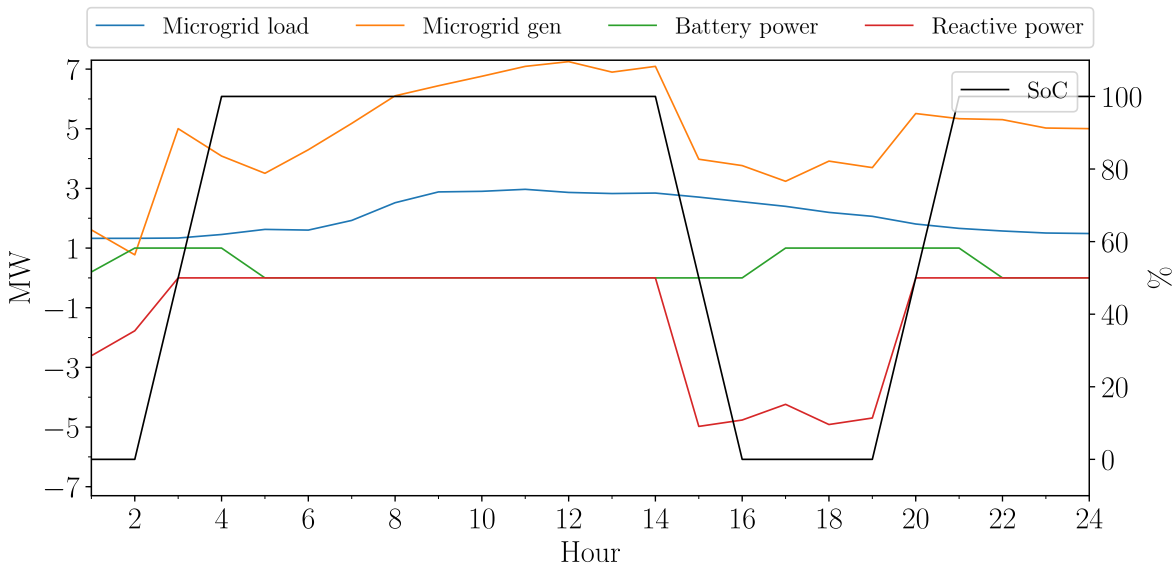
Figure (7.10) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 20 on the 4th of June

Connection with voltage regulation

Figure 7.11 illustrates how the battery operates during the two voltage regulation strategies. Both the voltage regulation strategies regulate for hour 1 to 2 and hour 15 to 19.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.11) Load, generation and battery in the microgrid with the microgrid connected to bus 20 on the 4th of June

Figures 7.12a and 7.12b illustrate the voltage profiles for the battery regulation strategy and the all regulation strategy respectively. Both strategies manage to restore the voltages during hour 1 where the battery can use the already stored capacity to recover the voltages. During the second hour, both the regulation strategies aggravate the voltage in the utility compared to the strategies without regulation. The battery is required to draw active power from the system to perform voltage regulation. This result can be explained by the high R/X ratio for the lines far down in the main radial, telling that the active power is more important for the voltage in the system than the reactive power, as illustrated in Section 5.4.7.

It can be observed from Figure 7.11b that the voltages are restored for hour 16 and 17 for the battery regulation strategy. For this situation, the battery can regulate with already stored capacity and meanwhile contribute with the active power generated from the DERs. In the all regulation strategy, the voltage will be aggravated for all the hours compared to the case without regulation strategy, and for hour 17 to 19 also compared to the base case. In this case, the best regulation strategy will be to only use the battery regulation strategy since the active power influences the system in a greater manner than reactive power. An even better strategy might be to let the microgrid contribute with active power regulation from the stored capacity in the battery instead of contributing with reactive power compensation. By comparing the voltage profiles for the battery regulation strategy in Figure 7.11a and the voltage profiles from the battery strategy, the voltage is worsened for the hours where the battery needs to store active power to contribute with reactive power compensation, illustrating the importance of active power.

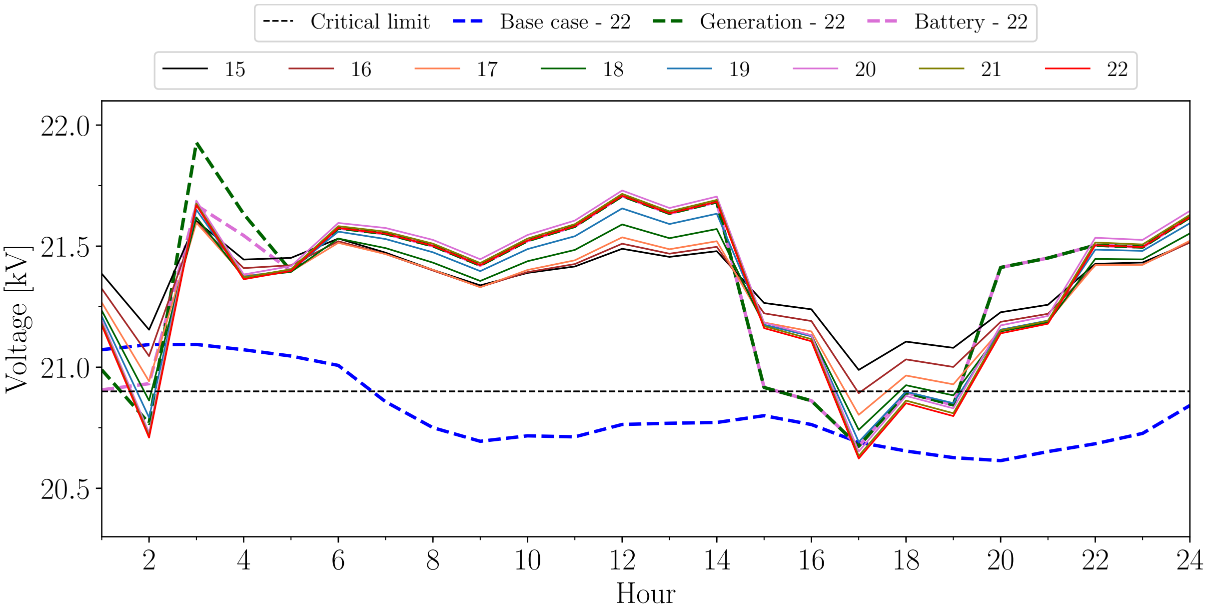
Table 7.8 and Table 7.9 contain the increase in voltage on bus 22 for both regulation strategies compared to the base case for the worst base case hour, for the worst hour during this case and the hour with the highest and lowest effect for both regulation modes.

Table (7.8) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

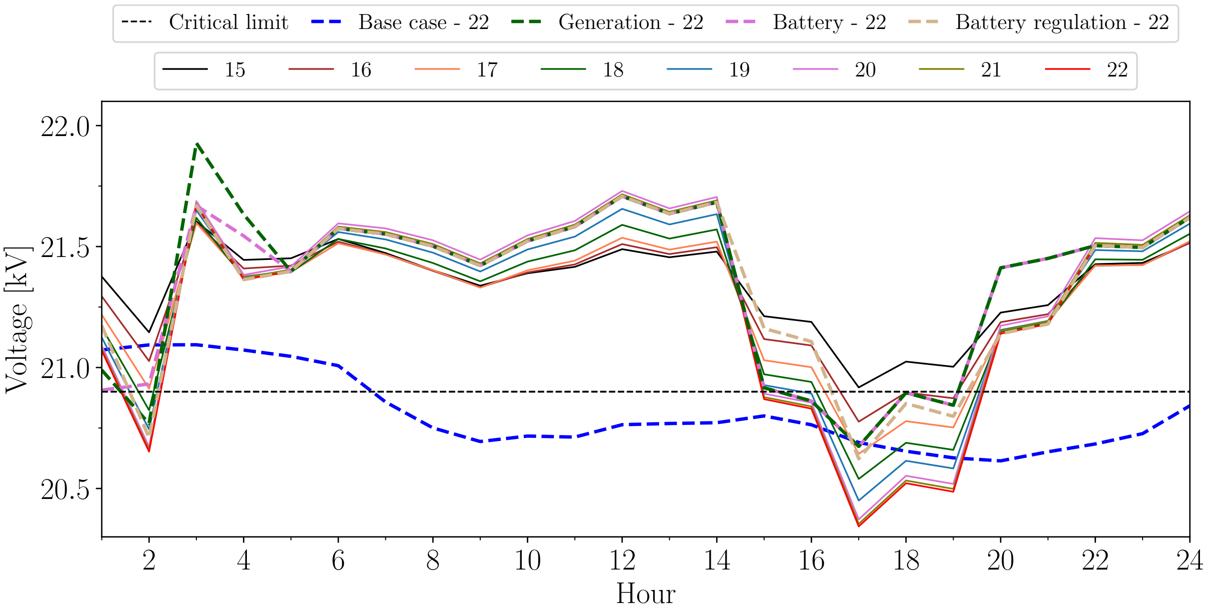
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	21	2	17	20
% Increase, battery regulation	2.557	-1.821	-0.325	2.550

Table (7.9) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	21	2	17	20
% Increase, all regulation	2.557	-2.091	-1.677	2.550



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.12) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 20 on the 4th of June

7.1.3 Demand response

The microgrid operation based on the two different demand response strategies is presented in the following sections. These two strategies do not consider any situation outside of the microgrid. The operation is therefore independent of the placement of the microgrid and will apply for all the different placement cases.

The presented figures in this section will operate with time on the x-axis. Whenever the load in one hour is referred to, the authors refer to the load in the period between the previous hour and the stated hour. For instance, the load in hour 1, means the load in the period between 0 AM and 1 AM. The loads are presented as constant during one hour and represent the average load through the hour.

Price based program

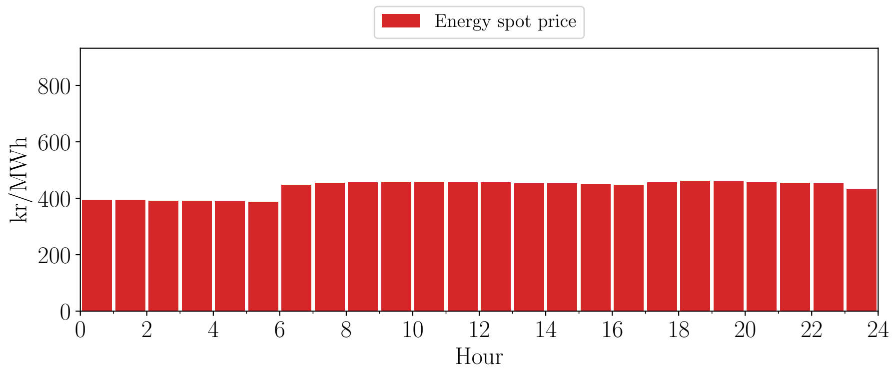
Figure 7.13a shows how the microgrid responds per hour to the price signals from the 4th of June. All the prices will be given in kr/MWh. Figure 7.13d presents the behaviour of the microgrid when the loads and the generation are combined. The blue bars illustrating the loads without demand response, are the total load when the battery is not in use and the household temperature is kept constant at 22 ˚ C. Figure 7.13b presents the charging and discharging of the battery as a response to the price signals in Figure 7.13a. Figure 7.13c illustrates how the households in the microgrid change their heating loads to make the total electricity cost through the day as low as possible.

The electricity price has small variations throughout the day. The highest price is 460.7 kr/MWh in hour 19, while the lowest price is 386.2 kr/MWh in hour 6. The prices do not fluctuate enough to obtain big enough differences to facilitate a lot of demand response actions. The battery will only charge and discharge once in the mentioned hours 6 and 19 respectively. The charging and discharging of the battery only takes place during the time the price difference is big enough to compensate for the losses due to the battery efficiency. It charges at the cheapest hour and discharges at the most expensive hour.

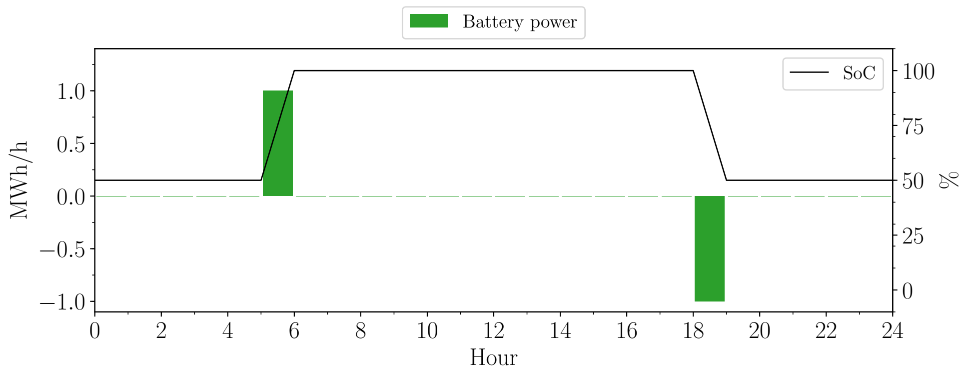
The households will increase their load to reach the upper temperature limit in hour 6 since this is the cheapest price hour, thus the high peak in Figure 7.13c in hour 6. As the price is higher during the other hours, the households try to minimize their consumption, resulting in the lowest temperature limit to be obtained. The households reduce their loads in hour 7 to 10 instead of hour 19, when the price is at the highest. The reason is explained by the small price difference between hour 7 to 19, making the additional load needed to keep the temperature up at 23.5 °C not profitable.

Figure 7.13c illustrates very well that between hour 11 and 23 the household loads are lower when the temperature is held constant at 20.5 ˚C instead of 22 ˚C because of less heat loss. Therefore, this strategy prefers to keep the temperature as low as allowed when there are not big enough price differences to perform other actions. With the assumption that the microgrid can sell and buy electricity at the same price, the response actions save a total of 195 kr for the microgrid during this day, where 75 kr comes from the battery actions and 120 kr from household actions.

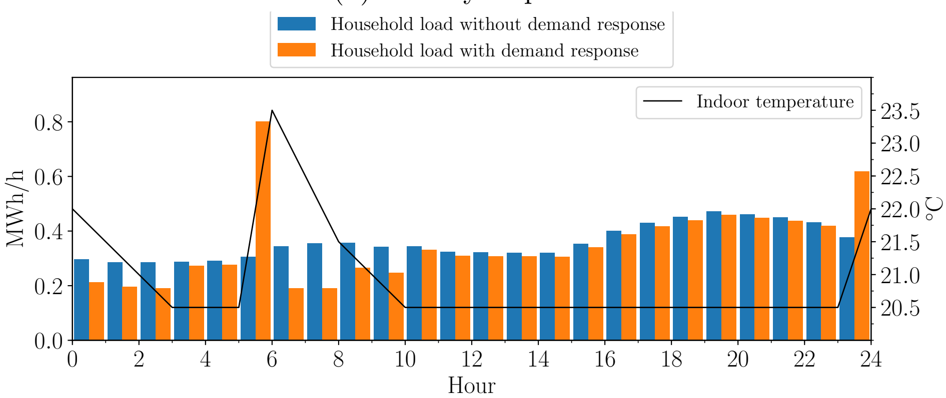
The total load in the microgrid obtain none to small difference, except for the two hours when the battery charges and discharges with full power.



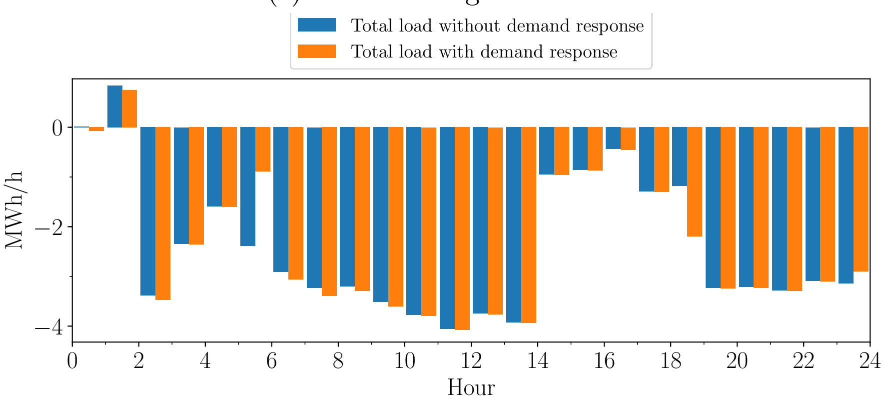
(a) Energy price 4th of June 2018



(b) Battery response



(c) Load shifting in households



(d) Total load in microgrid

Figure (7.13) Demand response with price based program on the 4th of June

Peak shaving

Figure 7.14 shows the demand response in the microgrid when the peak shaving program is applied. The 4th of June is chosen because of the good conditions for power generation from DERs that day. Because of that, it can be imagined that this day will not influence the measured power part of the network tariff if the tariff is calculated from the highest peaks during the whole month. When there is a lot of generation, the total load in the microgrid will appear low for the DSO. If the network tariff is based on the peak for each day, it can also be beneficial to perform peak shaving this day. When the peak shaving strategy is performed, it manages to get the total load at all hours below zero, illustrated in Figure 7.14c.

Although both the battery and the households use all the capacity they have available to lower the total microgrid load in the first two hours, these are still the hours with the highest load. This can be seen through Figure 7.3a, illustrating that these two hours are the hours with the lowest amount of produced active power from the DERs in the microgrid. This result is the reason why no more peak shaving actions are done later this day. The battery charges on the hours where the total load is most negative in order to get the state of charge back to the initial value, this can be seen in Figures 7.14a and 7.14c.

(a) Battery response

(b) Load shifting in households

(c) Total load in microgrid

Figure (7.14) Demand response with peak shaving program on the 4th of June

Voltage analysis including demand response scenarios

Figure 7.15 displays the per hour voltage on bus 22 for all the strategies including the demand response programs for the three different placements of the microgrid on the 4th of June.

It can be seen that both the demand response programs do not manage to restore the voltage levels above the critical limit for hour 9 and 10 as the voltage regulation strategies do when the microgrid is connected to bus 10. This can be explained by the fact that there are no incentives for any of the demand response programs in those hours to change the demand in the microgrid. On the other hand, it can be seen that the peak shaving program improves the voltage compared to the other strategies in hour 2 for all the different microgrid placements. This is during an hour where the total load exceeds the production in the microgrid and all the strategies perform, making the peak shaving strategy the best strategy for this hour regarding the voltage profiles.

In total, the demand response strategies do not improve the voltage levels significant when the microgrid is connected to bus 10 and 15, and the all regulation strategy is still the best strategy for a microgrid placement on bus 10. When the microgrid is connected to bus 20, the demand response strategies, together with the battery regulation strategy, limit the duration of critically low voltages to 4 hours.

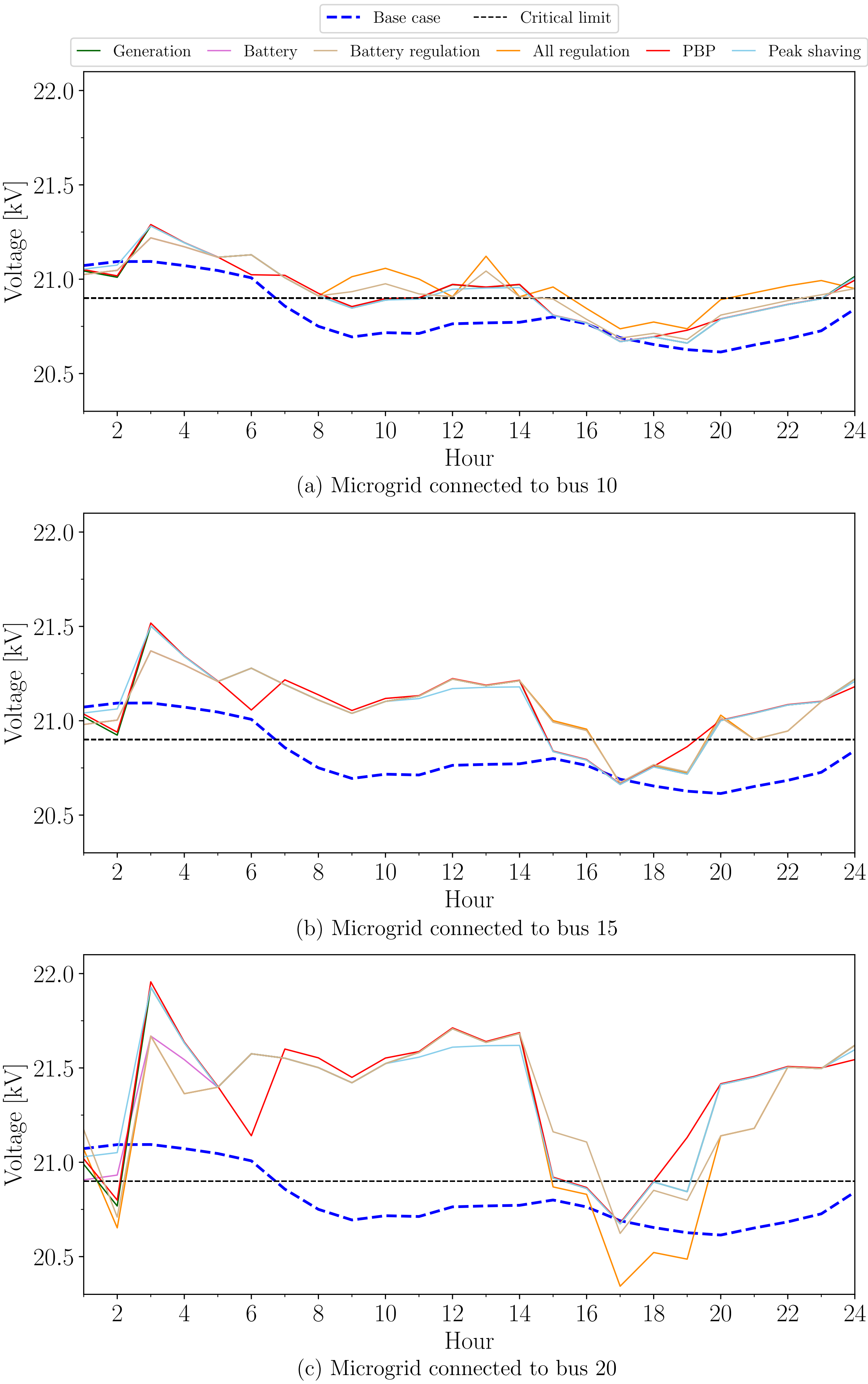


Figure (7.15) Voltage profiles on bus 22 for all strategies on the 4th of June

7.1.4 Line loading percentage

Figure 7.16 displays the loading percentage for line 4 and 13 with the different placements of the microgrid on the 4th of June. It may be desirable to compare the line loading percentages to Figures 7.3, 7.5, 7.8 and 7.11 which illustrate the microgrid load, generation and battery operation, as well as the voltage profiles in Figure 7.15. The line loading percentages can be used to see correlations between the loading percentage, the operation of the microgrid and the change in voltage level.

Throughout the descriptions of the line loading percentage, the terms downstream and upstream will be used to describe the placement of the microgrid compared to a line. Upstream is here consistently used to describe that the microgrid is closer to the slack bus compared to the reference line in the feeder. Downstream is used to describe the opposite placement.

Figure 7.16a II, illustrating the loading percentage on line 13 when the microgrid is placed on bus 10, clearly stands out compared to the other figures. The placement of the microgrid has a great impact on the loading percentage in the two lines except for line 13 in the case when the microgrid is connected to bus 10. In that case, the microgrid is placed upstream of the line and all the buses further out in the system still have the same demand regardless of the operation of the microgrid. Therefore the same amount of power will flow through line 13, and the loading percent will not be considerably changed.

For all the other cases, the microgrid has a great impact on the loading percentage, since the microgrid is placed downstream of the line. All the strategies, except the all regulation strategy, seems to more or less reflect the curve for the generation in the microgrid, seen in Figure 7.3. This illustrates that the line loading in this system is very sensitive to the power production in the microgrid.

When the microgrid produce more power than it consumes, the loading percentage is lower than the base case for all the strategies except some hours where the battery regulation strategy and the all regulation strategy performs. It is clear that the all regulation strategy causes the worst loading for the lines. The high loading is happening in hours when the battery converts all the produced active power to reactive, resulting in the distribution system transferring more active power trough the lines compared to the other cases to meet the demand. If the generated reactive power do not meet the reactive power demand downstream the microgrid, the reactive power will flow through the lines upstream of the microgrid. The same effect is seen for the hours where the battery regulation strategy needs to draw active power from the grid to contribute with reactive power compensation. In Figure 7.16a I, the all regulation strategy performs during multiple hours compared to the other microgrid placements, causing the line loading to increase highly for a number of hours compared to the other placements of the microgrid.

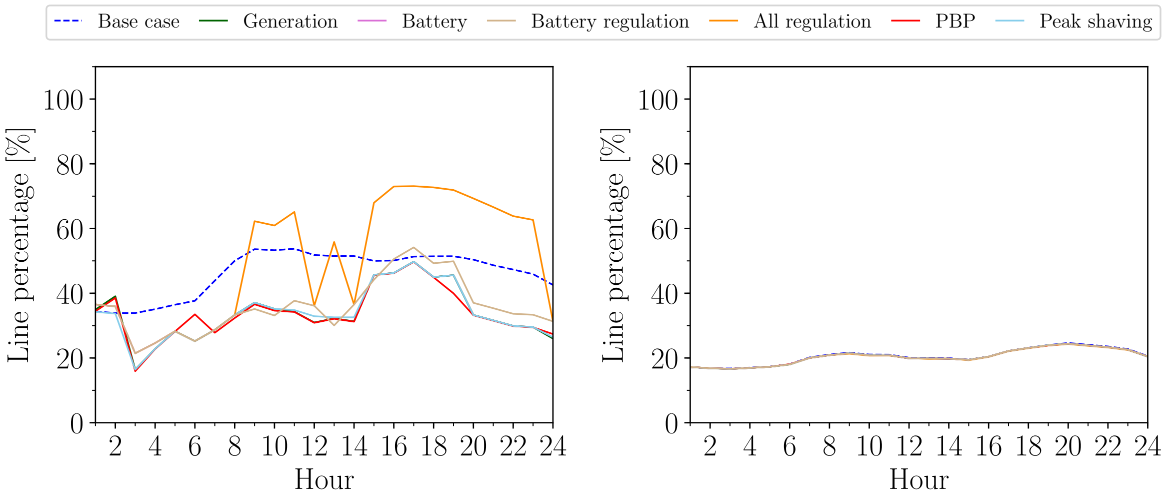
Hour 2 is the only hour where load demand exceeds the production in the microgrid. This effect is reflected in a higher loading percentage for all the strategies, except the peak shaving strategy, compared to the base case. The reason for this is that the distribution system sees the microgrid as an additional load, and therefore supply more power through the lines upstream of the microgrid. Since the peak shaving strategy manage to get a surplus of energy generation in the microgrid during this hour, the line loading for the peak shaving strategy is decreased compared to the other strategies.

Figure 7.16 illustrates that the four strategies, the generation strategy, the battery strategy, the peak shaving strategy and the price based strategy, result in almost equal line loading percentage for both line 4 and 13. The PBP strategy deviates slightly during hour 6 and 19, which are the two hours the battery charge and discharge respectively.

Table 7.10 displays the line loading percentage for the generation strategy at hour 17 with the microgrid connected to the three different buses. The table aims to illustrate how the different line loading are influenced by the placement of the microgrid. Compared to the other strategies, the generation strategy do not follow any specific strategy. Thus, the strategy is more suitable for comparison between the different microgrid placements. Hour 17 is chosen based on the obtained high line loading for multiple of the strategies. The table disclose that the line loading for both lines are not influenced in any great matter by the microgrid placement.

Table (7.10) Lowest line loading peaks for line 4 and 13 with different placings of the microgrid

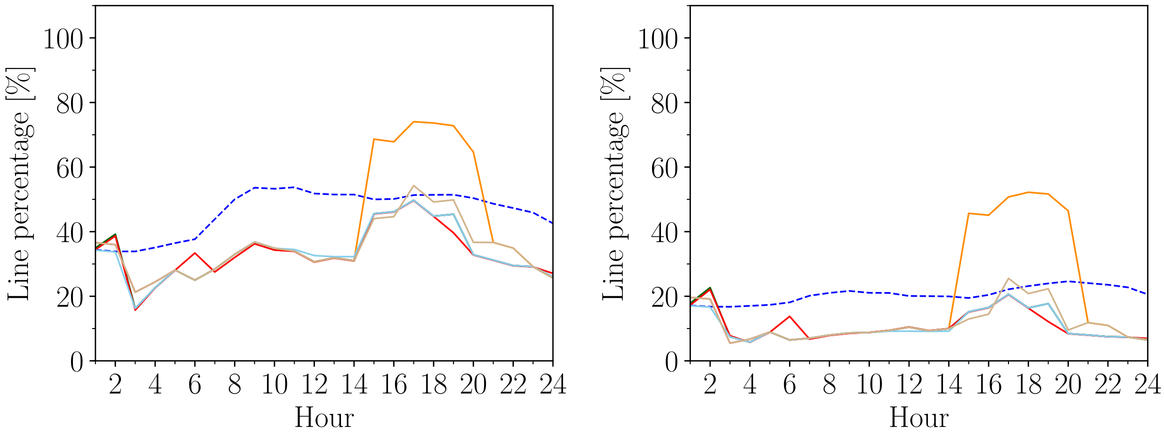
	Bus 10	**Bus 15**	**Bus 20**
Line loading line 4	49.76 %	49.72 %	49.69 %
Line loading line 13	22.17 %	20.62 %	20.59 %



(I) Loading percentage on line 4

(II) Loading percentage on line 13

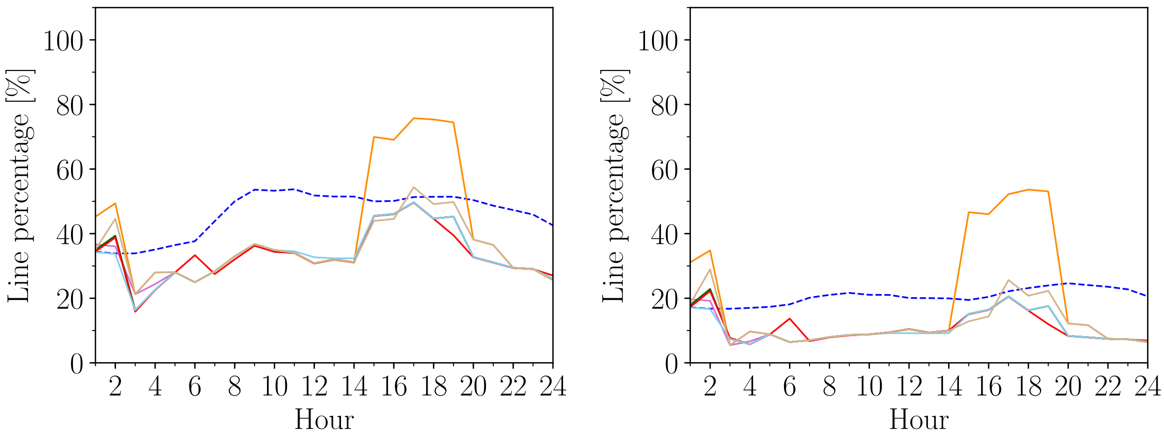
(a) Bus 10



(I) Loading percentage on line 4

(II) Loading percentage on line 13

(b) Bus 15



(I) Loading percentage on line 4

(II) Loading percentage on line 13

(c) Bus 20

Figure (7.16) Loading percentage on the 4th of June

7.2 Day 2: 7th of June

7.2.1 Base case

The 7th of June represents an almost equal demand day as the 4th of June, but aims to illustrate a worst-case day due to the low penetration of generated power from the DERs in the microgrid. Figure 7.17 displays the load demand in the 33-bus distribution system for this day and Figure 7.18 illustrates the voltage profiles for the eight buses furthest down in the main radial in the system for the base case. The hours with a voltage problem expand from hour 7 to hour 24. The worst hour is hour 19, where the bus voltage on bus 22 is 20.65 kV.

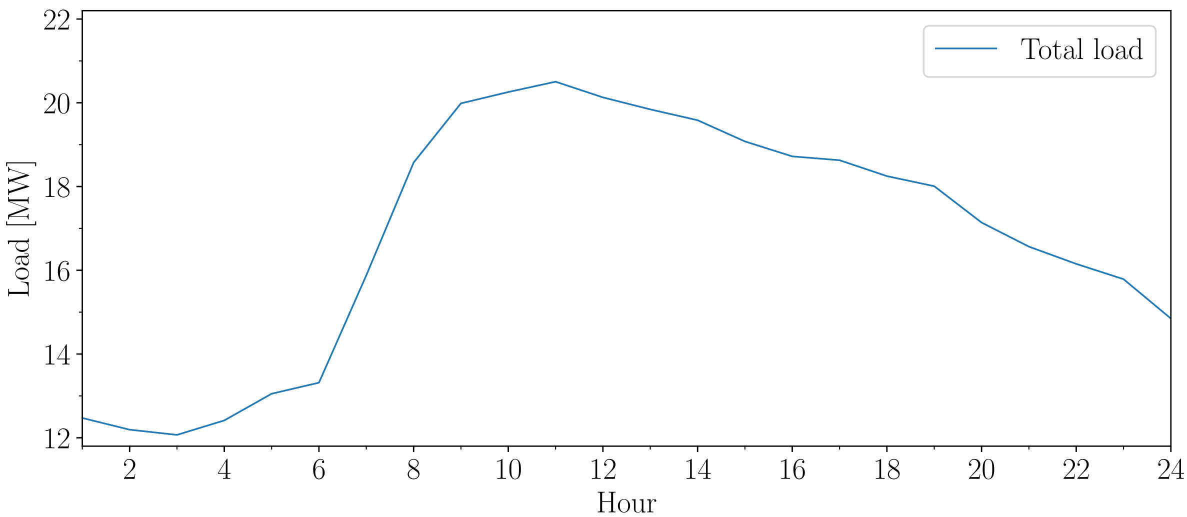


Figure (7.17) Base case: Active load profiles in the 33-bus network on the 7th of June

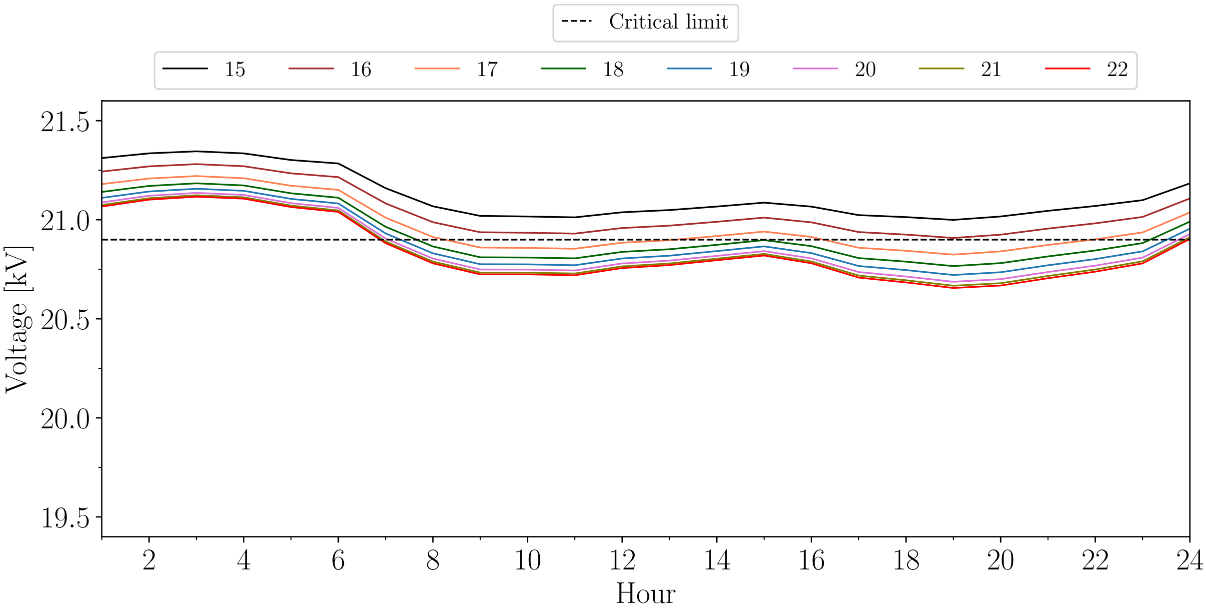
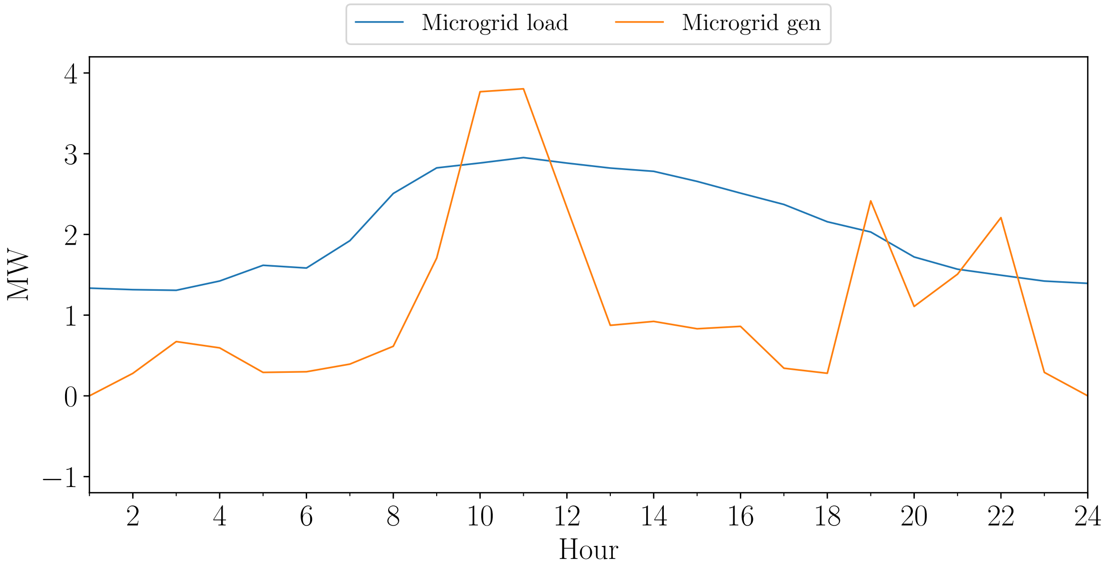


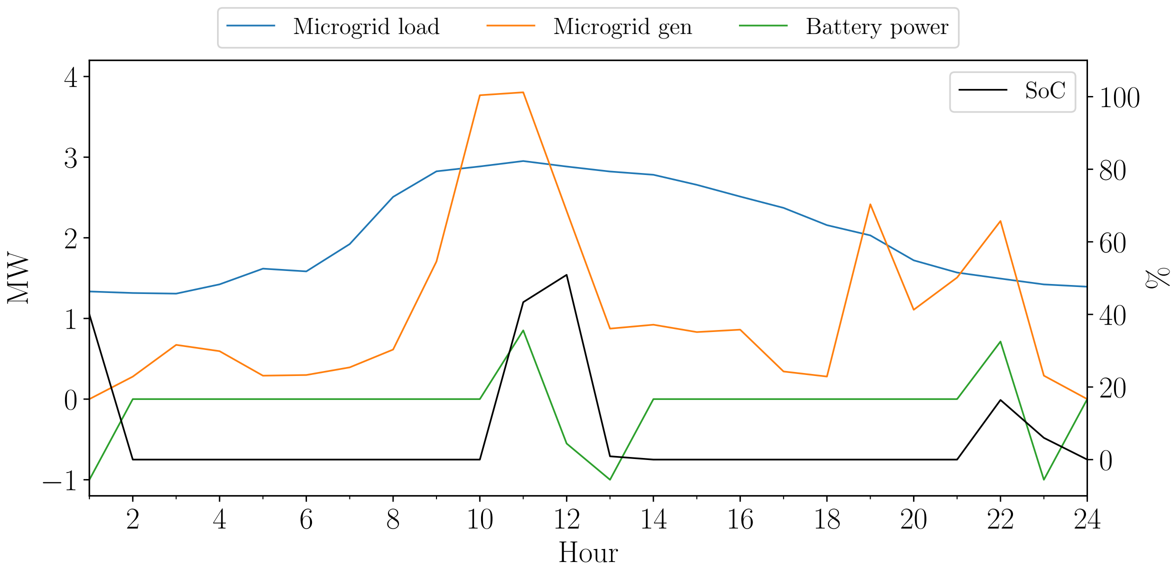
Figure (7.18) Base case: Voltage profiles for the most vulnerable buses on the 7th of June

7.2.2 Connection of microgrid and voltage regulation

Figure 7.19a illustrates the total demand and production in the microgrid for this day. Figure 7.19b shows the same plot including the state of charge of the battery and the charging and discharging rate. The battery discharges during the first hour since the total demand exceeds the production. The battery starts with a SoC equal to 40 % at the beginning of the day. The battery is unable to store any power until hour 10, where it stores until hour 12. After this, the battery is able to store some power again at hour 21, before the demand exceeds the production again. The battery is never able to be fully charged since the production is to low compared to the demand in the microgrid.



(a) Without battery



(b) With battery

Figure (7.19) Load, generation and battery in the microgrid on the 7th of June

Microgrid connected to bus 10

Connection without voltage regulation

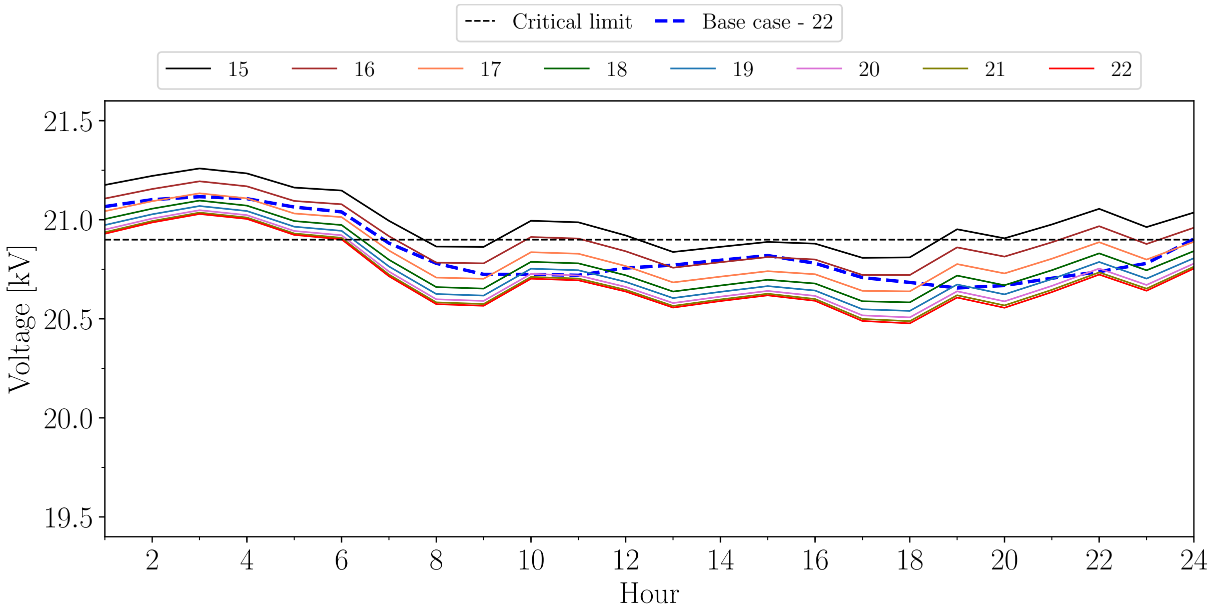
The microgrid is first connected to bus 10 in the main distribution system. In Figures 7.20a and 7.20b, the voltage profiles for the eight buses furthest down in the main radial are presented for a situation without and with a battery connected respectively. The blue dotted line illustrates the voltage on bus 22 from the base case. The results clearly illustrate that the connection of the microgrid when the penetration of generated active power is low results in even worse voltage levels than for the base case. The amount of produced active power during the hour with the highest production in the microgrid is not enough to help the voltage profiles in the main system. This is because the load demand in the microgrid is too high compared to the generation during most of the day, and the system will see the microgrid as an additional load. This results in the voltage levels dropping too far in these hours and they are also unable to be restored for the hours with slightly higher production.

By observing Figure 7.20b, it can be seen that for the hours when the battery is storing available production, the voltage levels will drop compared to the generation strategy. On the other hand, the voltage profiles are improved in the hours where the battery has available energy that can be delivered to the system. During hours where the battery is empty and neither charge or discharge, the voltage profiles for the generation strategy and battery strategy are equal. It is hard through this analysis to determine if the battery strategy is better than the generation strategy, since the effect shifts between charging and discharging hours. Likewise, as for the the base case, the voltage levels will be below the critical limit from hour 7 to hour 24, but with even poorer voltages profiles.

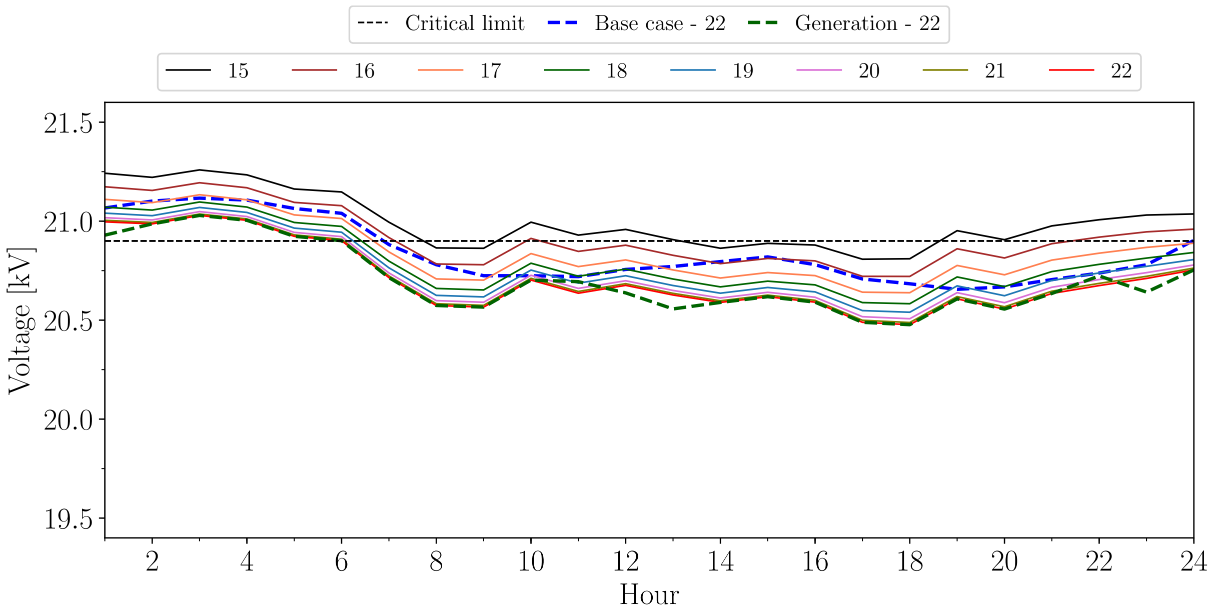
Table 7.11 contains the increased percentage in the voltage for bus 22 for the battery strategy compared to the base case for the worst hour, the new worst hour and the hours with the highest and lowest increase.

Table (7.11) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	10	17	18	19
% Increase, battery	-0.105	-1.057	-0.999	-0.233



(a) Without battery

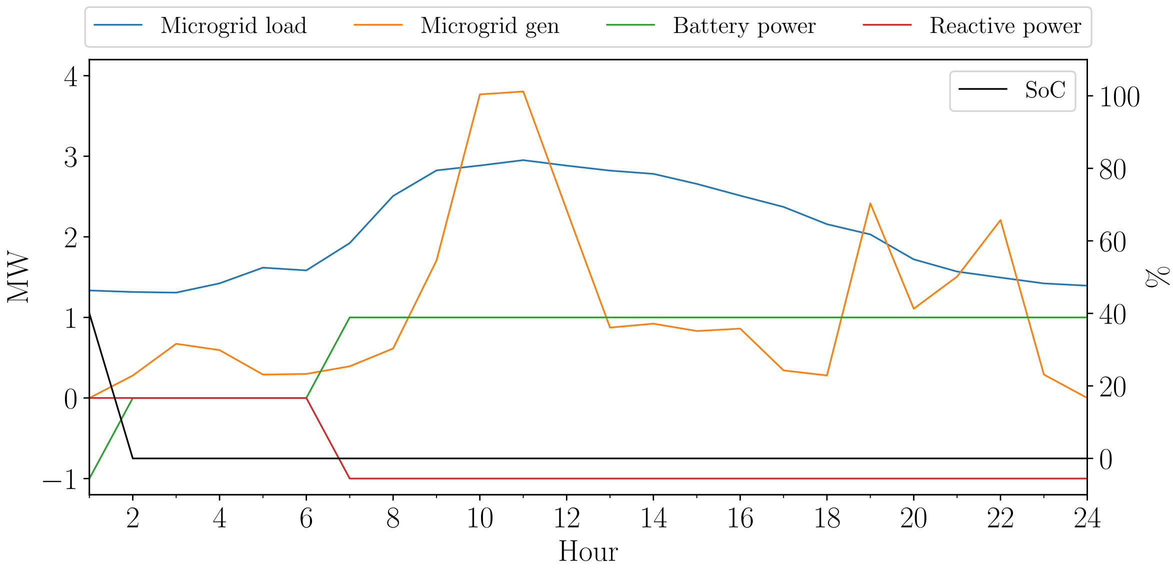


(b) With battery

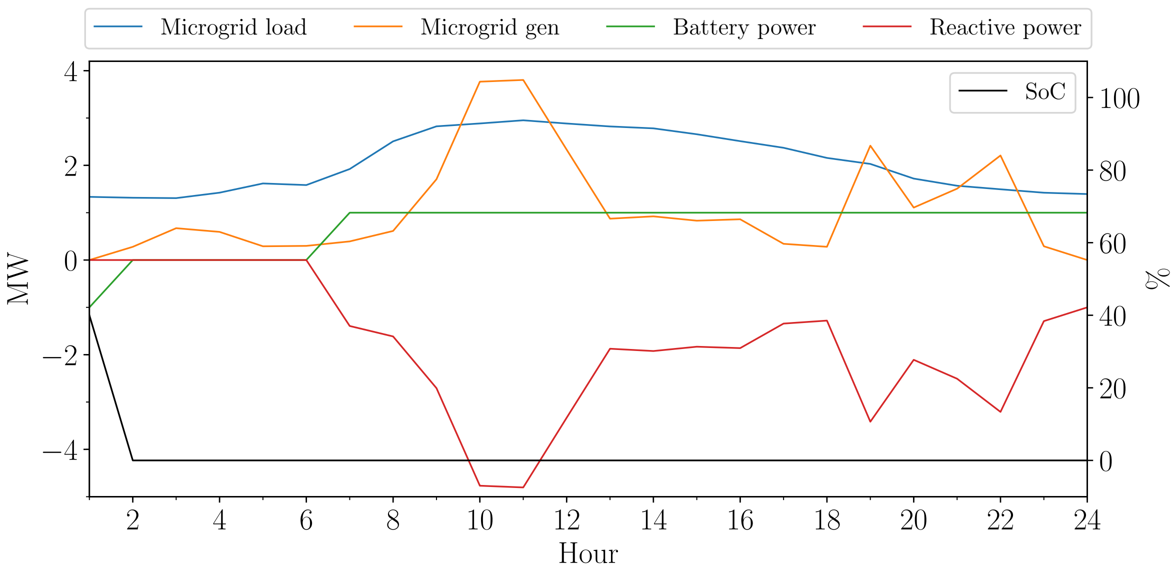
Figure (7.20) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 10 on the 7th of June

Connection with voltage regulation

From Figure 7.20, it is clear that hours 6 to 24 will need regulation after connecting the microgrid. Figure 7.21a and Figure 7.21b illustrate the amount of reactive power used to regulate the voltages and the amount of stored active power in the battery for the case with battery regulation and regulation with all production units respectively.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.21) Load, generation and battery in the microgrid with the microgrid connected bus 10 on the 7th of June

Figures 7.22a and 7.22b display the voltage profiles for the eight buses furthest down in the main radial for the battery regulation strategy and all regulation strategy respectively, including the voltage on bus 22 for the other discussed strategies during this day and placing of the microgrid. None of the regulation strategies are able to restore the voltage profiles during all the regulation hours.

By comparing the cases in Figure 7.22b, it can be seen that the all regulation strategy gives better voltage profiles. During the few hours with higher production than load in the microgrid, the all regulation strategy is able to improve the voltage levels compared to the base case. This is not the case during the hours when the demand exceeds the production in the microgrid, and the microgrid will be seen as an additional load for the system.

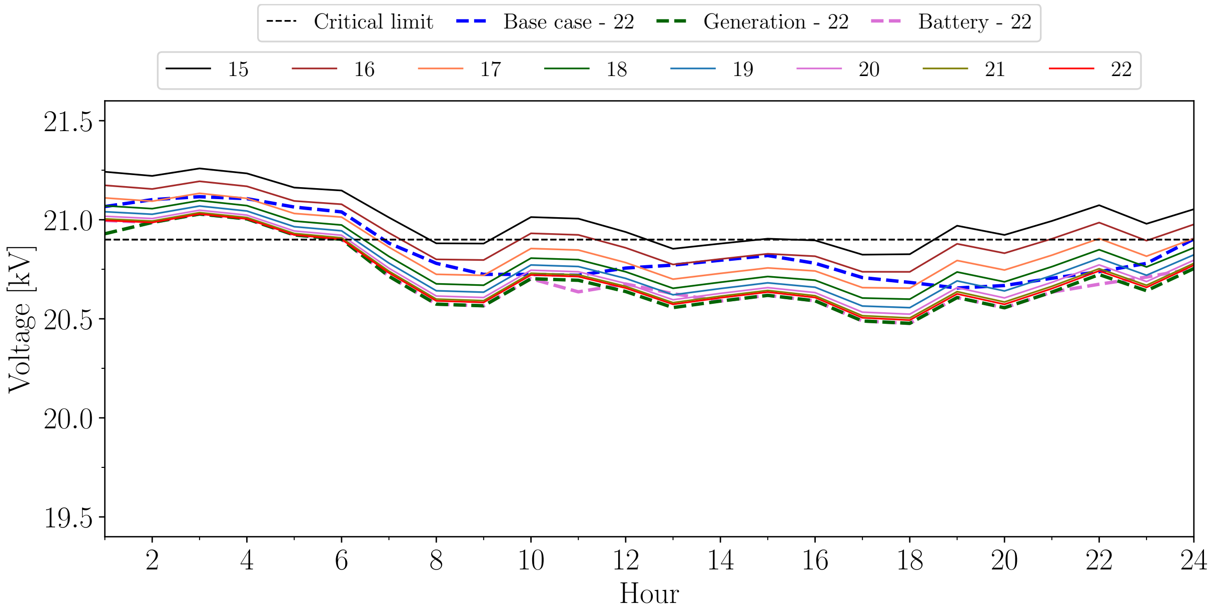
Table 7.12 and Table 7.13 show the percentage increase for both the regulation strategies compared to the base case for bus 22. The cases are based on the worst hour in the base case, the worst new hour for this case and the hours with the highest and lowest increase for both the regulation strategies.

Table (7.12) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

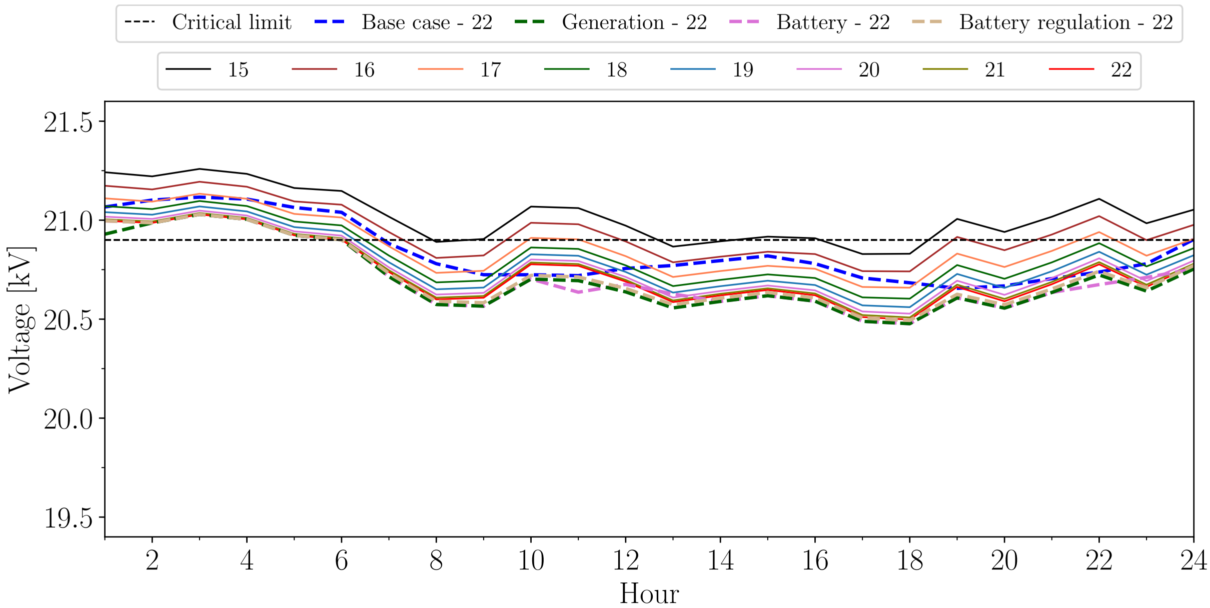
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	22	17	18	19
% Increase, battery regulation	0.019	-0.979	-0.920	-0.145

Table (7.13) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	10	17	18	19
% Increase, all regulation	0.255	-0.954	-0.899	0.035



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.22) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 10 on the 7th of June

7.2.2.1 Microgrid connected to bus 15

Connection without voltage regulation

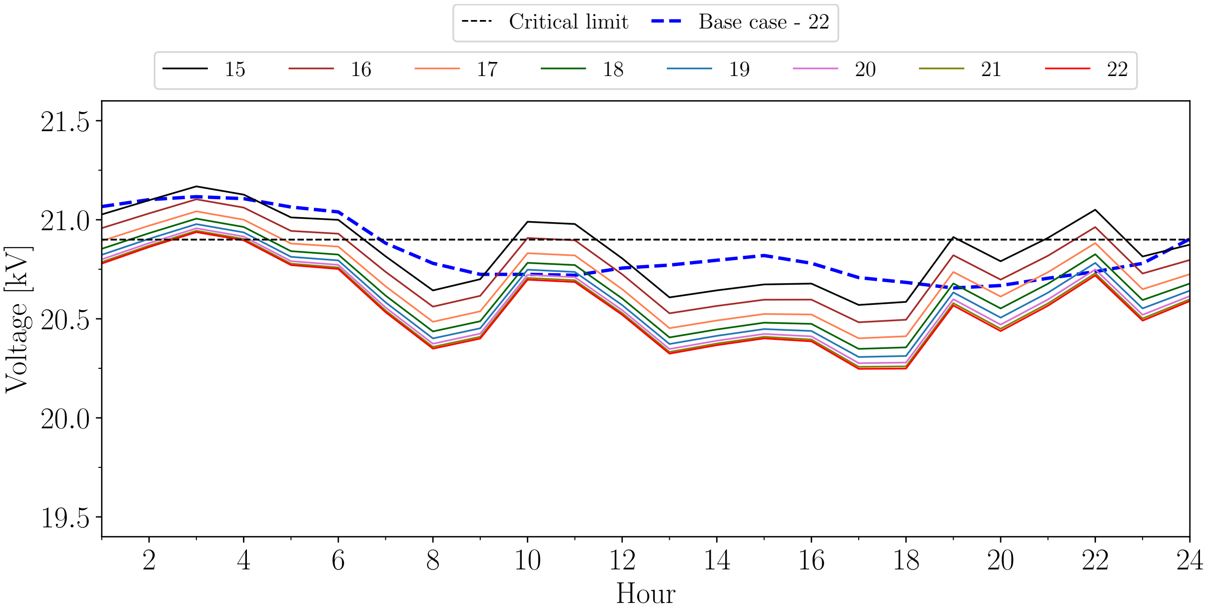
In this case the microgrid will be connected to bus 15 in the utility. Figure 7.23 illustrates the effect on the voltage profiles of connecting the microgrid for the generation strategy and the battery strategy, for the eight buses furthest down in the main radial. By comparing the voltage profiles for this placement with the previous placement on bus 10, the voltage levels have been worsened. Since this day contains low penetration of produced power from the DERs, the microgrid is seen as a load for the distribution system during most of the hours. Thus, the connection of the microgrid at bus 15 gives worse voltage profiles since the power supplied to the microgrid loads need to be transferred over longer line distance, resulting in higher power losses and voltage drops.

For hour 1, the battery strategy is able to preserve the voltage levels by discharging stored active power. Likewise as for the case with microgrid placement at bus 10, it can be observed by comparing the two cases in Figure 7.23b that the voltages will be lower during the hours when the battery store energy, while the voltages will be improved during hours where the battery discharges for the battery strategy compared to the generation strategy. The results illustrate a situation that will need regulation at all hours except hour 1 and 3.

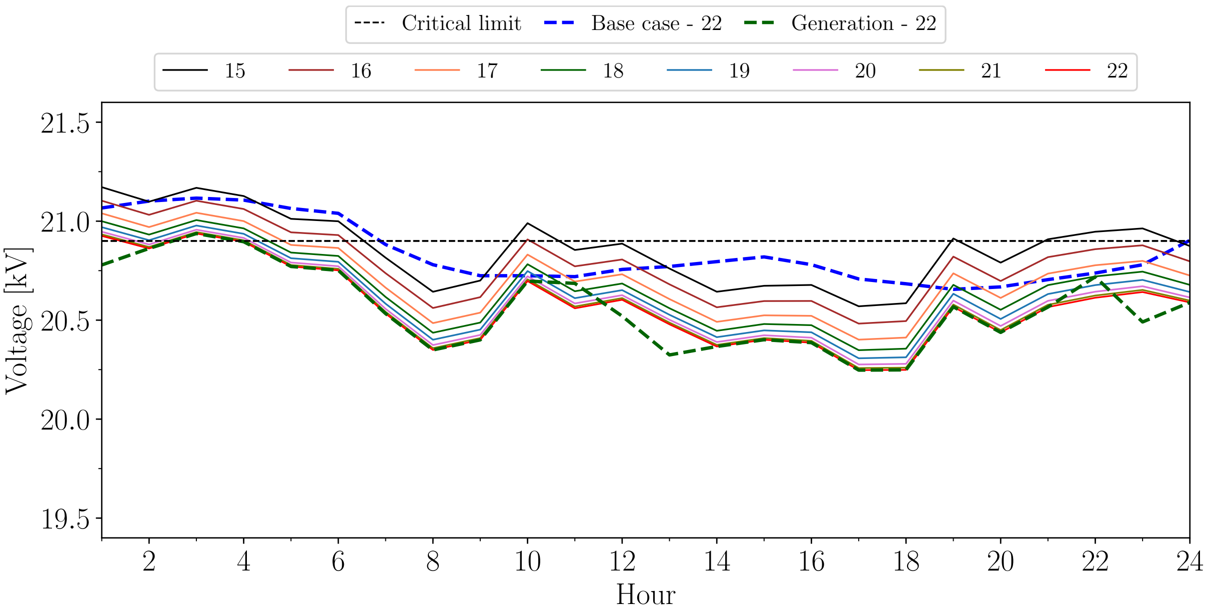
Table 7.14 contains the percentage increase in the voltage for bus 22 for the battery strategy compared to the base case. The four cases illustrates the hour with highest increase, the hour with lowest increase, the worst hour for this case and the worst hour from the base case.

Table (7.14) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	10	17	18	19
% Increase, battery	-0.130	-2.224	-2.103	-0.428



(a) Without battery

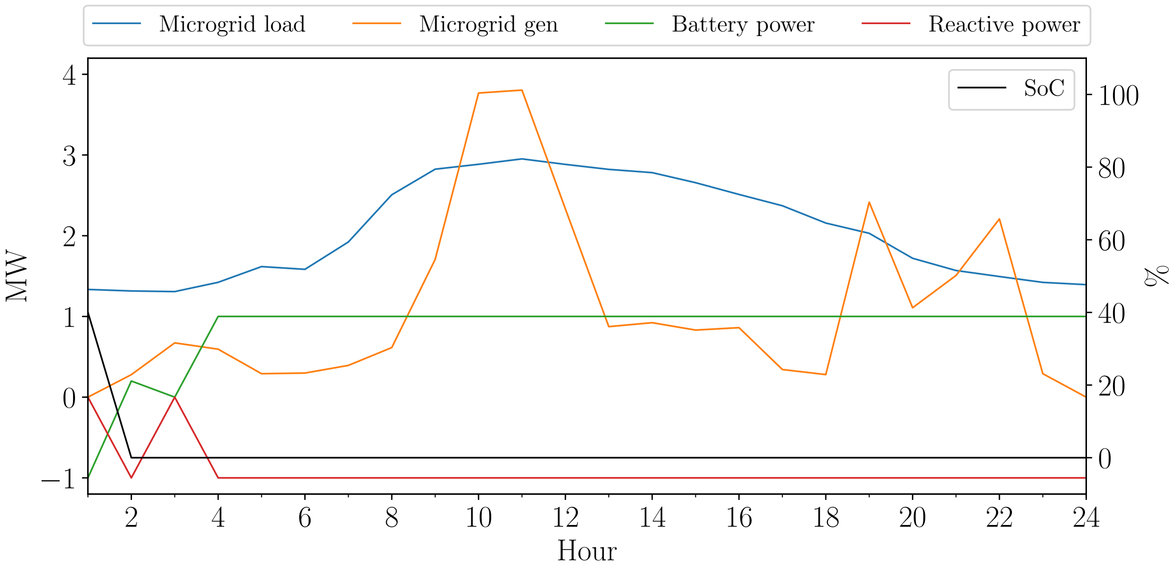


(b) With battery

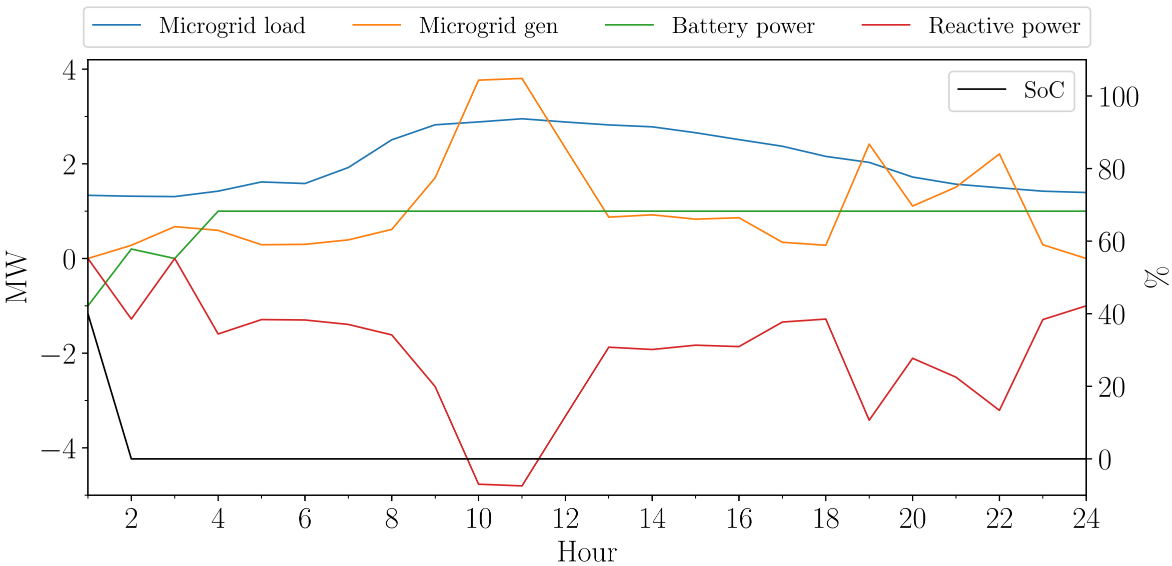
Figure (7.23) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 15 on the 7th of June

Connection with voltage regulation

Figure 7.24 presents the battery activities when both regulation strategies are introduced. As expected, it can be observed that the battery will try to regulate the voltage at the hours predicted in the previous case.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.24) Load, generation and battery in the microgrid with the microgrid connected to bus 15 on the 7th of June

Figure 7.25 illustrates the voltage profiles for the eight buses furthest down in the main radial including the voltage on bus 22 for the previous strategies with the microgrid placed on bus 15 for both regulation strategies. Both regulation strategies are able to preserve the voltage levels during hour 2, which is the first hour with regulation. From Figure 7.24, it can be observed that the battery is able to regulate with stored capacity during this hour.

For the rest of the day, there are only small differences between the three cases, the battery strategy, the battery regulation strategy and the all regulation strategy, similar to what was seen on the 4th of June. The results illustrate as on the 4th of June that the all regulation strategy gives slightly better outcomes for the voltage profiles compared to the other two strategies. This effect can be seen in Table C.9 and C.10 or in Table 7.14, 7.15 and 7.16.

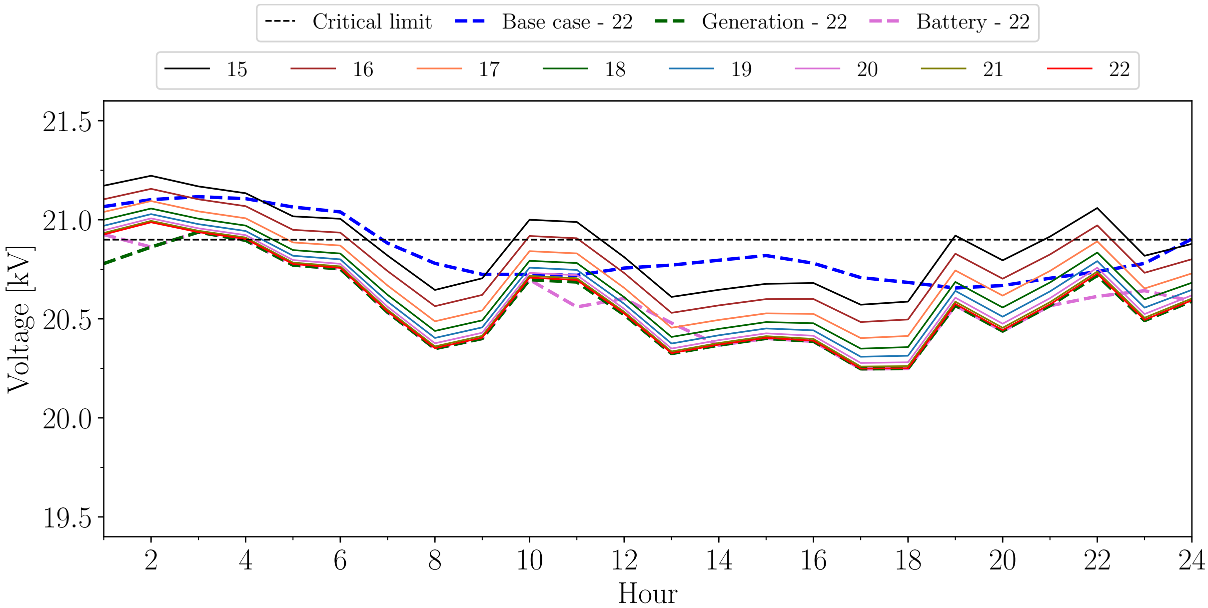
Tables 7.15 and 7.16 illustrates the percentage increase on bus 22 for both regulation strategies compared to base case. The illustrated hours are, the worst case hour for this case, the worst hour from the base case and the hours with the highest and lowest increase.

Table (7.15) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

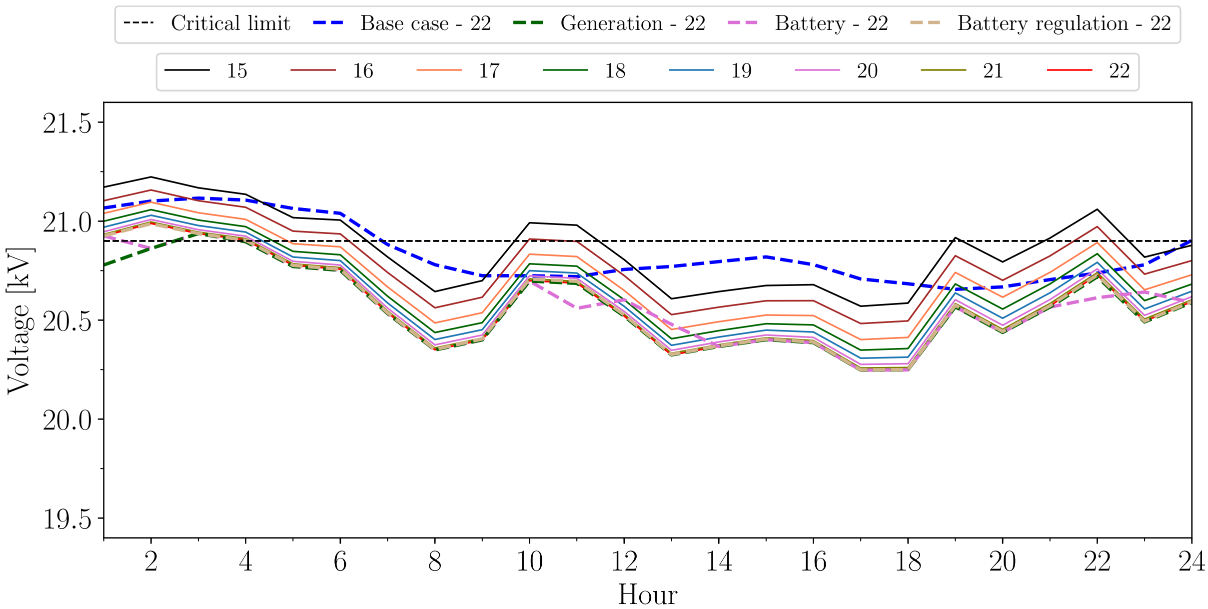
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	22	17	18	19
% Increase, battery regulation	-0.050	-2.218	-2.096	-0.390

Table (7.16) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	22	17	18	19
% Increase, all regulation	-0.045	-2.222	-2.099	-0.406



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.25) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 15 on the 7th of June

Microgrid connected to bus 20

Connection without voltage regulation

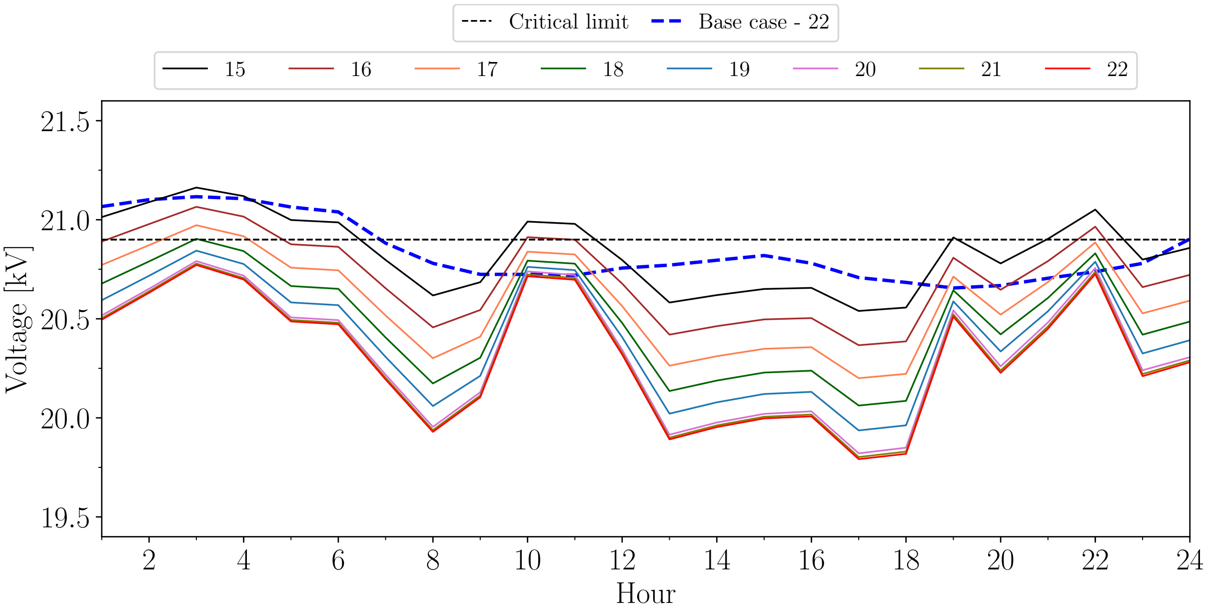
The microgrid is now placed on bus 20 in the main distribution system. In Figure 7.26, the voltage profiles for the generation strategy and the battery strategy are displayed. When introducing the microgrid, the voltage levels for this microgrid placement will drop below the critical limit the whole day. Compared to the other two connection points of the microgrid, this is the worst placement of the microgrid. The is due to the longer transferring distances for the power to reach the additional loads in the microgrid.

The same effect as for the other two placements of the microgrid will happen for this case regarding the voltage profiles between the generation strategy and the battery strategy. The results illustrate that the battery strategy gives slightly worse voltage profiles when the battery store energy. During the hours when the battery discharges, the voltage levels are improved compared to the generation strategy. This effect illustrates the importance of active power produced near the investigated loads.

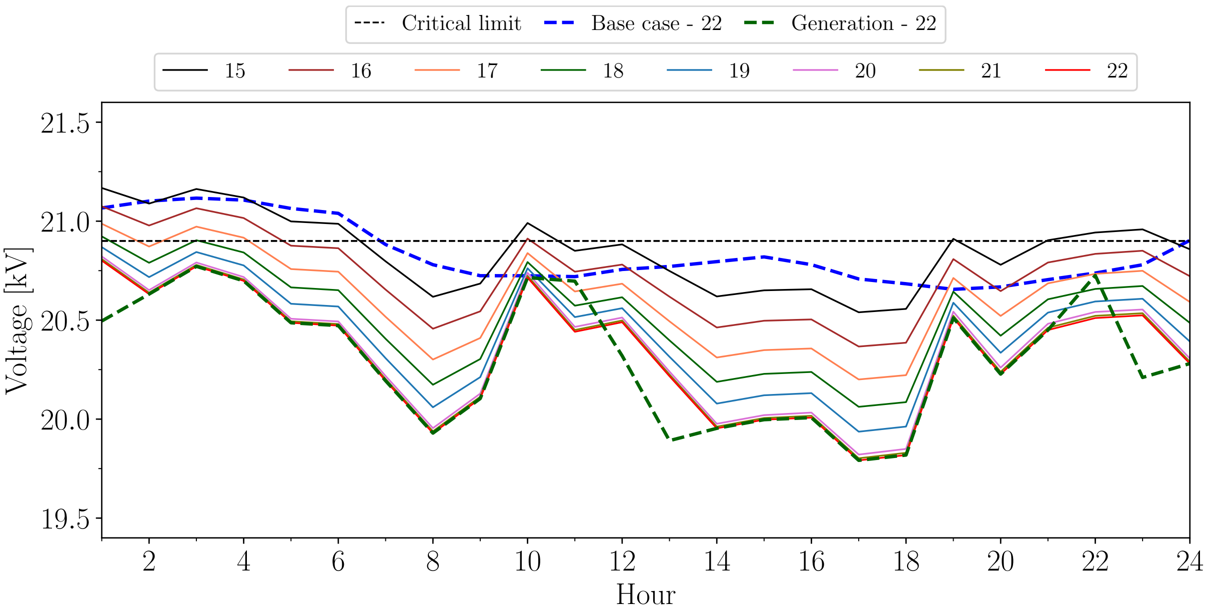
Table 7.17 contains the percentage increase for the battery strategy compared to the base case for four different situation hours.

Table (7.17) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	10	17	18	19
% Increase, battery	-0.045	-4.425	-4.138	-0.700



(a) Without battery

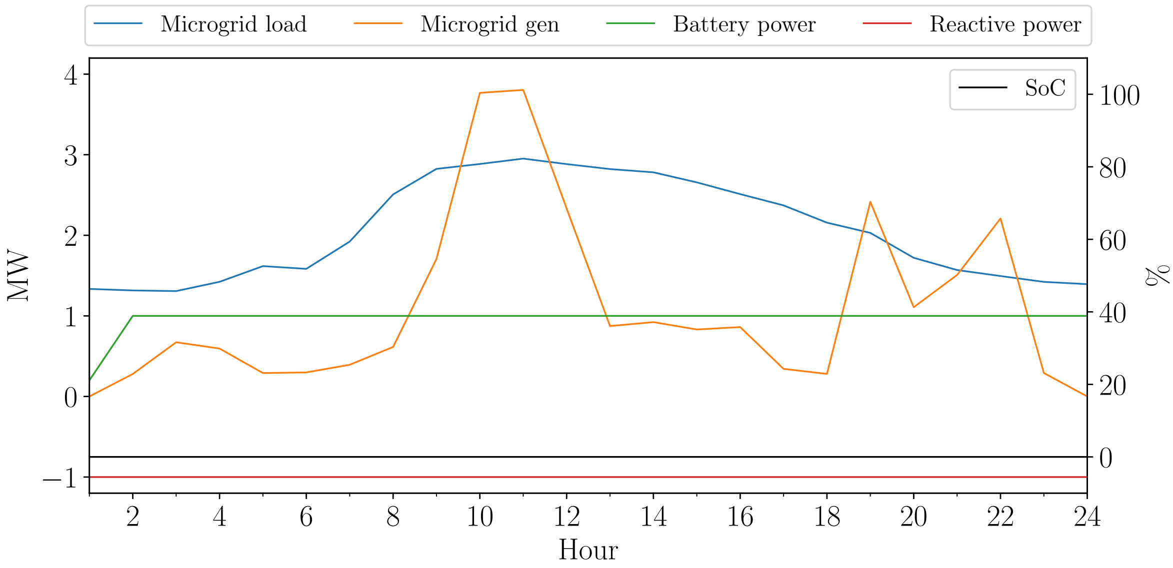


(b) With battery

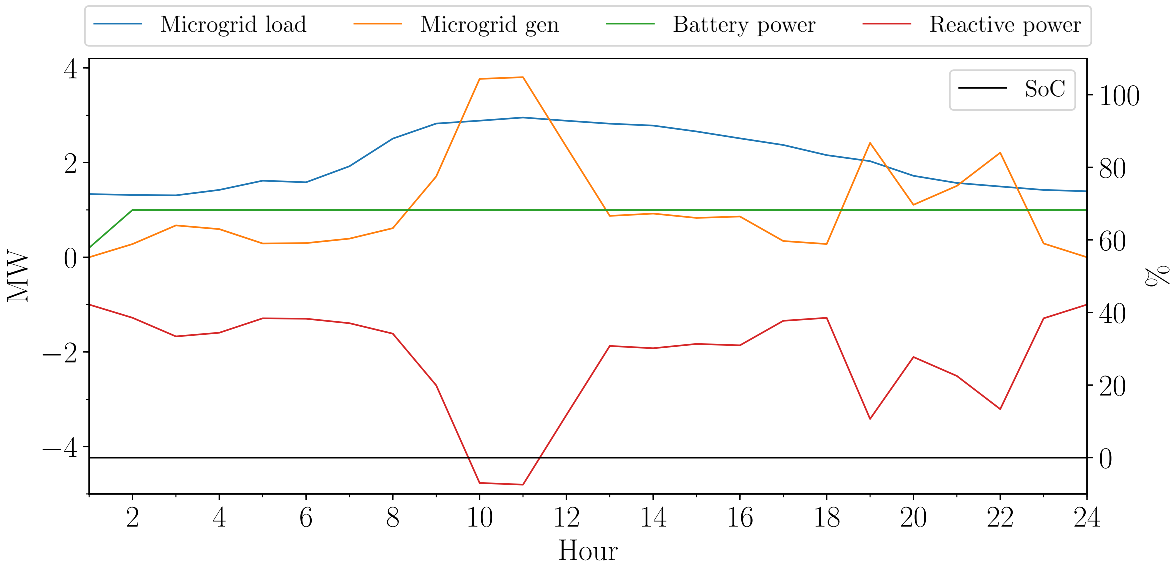
Figure (7.26) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 20 on the 7th of June

Connection with voltage regulation

Figure 7.27 illustrates how the battery operates for the two regulation strategies. It becomes clear that both the regulation methods will regulate for all the hours during the day with this microgrid placement.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.27) Load, generation and battery in the microgrid with the microgrid connected to bus 20 on the 7th of June

The voltage profiles when introducing regulation strategies are presented in Figure 7.28. The plots points out that both the regulation strategies worsened the voltage level situation compared to the other investigated cases for this microgrid placement. The all regulation strategy results in the worst voltage profiles. Thus, the system will be required to transfer a higher amount of active power to compensate for the loss of the active power generated from the DERs that have been converted to reactive power. This result is expected and has a similar pattern as on the 4th of June where the microgrid is connected to bus 20. This result illustrates the importance of the active power in the system, and will most likely benefit a voltage regulation regulating with active power compensation.

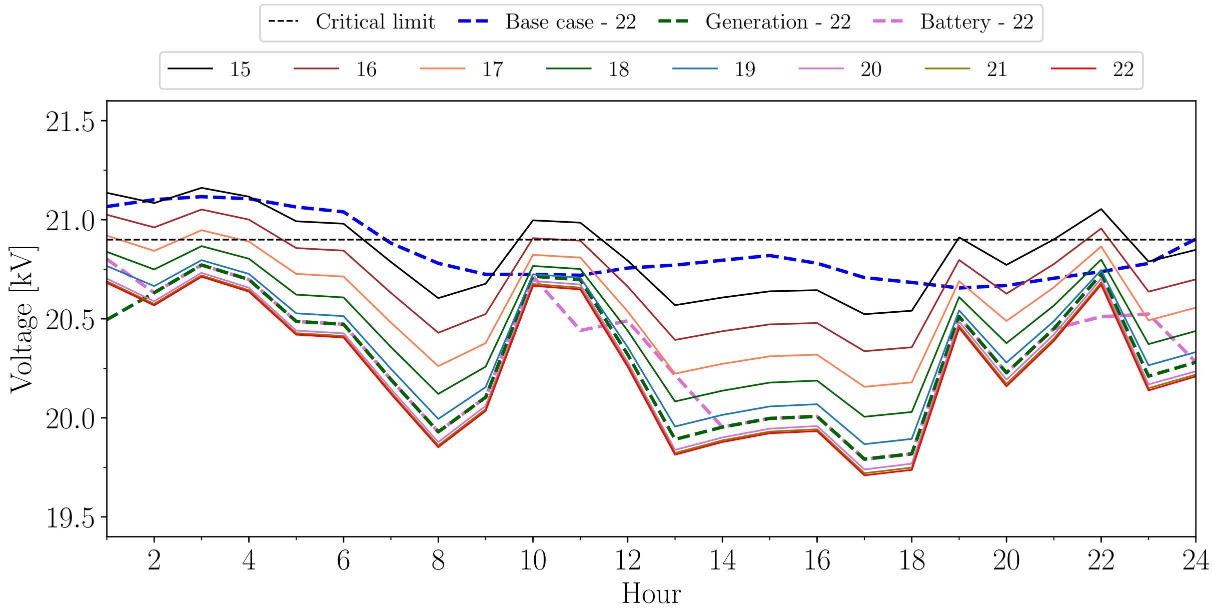
Tables 7.18 and 7.19 display the percentage increase for both the voltage regulation strategies compared to the base case. The same comparison hours as illustrated in earlier cases are present here.

Table (7.18) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

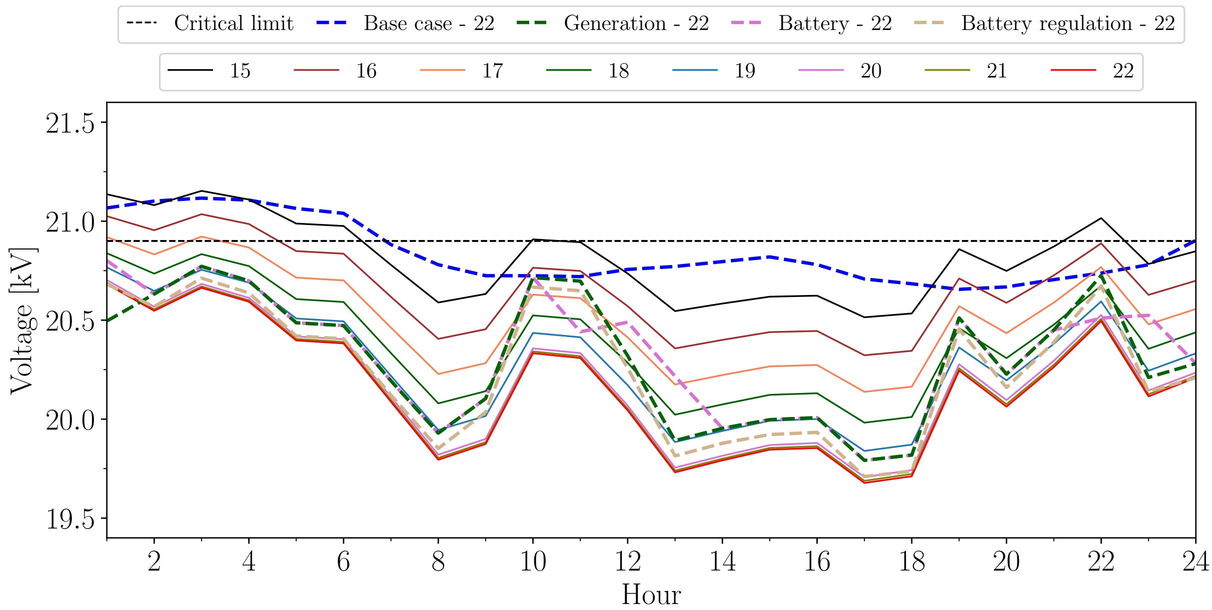
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	10	17	18	19
% Increase, battery regulation	-0.278	-4.819	-4.575	-0.975

Table (7.19) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	22	17	18	19
% Increase, all regulation	-1.170	-5.007	-4.701	-1.988



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.28) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 20 on the 7th of June

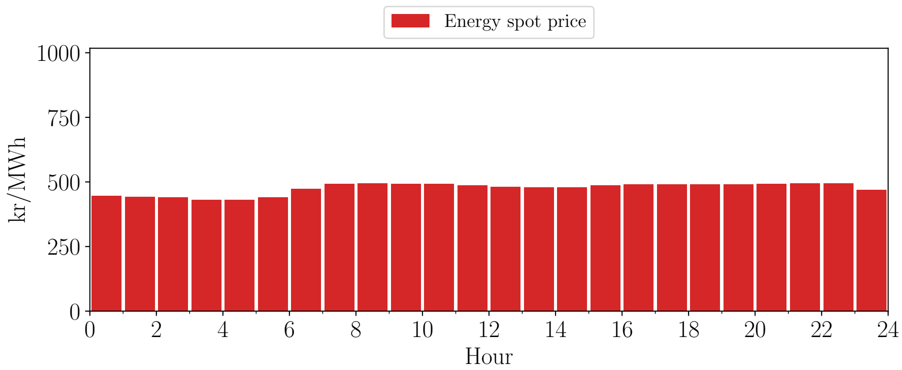
7.2.3 Demand response

The content in this section will presented in a similar manner as in Section 7.1.3.

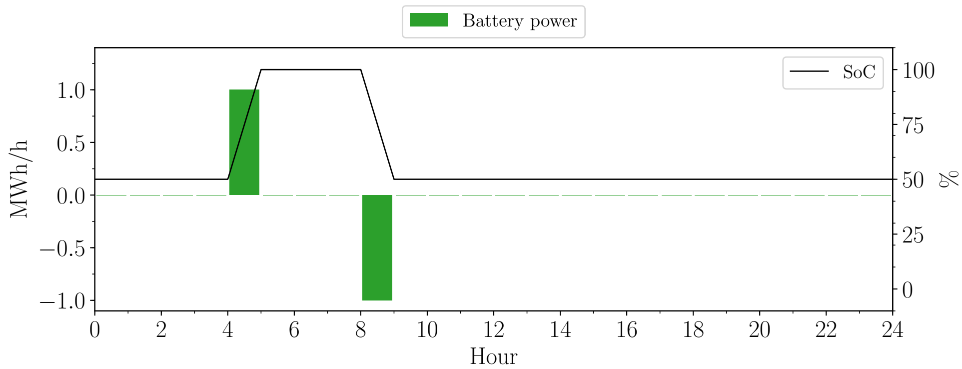
Price based program

Figure 7.29 shows how the microgrid responds to the price signals from the 7th of June on an hourly basis. The price variation this day is even lower than on the 4th of June. The lowest price is 429.8 kr/MWh in hour 5, and the highest price is 495.1 kr/MWh in hour 9. The hourly price variation is presented in Figure 7.29a. Figure 7.29b illustrates that the price difference is big enough for the battery to charge and discharge at full power once during the whole day. Thus, the price differences are not big enough for the indoor temperate to be increased in any greater extent during the day giving the households to keep the temperature at the lowest limit. This effect can be seen in Figure 7.29c. The temperature increases at the last hour since the algorithm is build on defaulting the temperature at the beginning and end of the day. In total, the response actions save 196 kr for the microgrid, where 65 kr is saved from the battery actions and 132 kr saved from the households actions.

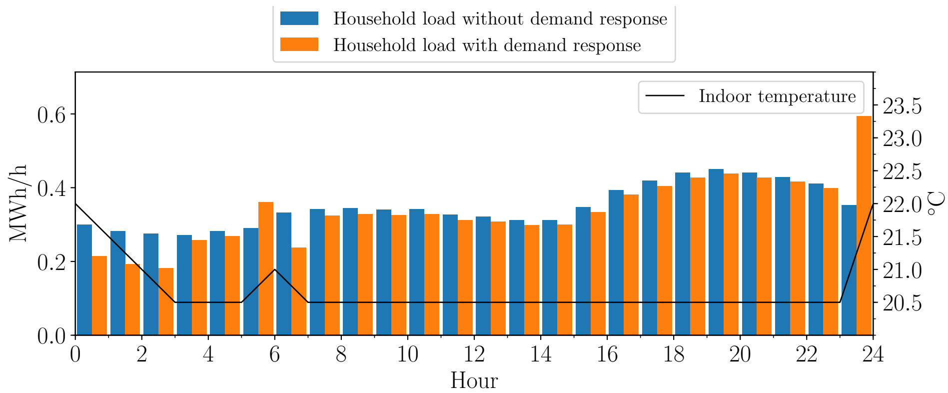
Figure 7.29d illustrates the total load in the microgrid with and without the demand response strategy. Since the strategy does not consider the total load, but only price, it causes the total load in the microgrid to increase higher than the highest peak without any demand response. The highest peak without demand response is 2.27 MWh/h in hour 17, while the new peak is 2.49 MWh/h in hour 5, which is the hour the battery store energy. This effect can cause problems and dangers if the the capacity limits on the line between the microgrid and the utility is exceeded. It can also have a negative impact on power losses, capacities on other lines in the system and voltage levels in the utility grid if this new and increased peak corresponds with the peak in the utility grid.



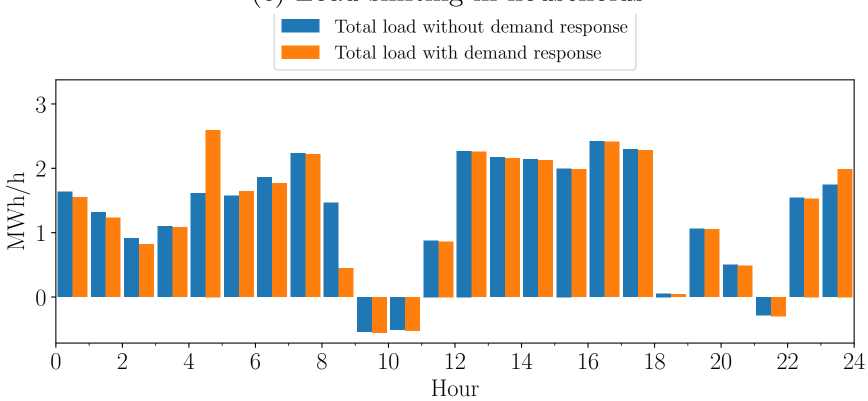
(a) Energy price 7th of June 2018



(b) Battery response



(c) Load shifting in households



(d) Total load in microgrid

Figure (7.29) Demand response with price based program on the 7th of June

Peak shaving

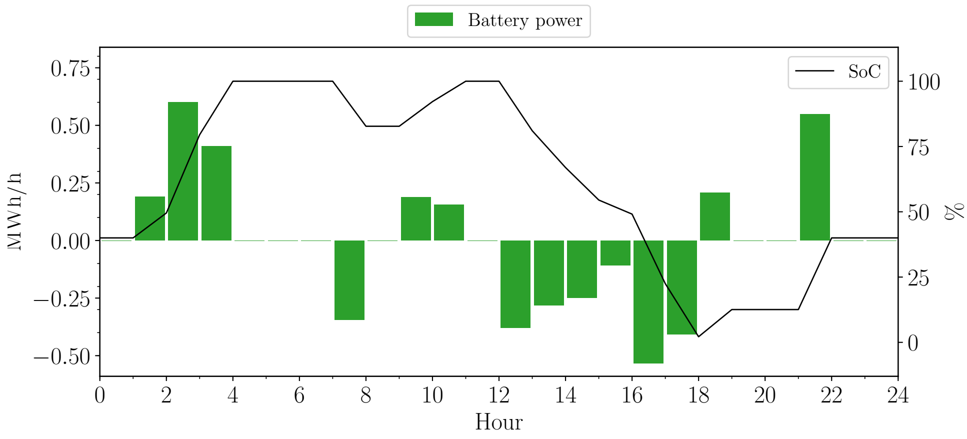
Figure 7.30 shows the demand response in the microgrid when the peak shaving program is applied. It can be imagined that this day is an important day to perform peak shaving, if the measured power part in the network tariff is calculated from the highest peaks during the month. This is due to the low generation in the microgrid and may result in higher load peaks compared to an average day in June.

In Figure 7.30c, the total load for the case with and without the peak shaving strategy is illustrated. The peak hour for the case without peak shaving strategy is hour 17 where the total load is 2.27 MWh/h. The results illustrate that the peak shaving strategy manage to lower this peak by 27.8 %, resulting in a new peak at 1.64 MWh/h, which is kept for multiple hours during the day.

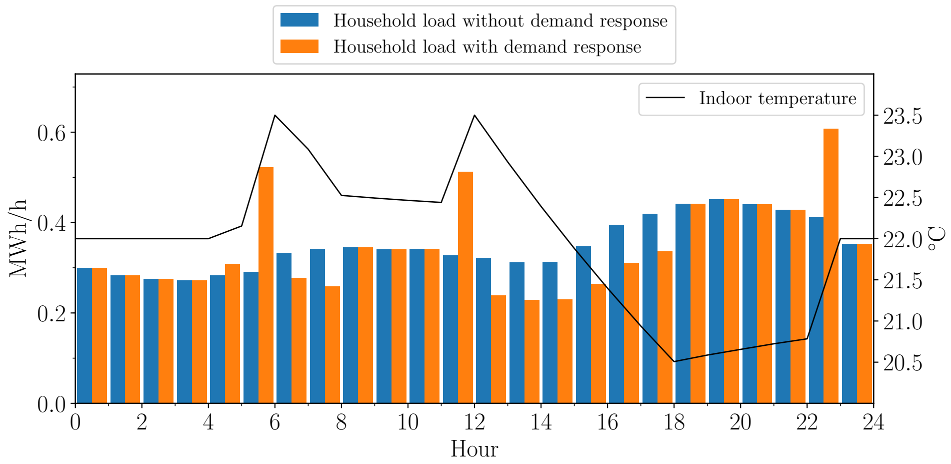
Figure 7.30a illustrates two periods, hour 8 and hours 13 to 18, where the battery performs peak shaving actions by discharging. For both periods the peak shaving strategy is able to reduce the total load in the microgrid. The great amount of generated power in the microgrid in hour 10 and 11 gives the battery the opportunity to charge before the next peak hours. The reason that the battery charges in hour 19 and 22 is to get the SoC back to the initial state of 40 %.

It can be seen from Figure 7.30b that the households increase their loads in hours 5, 6, 12 and 23. The reason for the increase in hours 5, 6 and 12 is to obtain the maximum allowed temperature in hour 7 and 13, when the peak shaving action is going to be performed. The total load in the microgrid in hour 6 would exceed the new wanted peak load if all the temperature increase had occurred at this hour. Therefore, the household loads are increased in hour 5. The peak at hour 23 comes as a result to get the SoC back to the initial state of 40 %.

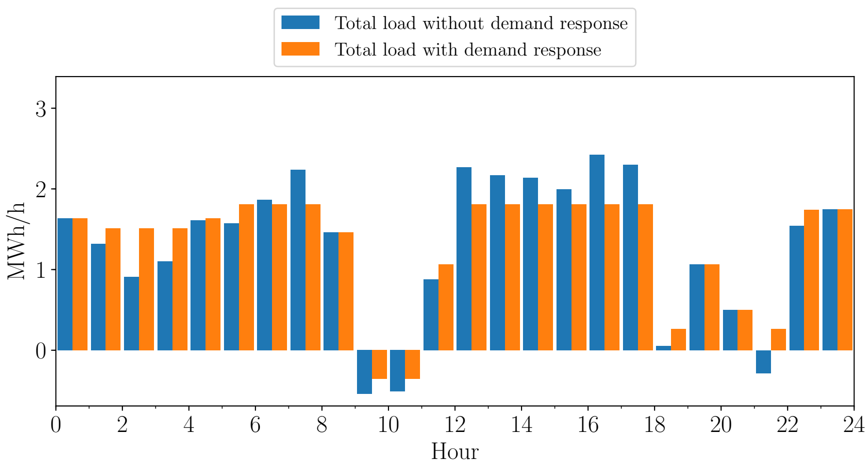
The total load in the microgrid in hour 7 is already without any demand response actions close to the new wanted total peak load. Therefore, most of the increase in indoor temperature prior hour 8 is done in hour 6.



(a) Battery response



(b) Load shifting in households



(c) Total load in microgrid

Figure (7.30) Demand response with peak shaving program on the 7th of June

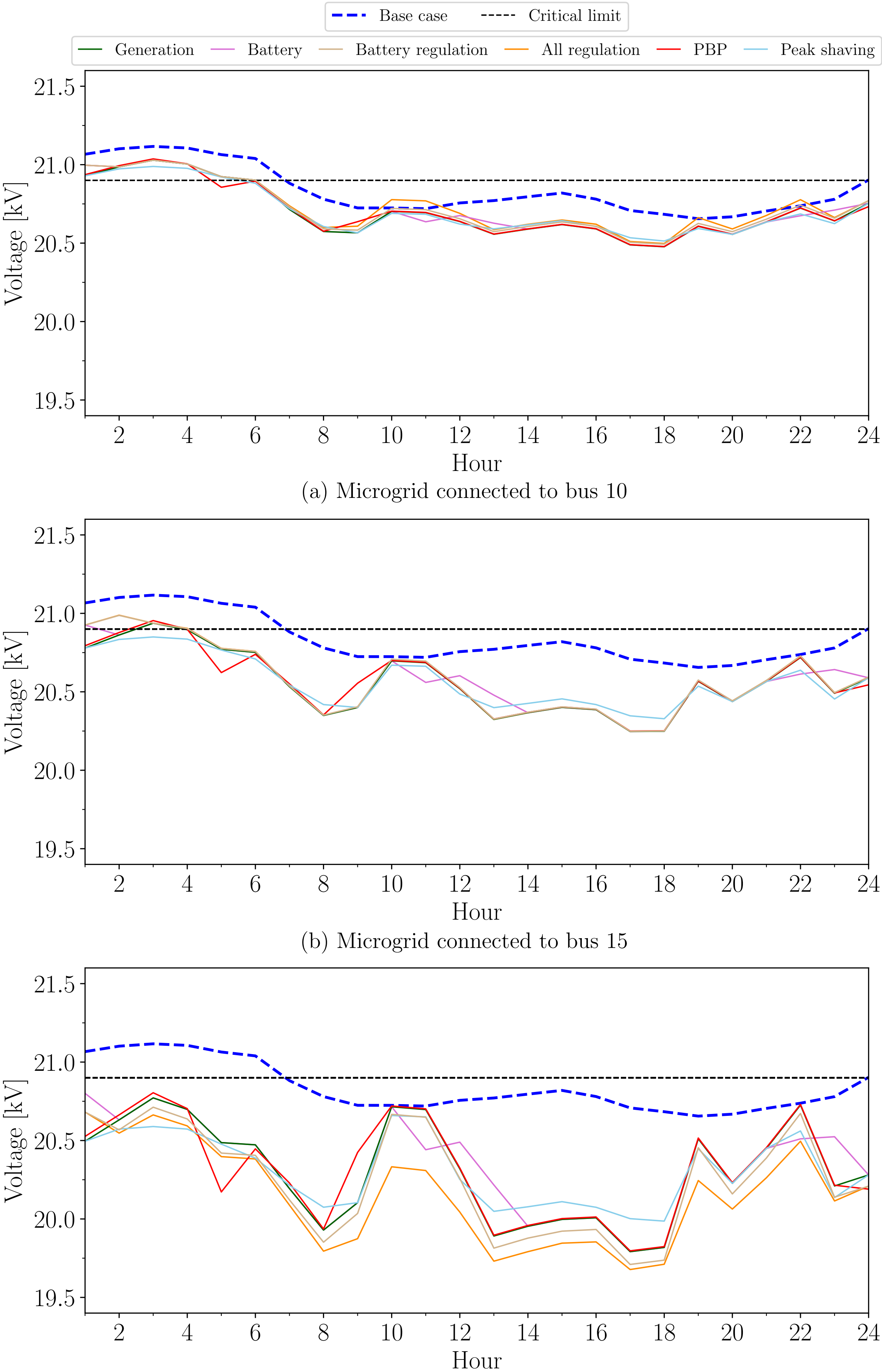
Voltage analysis including demand response scenarios

Figure 7.31 displays the hourly development in voltage on bus 22 for all the strategies including the demand response programs for the three different placements of the microgrid on the 7th of June.

When the microgrid is connected to bus 10, the demand response strategies does not make any greater impact on the bus voltages compared to other strategies, and obtains voltage profiles very similar to the generation strategy and the battery strategy. Nevertheless, the peak shaving strategy manages to increase the lowest voltage at hour 18 with 0.175 % from the generation strategy. The battery performs peak shaving actions during this hour, but the result illustrates that the peak shaving effect is low for this placement of the microgrid. The price based program will only influence the voltage profiles in a small extent during the two hours the battery charge and discharge for this strategy.

When the microgrid is connected to bus 15, it can be seen that the peak shaving program is slightly smoothing out the voltage curves, and manage to increase the worst voltage profile at hour 18, compared to the other strategies. The voltage level is increased with 0.476 % from the generation strategy. The peak shaving strategy manage to produce better voltage profiles compared to all the other scenarios during hour 8 and 13 to 18, which are the periods the battery perform peak shaving actions. The price based program mostly follows the generation strategy, as expected since there are only two hours the price based strategy perform. The price based strategy will cause some voltage jumps in the hours where the battery performs with full power, which can be observed at hour 5 and 9. The price based strategy manage to get the voltage levels over the critical limit in hour 3, while the peak shaving strategy never is able to restore the voltages levels over the critical limit.

When the microgrid is connected on bus 20, the peak shaving strategy smooths out the voltage curves even more. The effect the peak shaving strategy has on the voltage profiles compared to the other strategies, is greater for this placement of the microgrid compared to the others. The lowest voltage at hour 18 is for this case increased with 1.07 % from the generation strategy. It can be imagined from this tendency that this strategy could have worked well for this day and with the microgrid connected to bus 20 if the voltage curves initially were closer to the critical limit. The voltage difference between the price based program and the other strategies for the two hours where the strategy is performed has increased for this placement of the microgrid.



(a) Microgrid connected to bus 10

(b) Microgrid connected to bus 15

(c) Microgrid connected to bus 20

Figure (7.31) Voltage profiles for bus 22 for all strategies for the 7th of June

7.2.4 Line loading percentage

Figure 7.32 displays the loading percentage for line 4 and 13 with the different placements of the microgrid on the 7th of June. For comparison with the operation of the microgrid and the generation, load, battery and voltage curves for the same strategies, Figures 7.19, 7.21, 7.24, 7.27 and 7.31 can be used.

The same effect as for the 4th of June can be observed regarding line 13, when the microgrid is placed upstream of the line, illustrating that the microgrid operation does not influence the line. For the other cases, Figure 7.32 illustrates an even more clear tendency for the strategies to influence the loading percentage in a greater extent than what was seen on the 4th of June. All the strategies result in higher line loading compared to the base case for almost all the hours during this day. This result illustrates how sensitive the lines are to the power production in the microgrid. The loading curves for all the strategies, except the all regulation strategy, more or less reflects the microgrid generation curve, seen in Figure 7.19. Equal to what was seen on the 4th of June, the all regulation strategy gives the highest line loading percentages as expected. The increase compared to the other strategies is lower for this day, since the microgrid produces less active power that can be converted to reactive power. In all the cases, both the regulation strategies result in a higher line loading than all the other strategies. The only exceptions can be seen in hour 5 where the price based program gives a higher line loading than the battery regulation. The reason for this is that the battery stores active power, resulting in the network transferring more power over the lines.

One interesting observation is that the peak for the all regulation strategy happens at the same time as when the line loading in both lines for all the other strategies are low. That is in hour 10 and 11. The reason for this is that the generation is higher than the load in the microgrid in those hours. High generation is positive for the loading levels in all the strategies where this power is used to supply all the loads that are downstream of the studied line. The additional generation is not positive for the line loading when it is converted to reactive power, forcing the slack bus to transfer more active power, and the lines to obtain higher reactive and active power flow.

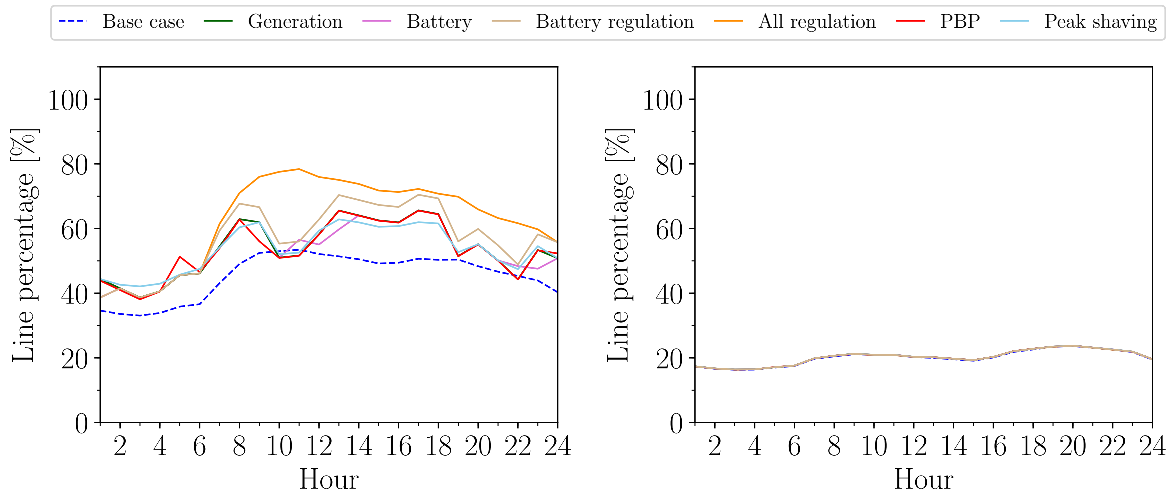
Equally to what was seen for the 4th of June, the four strategies, generation strategy, battery strategy, peak shaving strategy and PBP strategy, obtain almost equal line loading for both lines despite of the different microgrid placements. During hour 8 and hour 13 to 18 the line loading for the peak shaving strategy obtains a slightly lower loading compared to the other strategies. These are the hours where the peak shaving strategy performs by reducing the total load in the microgrid, and the load curve in the microgrid correlates with the loading percentage curve. Thus, the strategy decreases the load at the same time the loading is highest. The PBP strategy obtains the same small deviation in the line loading curve for both lines as seen on the 4th of June compared to the other three strategies, during the two hours where the battery charge and discharge, at hour 5 and 9.

Table 7.20 displays the line loading percentage for the generation strategy at hour 13 with the microgrid connected to the three different buses. The table aims to illustrate how the different line loading are influenced by the placement of the microgrid. Compared to the other strategies, the generation strategy do not follow any specific strategy. Thus, the strategy is more suitable for comparison between the different microgrid placements. Hour 13 is chosen based on the obtained high line loading for multiple of the strategies.

The table disclose that the line loading for line 4 is not influenced in any great matter by the microgrid placement. The line loading for line 13 is increased for a microgrid placement at bus 15 and 20 compared to bus 10. This effect can be seen through the high demand in the microgrid, which need to be supplied through line 13 when the microgrid is placed at bus 15 and 20.

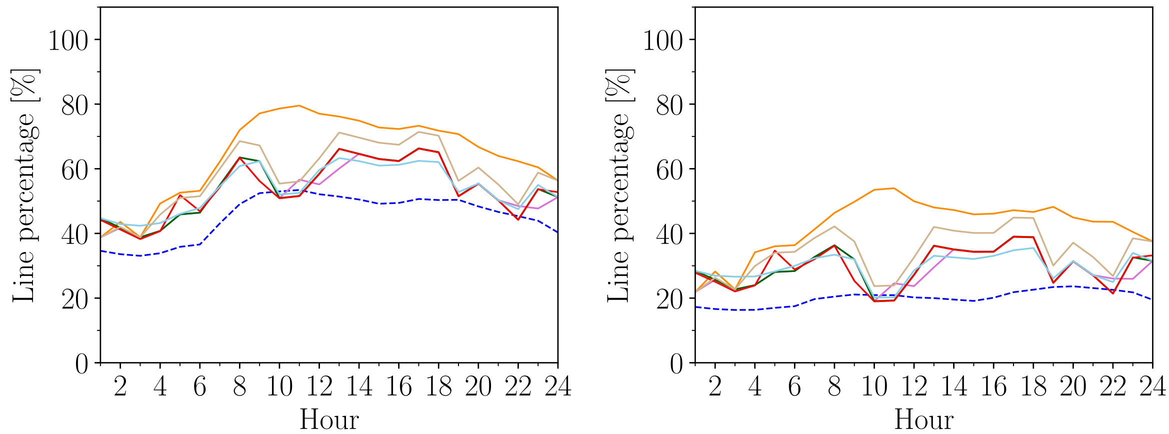
Table (7.20) Lowest line loading peaks for line 4 and 13 with different placings of the microgrid

Microgrid placement	**Bus 10**	**Bus 15**	**Bus 20**
Line loading line 4	65.58 %	66.20 %	66.92 %
Line loading line 13	20.20 %	36.24 %	37.05 %



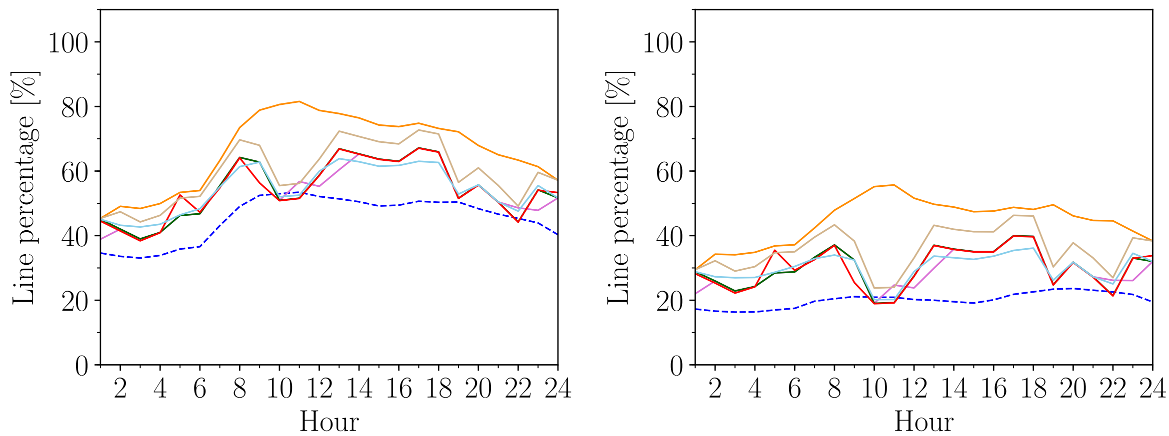
(I) Loading percentage on line 4 (II) Loading percentage on line 13

(a) Bus 10



(I) Loading percentage on line 4 (II) Loading percentage on line 13

(b) Bus 15



(I) Loading percentage on line 4 (II) Loading percentage on line 13

(c) Bus 20

Figure (7.32) Loading percentage for the 7th of June

7.3 Day 3: 1st of March

7.3.1 Base case

This day represents a very cold day and therefore an extra bad case situation. Figure 7.33 shows the load demand in the 33-bus system for this day. The load starts to drastically increase from hour 6 and reach a top between hour 9 and 11, before the demand slowly decreases. Figure 7.34 presents the voltage profiles for the eight buses furthest down in the main radial in the 33-bus system for this day. The voltage levels for the seven buses furthers down are never above the critical limit and the worst hour happens at hour 9, where the voltage at bus 22 is equal to 19.99 kV and the demand in the system meets its peak.

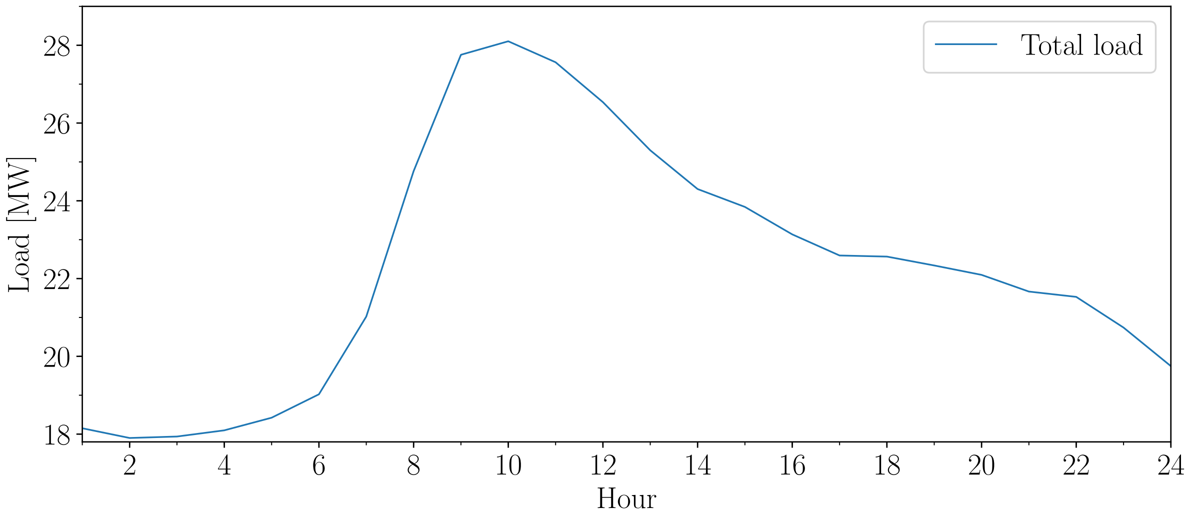


Figure (7.33) Base case: Active load profiles in the 33-bus network on the 1st of March

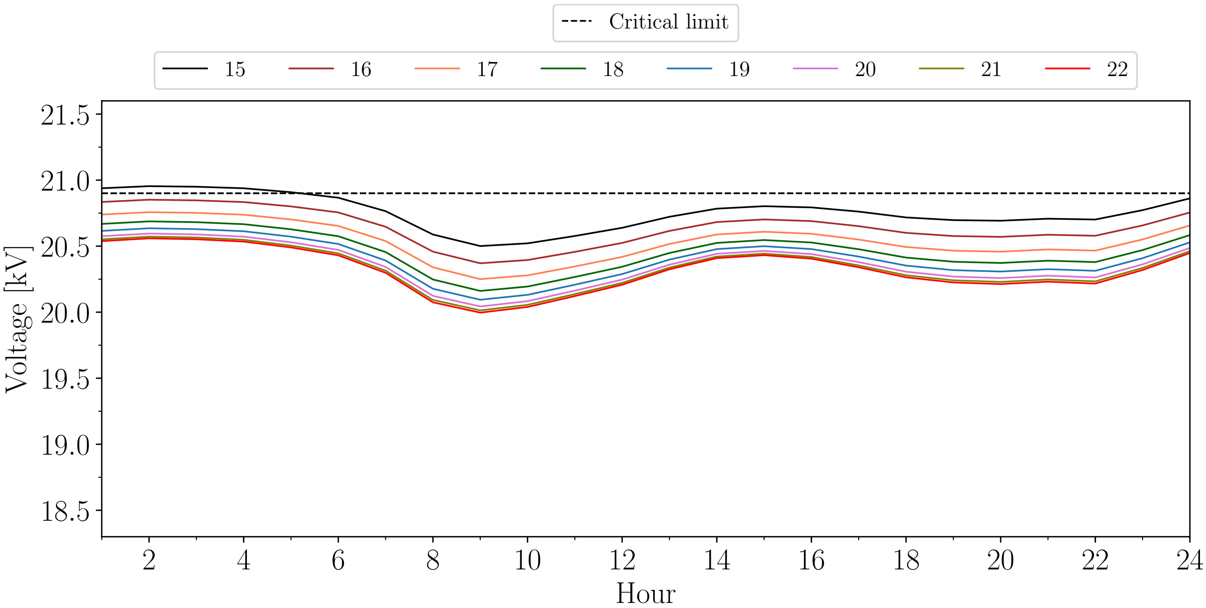
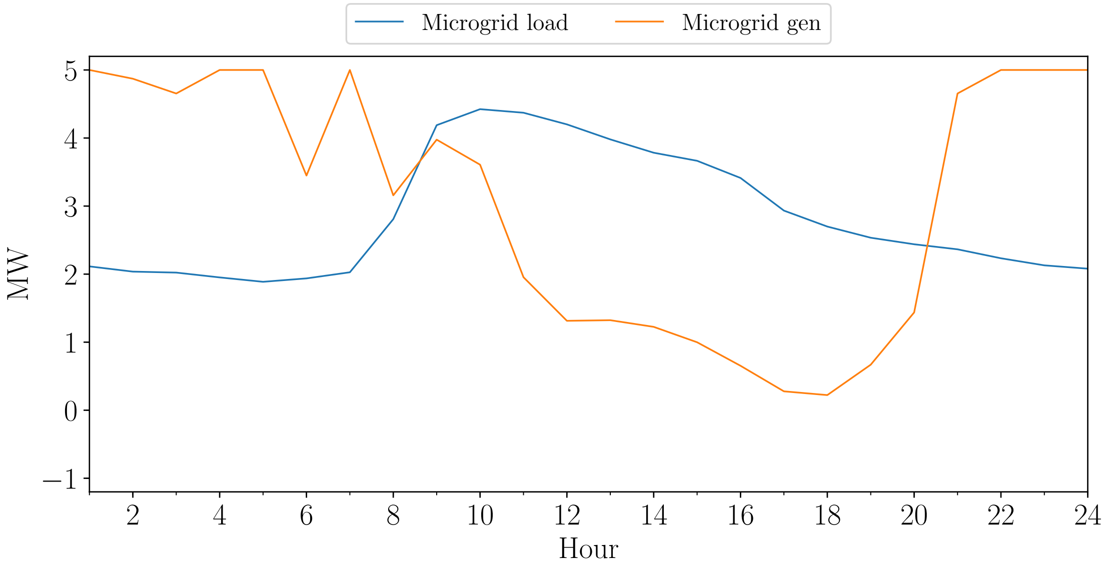


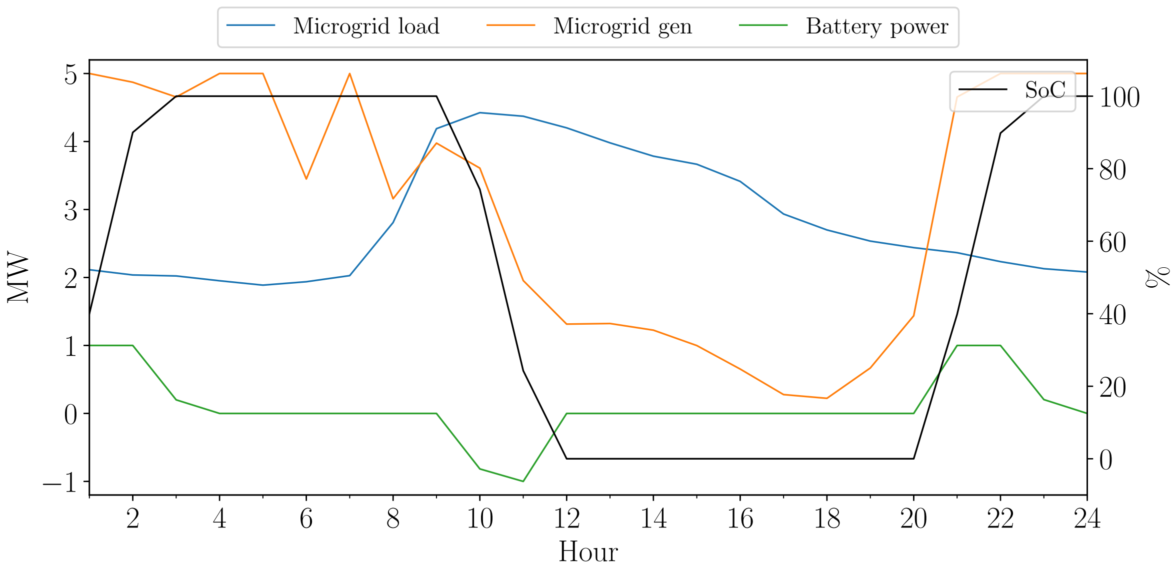
Figure (7.34) Base case: Voltage profiles for the most vulnerable buses on the 1st of March

7.3.2 Connection of microgrid and voltage regulation

Figure 7.35 contains the load, generation and battery operation for the microgrid during this day. The penetration of the generation is high during the first eight to nine hours before it drops and rises for the last four hours of the day. The battery charges and obtains a SoC of 100 % within the first three hours and then discharges when the peak demand happens at hour 9. The battery starts charging again around hour 20 and will be fully charged by hour 23.



(a) Without battery



(b) With battery

Figure (7.35) Load, generation and battery in the microgrid on the 1st of March

7.3.2.1 Microgrid connected to bus 10

Connection without voltage regulation

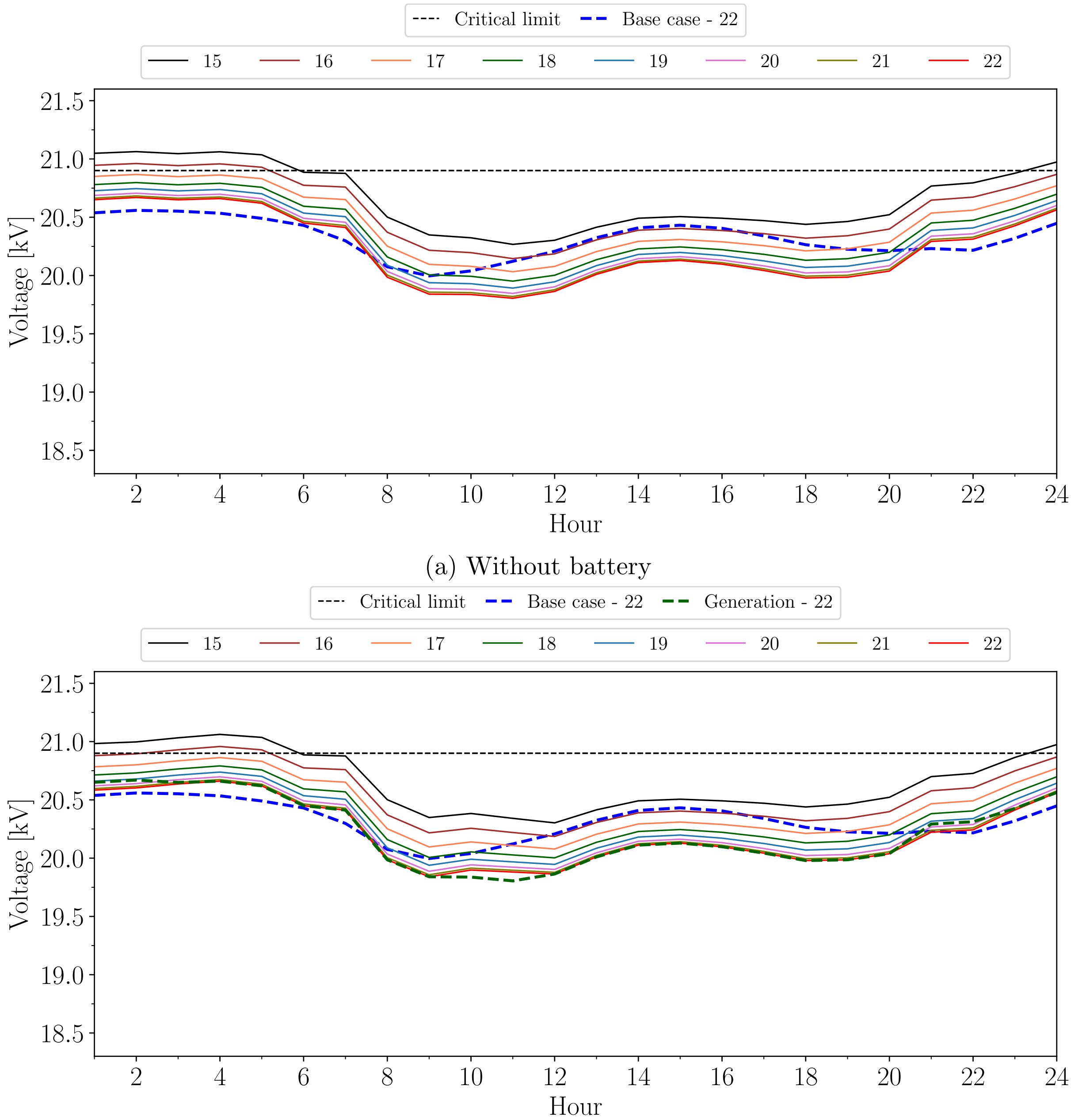
In this case, the microgrid will be connected to bus 10 in the main distribution system. Figures 7.36a and 7.36b present the voltage profiles for the eight buses furthest down in the main radial for the generation strategy and the battery strategy respectively. The main difference in the two strategies happens during the charging and discharging of the battery. The voltage levels drop slightly compared to the generation strategy when the battery charges, and the voltage levels increase slightly compared to the generation strategy when the battery discharges. This effect can be seen by comparing the green dotted line, illustrating the voltage on bus 22 for the generation strategy, with the voltage profiles for the battery strategy in Figure 7.36b. This was an expected result based on the other days.

With the introduction of the microgrid, the voltage profiles are not able to be restored within the critical limit. Compared to the voltage profile for bus 22 in the base case, seen as the blue dotted line in Figure 7.36, the production in the microgrid will manage to increase the voltage levels in the utility during the hours with high penetration of active power. The voltage profiles drop again when the production decreases and the demand in the microgrid exceeds the production. Thus, the main system will see the microgrid as a load instead of a generator. The worst hour for this case will still be hour 9 if the battery strategy is taken into account.

Table 7.21 presents the increase in voltage on bus 22 for the battery strategy compared to the base case for the worst hour in the base case, the worst hour in this case and the hours with the highest and lowest increase.

Table (7.21) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	5	12	9	9
% Increase, battery	0.634	-1.702	-0.783	-0.783



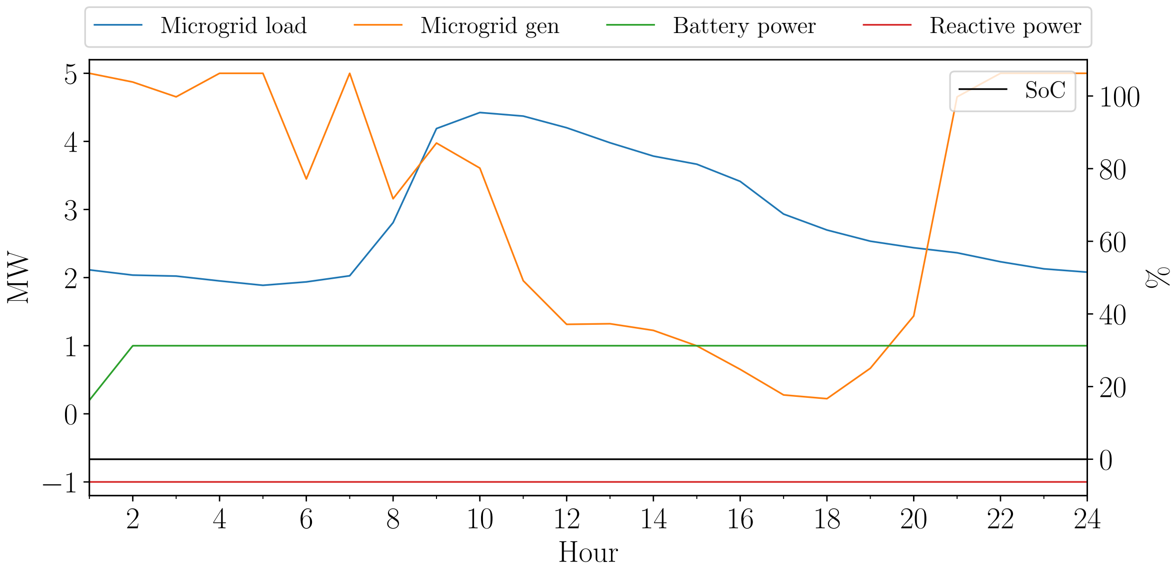
(a) Without battery

(b) With battery

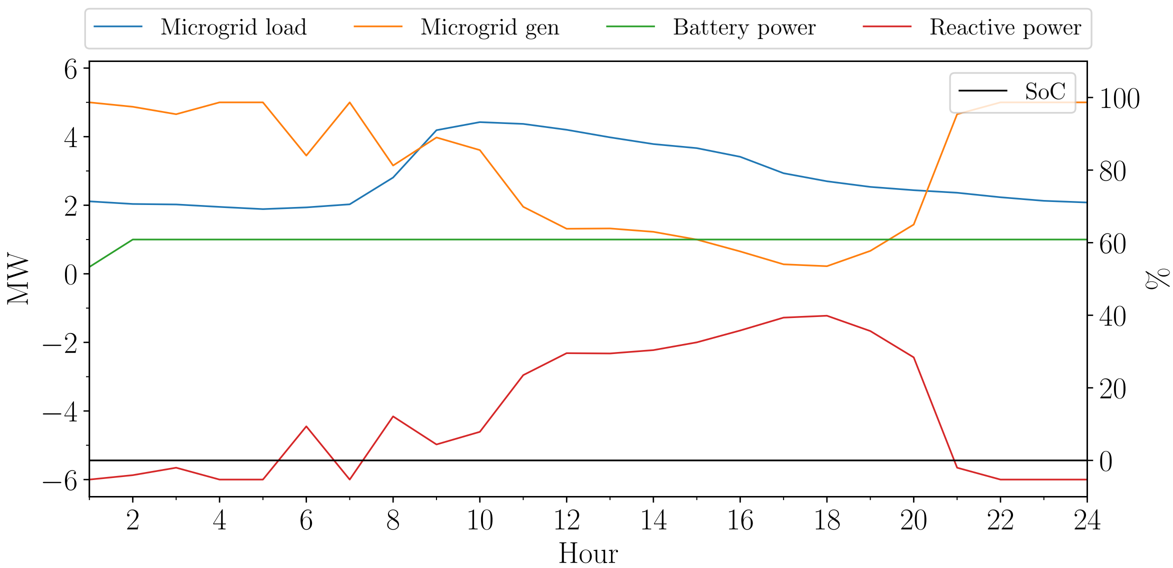
Figure (7.36) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 10 on the 1st of March

Connection with voltage regulation

With the introduction of voltage regulation, the battery will operate as presented in Figures 7.37a and 7.37b for the battery regulation strategy and the all regulation strategy respectively. As obtained from the previous case, regulation will be needed for every hour during this day.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.37) Load, generation and battery in the microgrid with the microgrid connected to bus 10 on the 1st of March

The voltage profiles for the eight buses furthest down in the main radial with the voltage profile on bus 22 for the other strategies can be seen in Figure 7.38 for both regulation strategies. During the hours with high penetration of active power in the microgrid, both regulation strategies will improve the voltage profiles. During the low production hours, the effect of the regulation will be small compared to the strategies without regulation.

For hour 10 and 11, it can be seen that the battery strategy obtains a slightly better voltage profile than both the regulation strategies. The reason is that at hour 10 and 11, the load exceeds the generation in the microgrid, and the battery will discharge giving more active power to the system. For the regulation strategies, the battery is empty during these hours since the previous hours have required regulation. Overall, the all regulation strategy gives better voltage profiles compared to the battery regulation strategy.

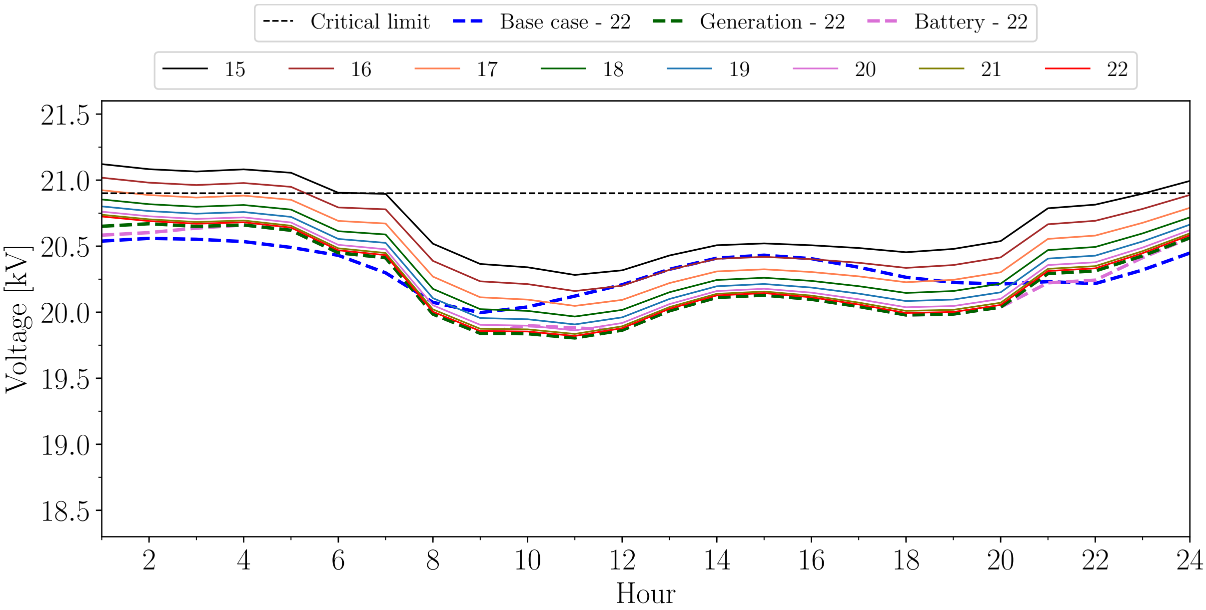
Tables 7.22 and 7.23 displays percentage increase for both the regulation strategies compared to the base case for the base case worst hour, the new worst hour for this case and the highest and lowest increase. The highest increase is obtained during the hour where the battery can contribute with regulation from stored capacity in the battery, as seen for the other investigated days.

Table (7.22) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

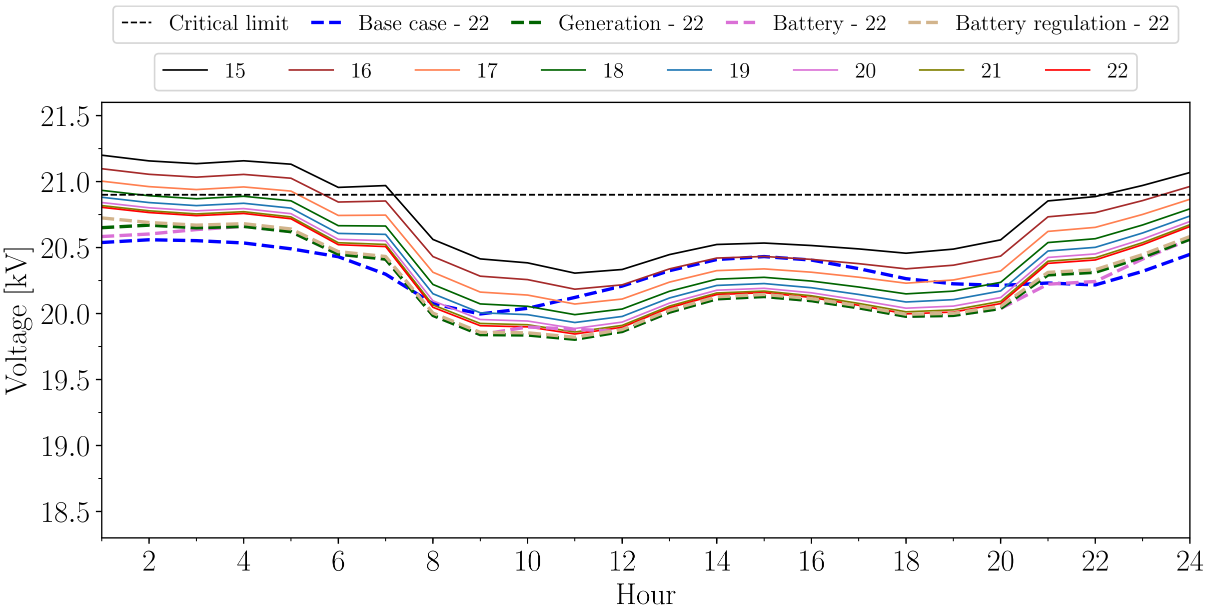
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	1	12	11	9
% Increase, battery regulation	0.907	-1.628	-1.500	-0.697

Table (7.23) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	1	12	11	9
% Increase, all regulation	1.297	-1.544	-1.378	-0.445



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.38) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 10 on the 1st of March

7.3.2.2 Microgrid connected to bus 15

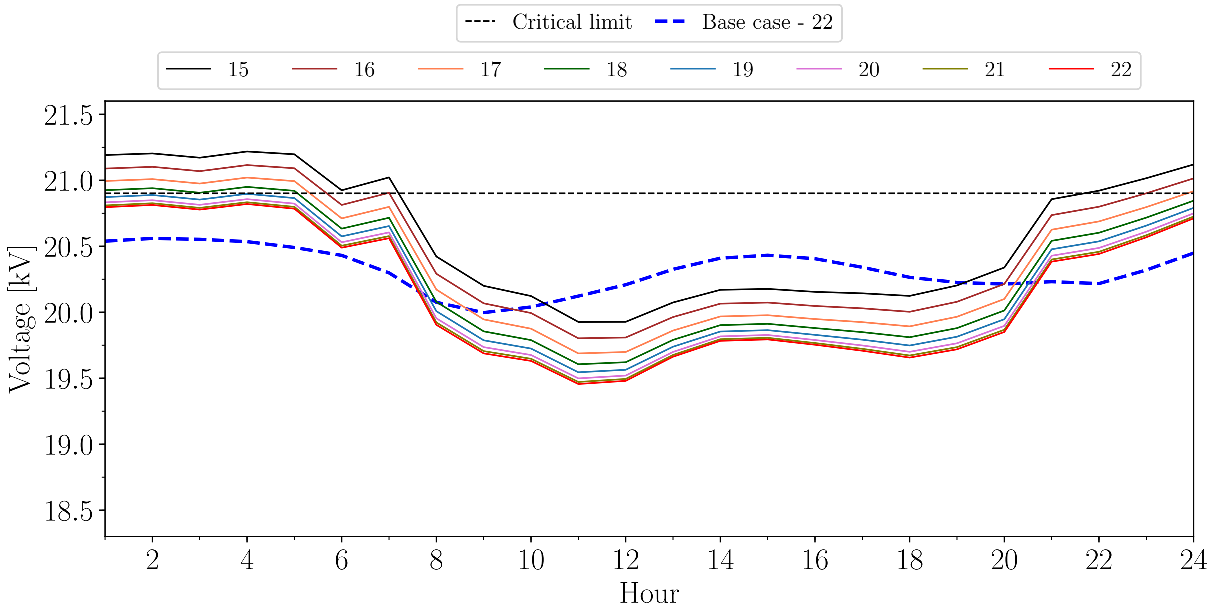
Connection without voltage regulation

In this case, the microgrid is connected to bus 15 in the main distribution system. Figure 7.39 shows the voltage profiles for the eight buses furthest down in the main radial for the generation strategy and the battery strategy. As for the previous placement of the microgrid, the connection of the microgrid will improve the voltage profiles for the hours with high penetration of produced active power, while worsening the voltage levels during the situations when the load demand in the microgrid exceeds the production. The result can be explained by the amount of transferred power in the system. During high generation hours, the produced power from the microgrid will be closer to the buses furthest away, but during low generation hours the main system will see the microgrid as a load and needs to transfer more power to meet the demand. Thus, the system will obtain higher voltage differences between the strategies and base case for this placement of the microgrid compared to the case where the microgrid was connected to bus 10. The battery strategy will give better voltage profiles than the generation strategy when the battery discharge stored power, while when the battery charge, the voltage levels drop compared to the generation strategy, as seen for the other cases.

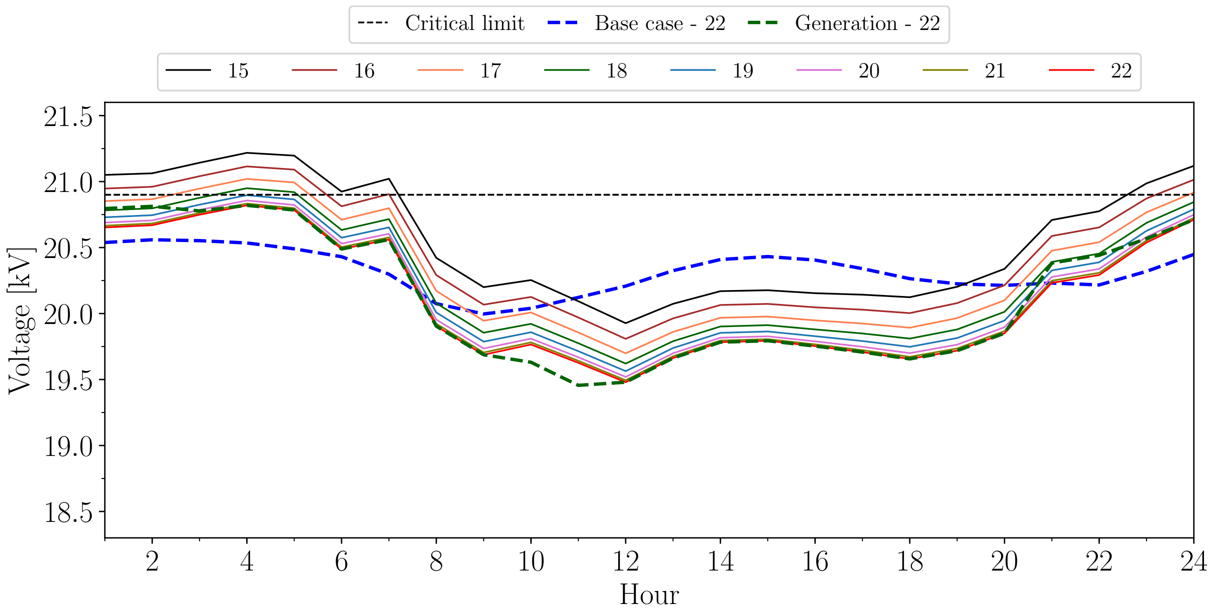
Table 7.24 displays the percentage increase for some important hours for the battery strategy compared to the base case.

Table (7.24) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	5	12	12	9
% Increase, battery	1.435	-3.604	-3.604	-1.545



(a) Without battery

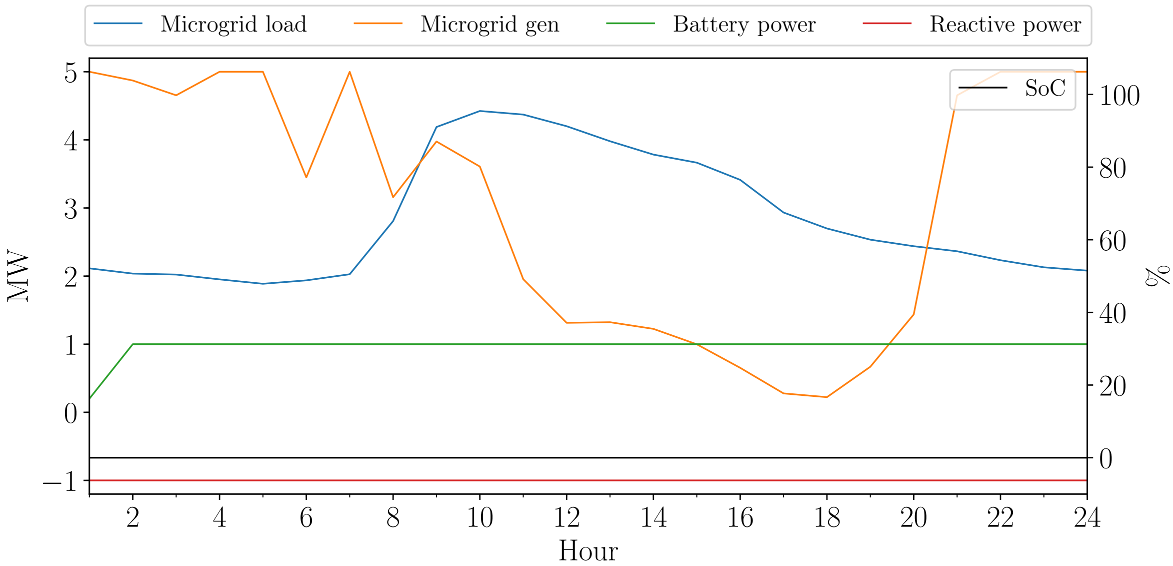


(b) With battery

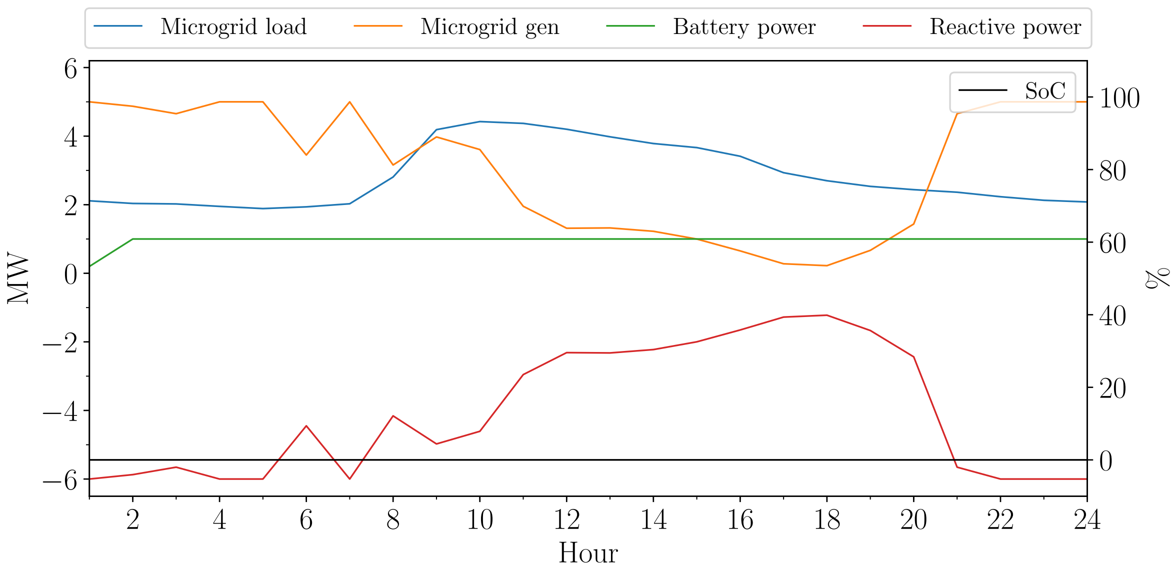
Figure (7.39) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 15 on the 1st of March

Connection with voltage regulation

The battery behavior when introducing voltage regulation is presented in Figure 7.40. As expected, the regulator will try to regulate the voltage in the system for every hour, equal to what was seen in Figure 7.37 when the microgrid was placed at bus 10.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.40) Load, generation and battery in the microgrid with the microgrid connected to bus 15 on the 1st of March.

The voltage profiles for both regulation strategies can be seen in Figure 7.41. A result similar to the previous days with the same connection point is obtained. The differences between the three different strategies, the battery strategy, the battery regulation strategy and the all regulation strategy are minor. The result obtained from Tables C.15 and C.16 or Tables 7.24, 7.25 and 7.26 illustrate, similar to the previous days, that the all regulation strategy gives a slightly better overall result than the two other discussed strategies.

None of the voltage strategies are able to recover the voltage levels, except from hour 1 where the regulators can use stored capacity from the battery. Compared to the base case, both voltage regulation strategies improve the voltage levels during high production hours, where the voltages are worsened during low production hours.

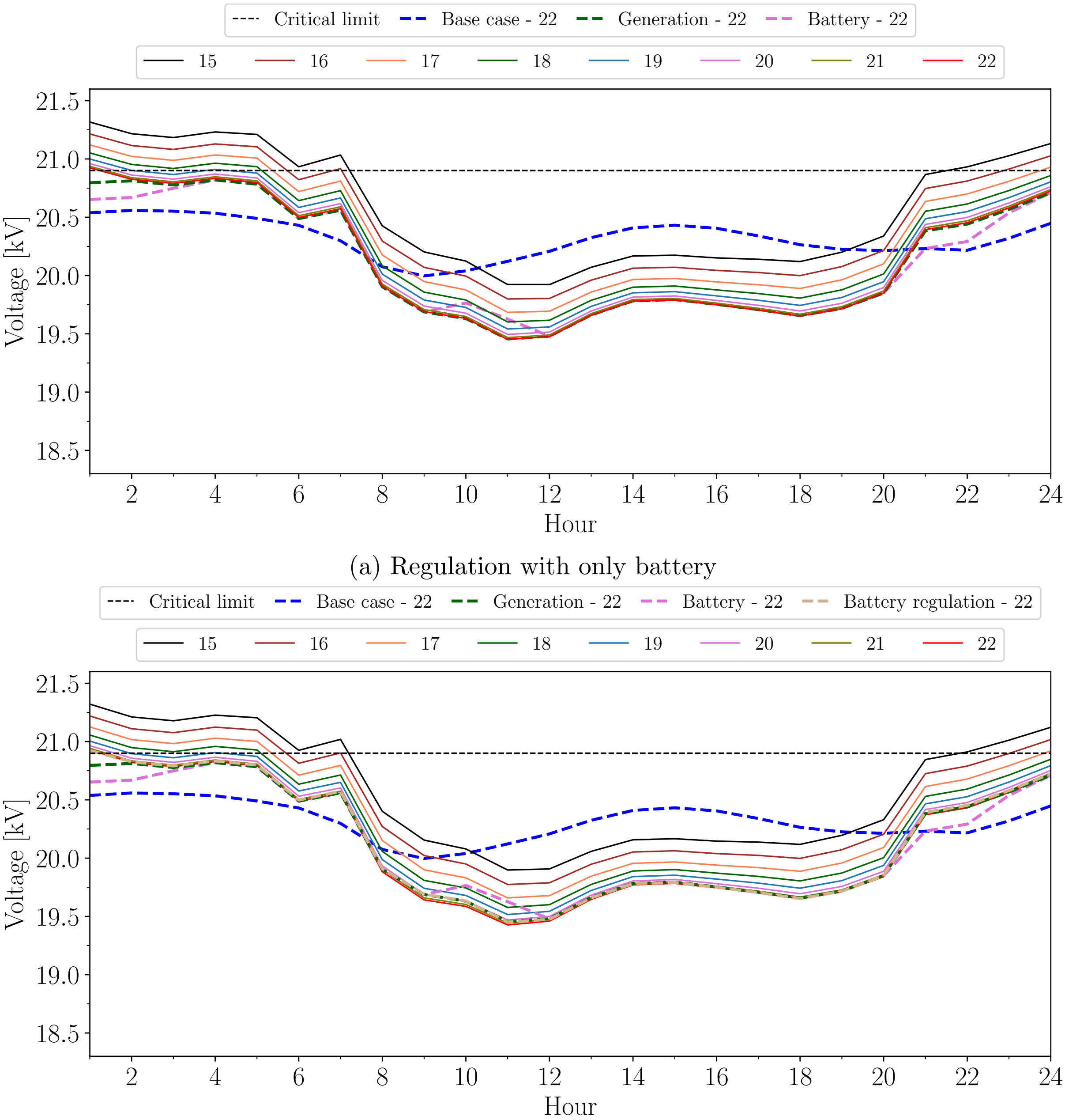
Tables 7.25 and 7.26 display the percentage increase in voltage on bus 22 for some regulation hours for both regulation strategies compared to the base case.

Table (7.25) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	1	12	11	9
% Increase, battery regulation	1.876	-3.672	-3.328	-1.530

Table (7.26) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	1	12	11	9
% Increase, all regulation	1.899	-3.703	-3.454	-1.775



(a) Regulation with only battery

(b) Regulation with all generation units

Figure (7.41) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 15 on the 1st of March

Microgrid connected to bus 20

Connection without voltage regulation

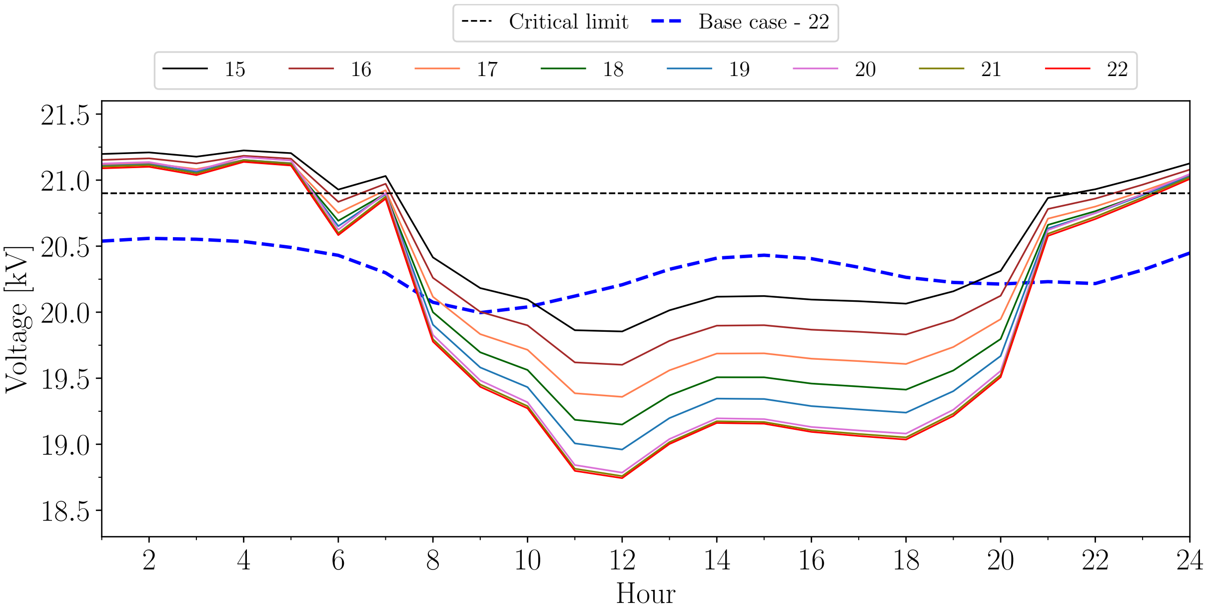
In the final case, the microgrid is connected to bus 20 in the main distribution system. Figure 7.42 shows the voltage profiles for the eight buses furthest down in the main radial for the generation strategy and the battery strategy. Compared to the two other connection points of the microgrid, this placement is actually able to restore the voltage levels for hour 1 to 5 and 23 to 24 for the generation strategy. For the battery strategy, the microgrid production is able to restore the voltage levels for hour 3 to 5 and 23 to 24. In the first two hours, the battery will store active power since the production exceeds the generation, resulting in less active power injected to the system. Therefore, a worse voltage profile than for the generation strategy is obtained.

The voltage profiles in Figure 7.42 have higher differences from the base case compared to the other two placements of the microgrid during this day. The result discloses the importance of short travelled energy. During the hours where the production is higher than the generation in the microgrid, the microgrid appears as a generation unit. This results in local production for the buses placed near the microgrid and results in higher voltage profiles. During the hours where the load exceeds the production in the microgrid, the microgrid is seen as a load. This results in more demand in the end of the main radial, requiring the system to transfer more power over the lines and thus, resulting in more power losses and the voltage levels drop.

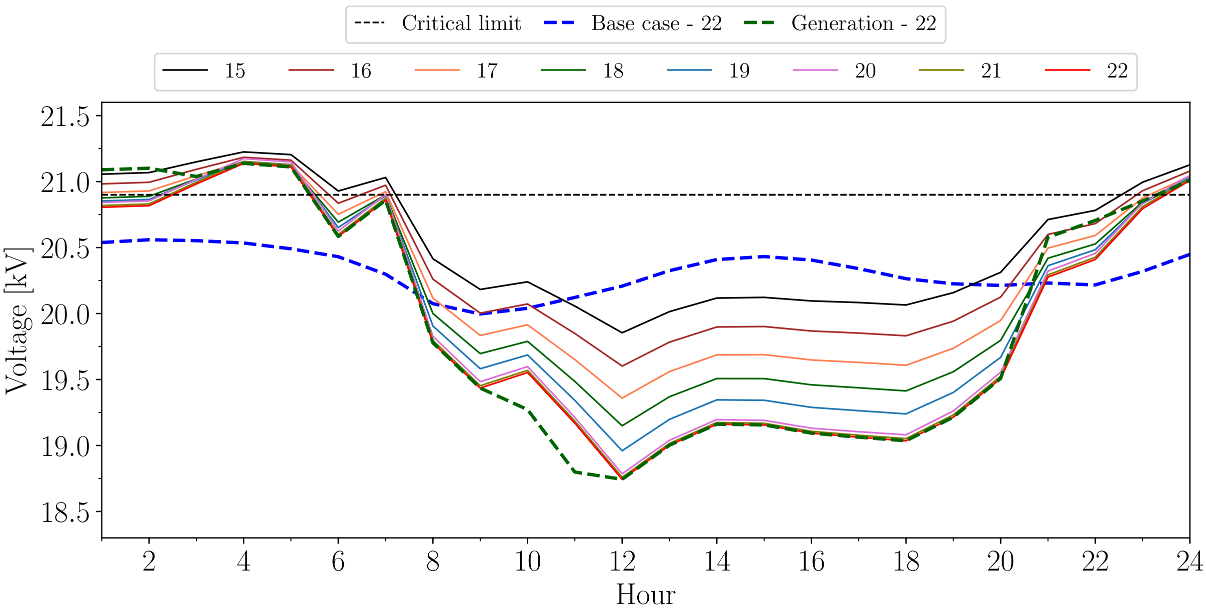
Table 7.27 shows the percentage increase in voltage at bus 22 for the battery strategy compared to the base case. The same case hours as for the other placements are displayed.

Table (7.27) Percentage increase in voltage on bus 22 for the battery strategy compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	5	12	12	9
% Increase, battery	3.028	-7.245	-7.245	-2.808



(a) Without battery

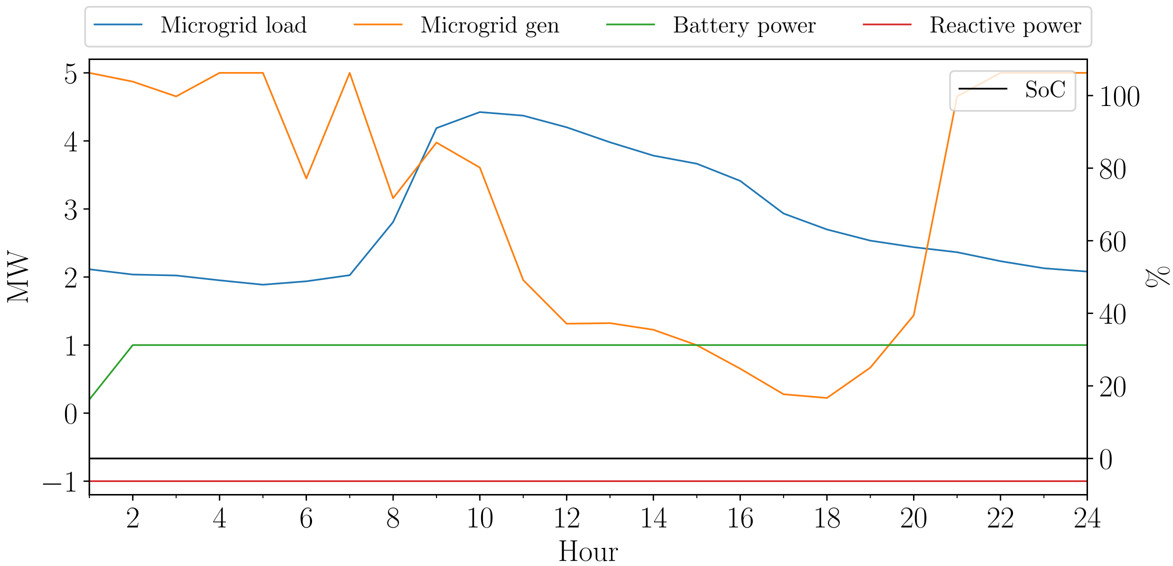


(b) With battery

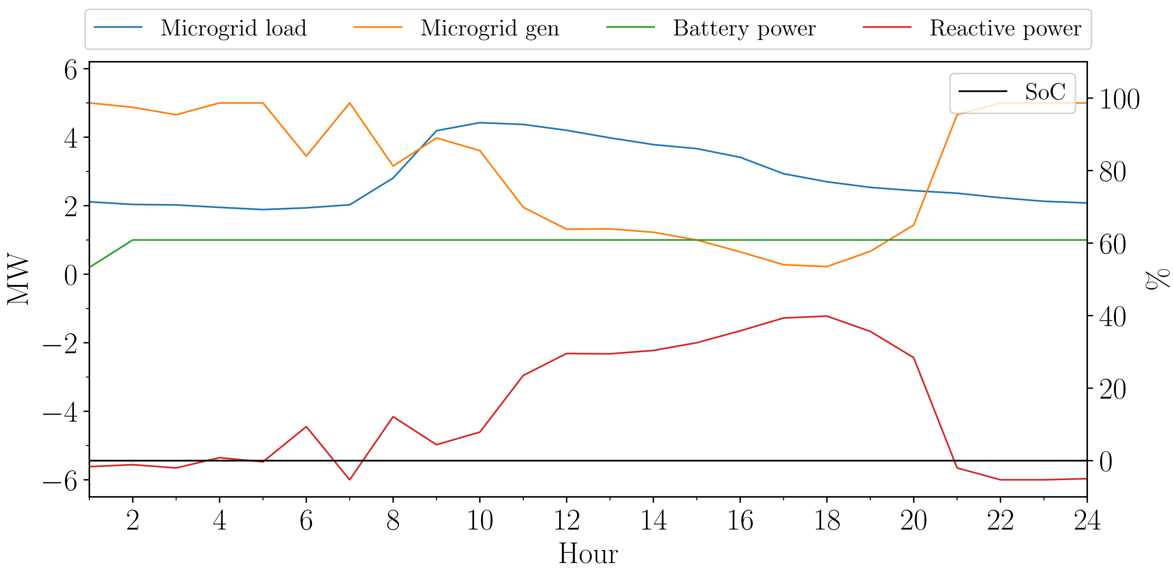
Figure (7.42) Voltage profiles for the most vulnerable buses with the microgrid connected to bus 20 on the 1st of March

Connection with voltage regulation

When introducing regulation, the battery will operate as seen in Figure 7.43 for both the regulation strategies. The figure shows that the system will regulate for all the hours. Since the voltage profiles drops below the critical limit in the battery strategy for the first hour illustrated in Figure 7.42b, the voltage regulator is required to act. Thus, the initially stored capacity in the battery will be used during this first hour. Furthermore, for the other hours with higher production than load in the microgrid, the battery will try to store power, resulting in the voltage levels dropping below the the critical limit, making the voltage regulator regulate. This case illustrates how the simple battery strategy destroys the voltage levels and might start unnecessary voltage regulation actions.



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.43) Load, generation and battery in the microgrid with the microgrid connected to bus 20 on the 1st of March

Figures 7.44a and 7.44b display the voltage profiles for the battery regulation strategy and the all regulation strategy respectively. By comparing the strategies, it is clearly that the battery regulation strategy gives better voltage profiles than the all regulation strategy. The voltage levels during hour 1 to 5 and 23 to 24 are restored for the battery regulation strategy. For the all regulation strategy, only the first hour is restored.

Both regulation strategies gives poorer voltage profiles than the situation obtained by the battery strategy. This illustrates, as for the other days, that with this placement of the microgrid, the system is more sensitive to active power than reactive power. The result is expected based on the R/X ration for the lines.

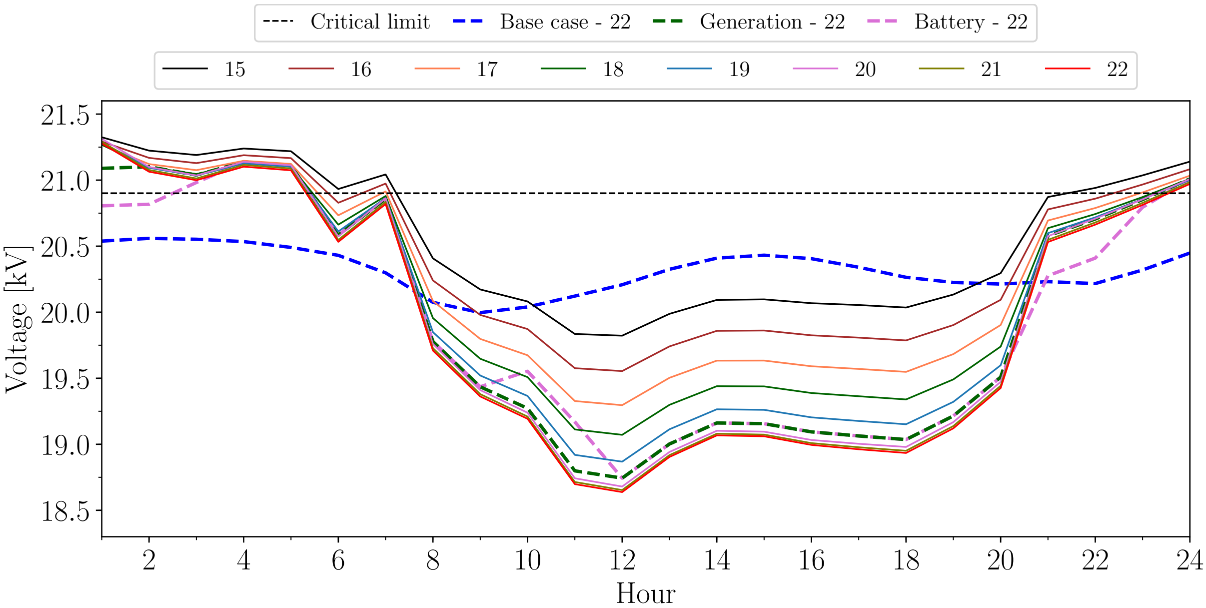
Tables 7.28 and 7.29 display the percentage increase in the voltage at bus 22 for both the regulation strategies compared to the base case. The results illustrate a worsened voltage profile situation compared to the base case, especially for hours with low production in the microgrid.

Table (7.28) Percentage increase in voltage on bus 22 for battery regulation compared to the base case

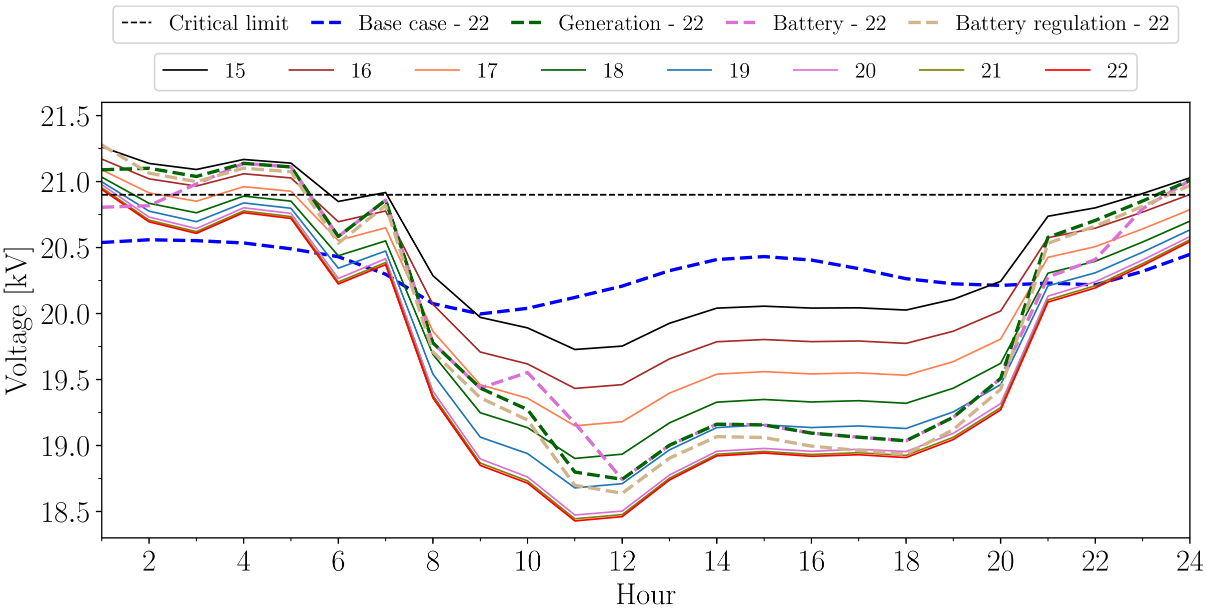
	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	1	12	12	9
% Increase, battery regulation	3.599	-7.769	-7.769	-3.174

Table (7.29) Percentage increase in voltage on bus 22 for all regulation compared to the base case

	Highest increase	**Lowest increase**	**Worst case hour**	**Base case worst hour**
Hour	1	12	11	9
% Increase, all regulation	1.958	-8.645	-8.417	-5.739



(a) Regulation with only battery



(b) Regulation with all generation units

Figure (7.44) Voltage profiles for the most vulnerable buses with regulation with the microgrid connected to bus 20 on the 1st of March

7.3.3 Demand response

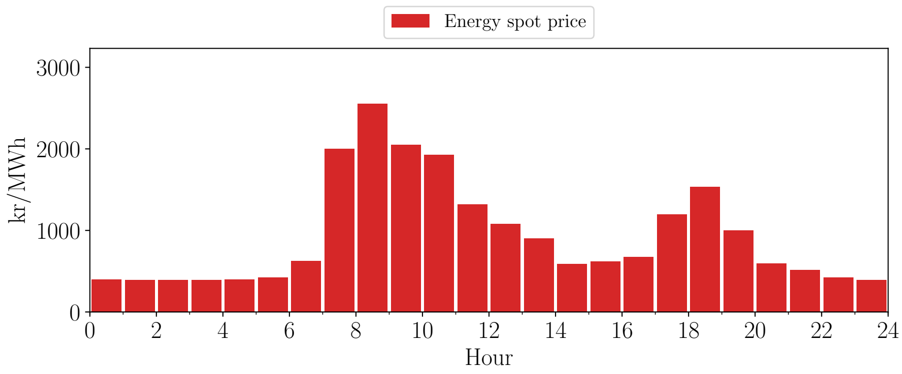
The content in this section will presented in a similar manner as in Section 7.1.3.

Price based program

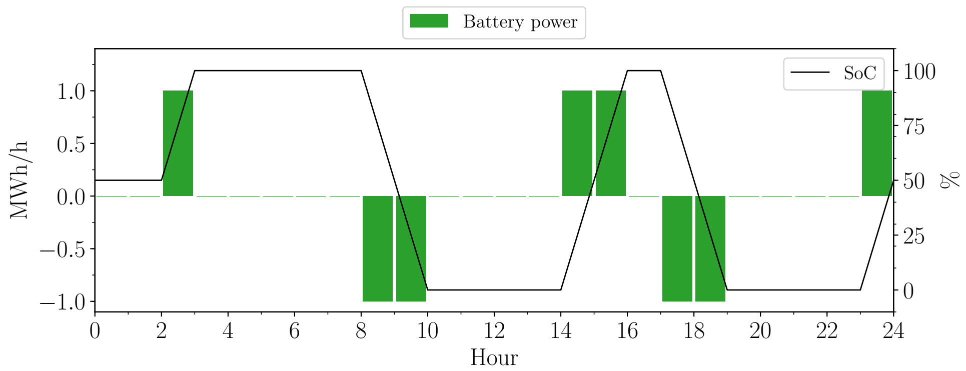
Figure 7.45 shows the microgrid response per hour to the price signals on the 1st of March. The price variations are very high for this day. The highest price is 2550.2 kr/MWh in hour 9, while the lowest price is 388.3 kr/MWh in hour 3. The reason for these extreme price variations is that the transmission capacity was on its maximum during multiple hours this day in this price area. The capacity problem caused very high price differences between different price areas in Norway that day. The high variations and the fact that there are two major peaks in the price diagram, cause more response actions this day than the previously discussed days. In total, the response actions saved 6773 kr for the microgrid, where the battery saved 5345 kr while the households saved 1429 kr. The assumption that the microgrid can buy and sell energy at the same price is also used here.

By comparing Figures 7.45a and 7.45d, the electricity price is low during the first seven hours where the total load in the microgrid is low. For hour 15 and 16 this effect is shifted, and the price is low for hours where the total load in the microgrid is high. This effect is reflected in Figure 7.45b and will result in the battery to start charging at these hours and the households to increase their loads in hour 15, which will result in two new and higher total load peaks for the PBP program. This is done to compensate for the more expensive hours 18 and 19, where the battery will discharge and the households will decrease their consumption. The total load peak in the microgrid is then increased by 38.1 % from 3.16 MWh/h to 4.37 MWh/h. The increased load peaks might result in problems for the lines and system components, especially if the new peaks correlates with high load peaks in the distribution network.

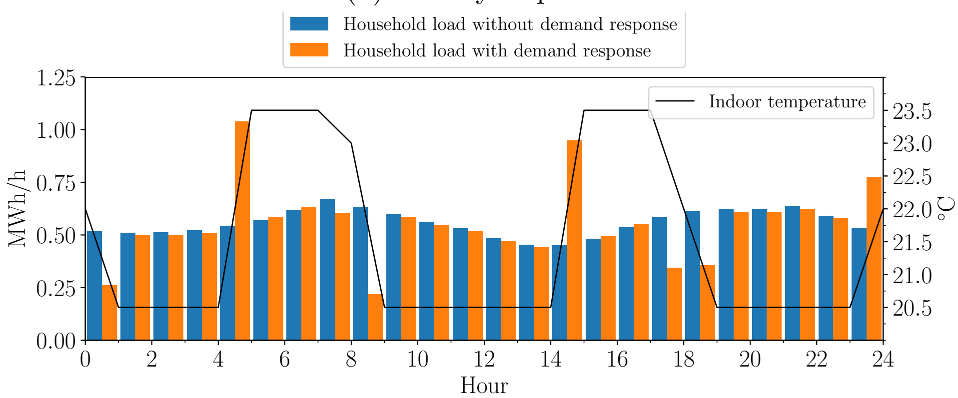
From Figure 7.45c, it can be found that a household load peak appears at hour 5 as a consequence of the low price at this hour. The reason for the peak to not occur at hour 3 where the price is lower, is the additional cost to keep the indoor temperature at a high level in two additional hours.



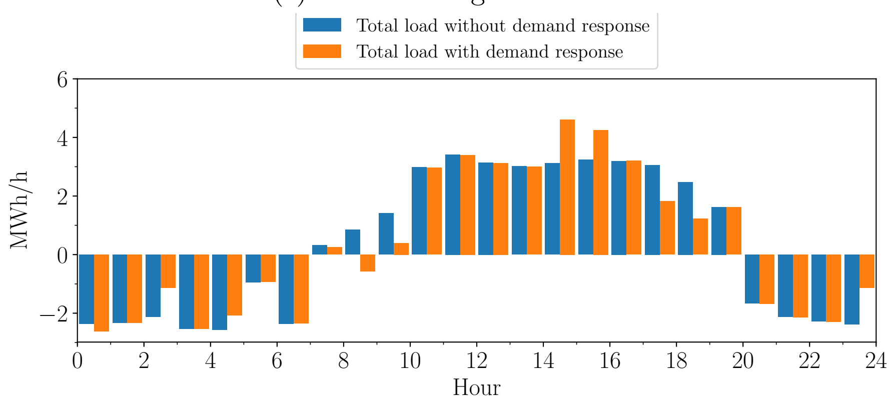
(a) Energy price 1st of Mars 2018



(b) Battery response



(c) Load shifting in households



(d) Total load in microgrid

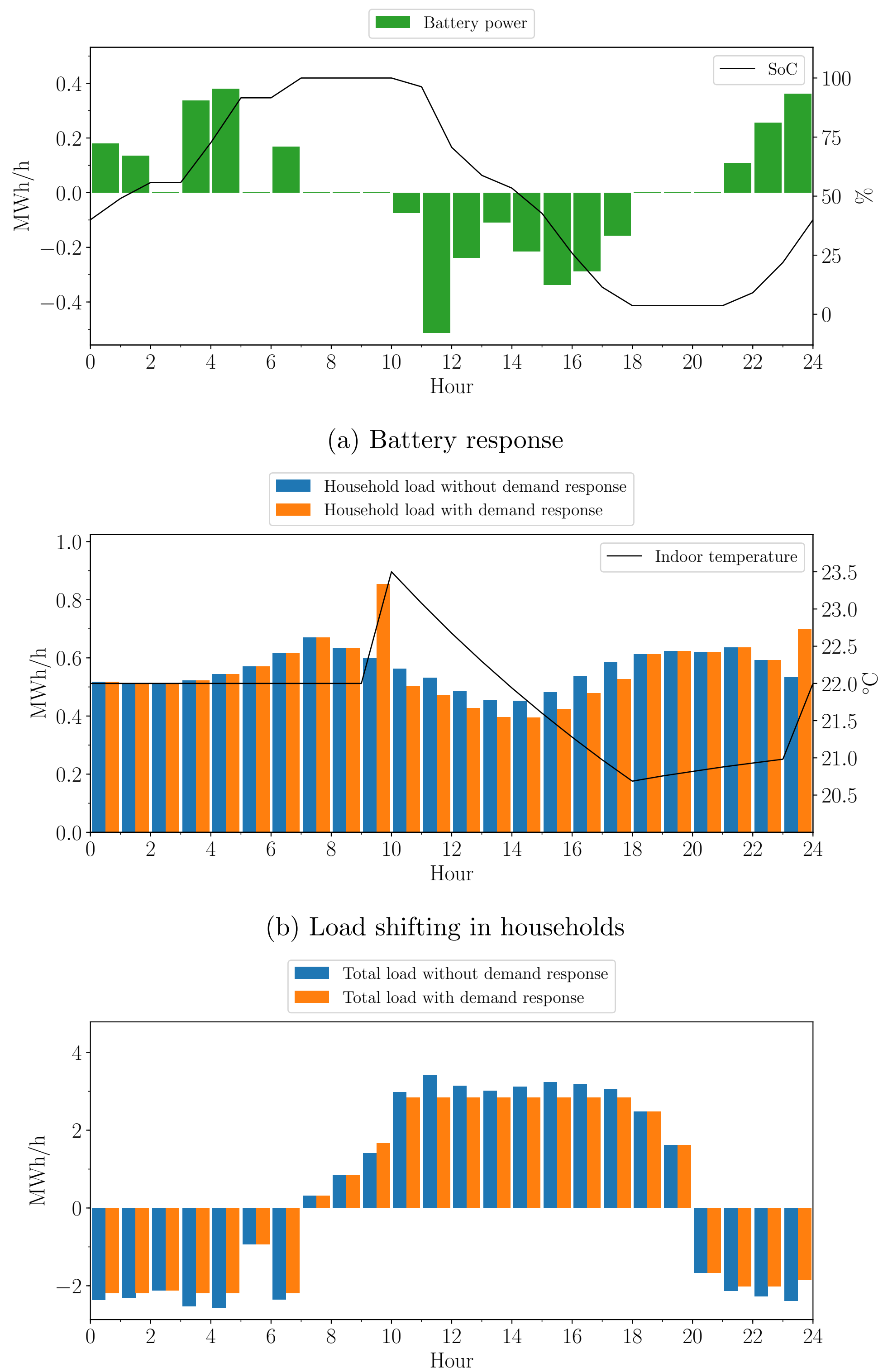
Figure (7.45) Demand response with price based program on the 1st of March

Peak shaving

Figure 7.46 shows the demand response in the microgrid when the peak shaving strategy is applied. The 1st of March is a very cold day, that might cause high loads in the microgrid at hours with low generation compared to other days in the same period. Because of that, peak shaving can be an important strategy if a measured power part is included in the network tariff.

From Figures 7.46a and 7.46b it can be found that the battery and households utilize all the flexibility in the system for hour 11 to 18 to decrease the total load seen in Figure 7.46c. This can be illustrated through the discharging of the battery and the decreased indoor temperature. The indoor temperatures of the households increase in hour 10, which is the last hour before peak shaving is performed. The battery charge in five hours prior hour 11, when the lowest load in the microgrid appears. The total peak load is then reduced with 17.2 % from 3.16 MWh/h to 2.62 MWh/h.

As illustrated in Figure 7.46b, the indoor temperature slowly starts to increase from hour 19. The reason is that the household loads in hour 19 to 23 do not differ from the loads without demand response. Since the loads without demand response aim to keep the temperature constant at 22 °C, the indoor temperature in the households with demand response will increase from 20.5 °C. The last peak at hour 24 is a result of obtaining an initial temperate value.



(c) Total load in microgrid

Figure (7.46) Demand response with peak shaving program on the 1st of March

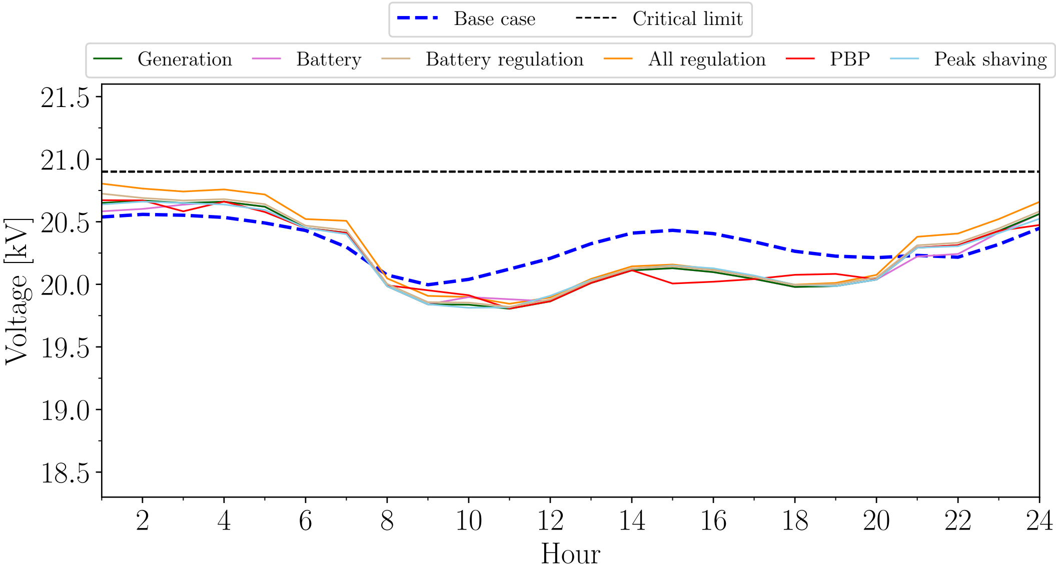
Voltage analysis including demand response scenarios

Figure 7.47 displays the hourly developing voltage levels on bus 22 for all the strategies included the demand response programs for the three different placements of the microgrid on the 1st of March.

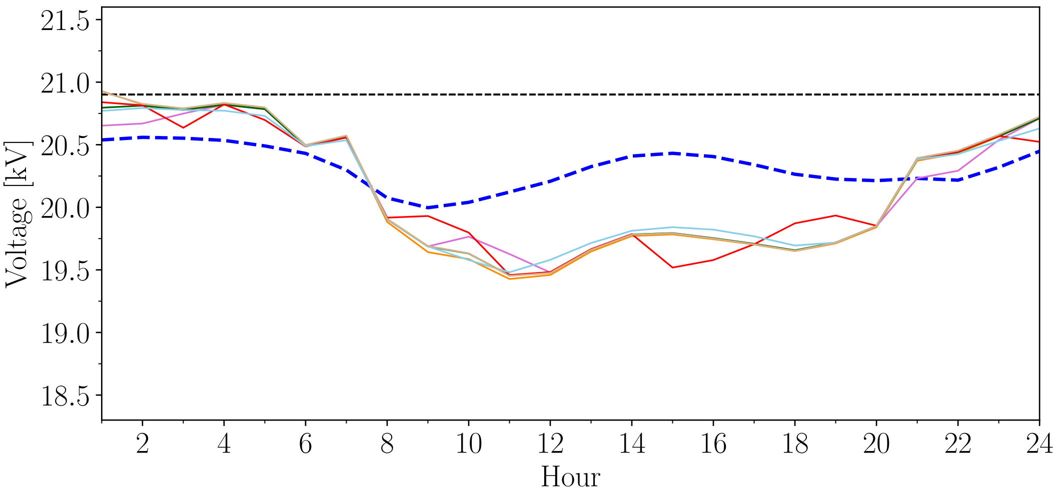
On this day, the same resulting voltage tendency from the demand response strategies can be seen in all the placements of the microgrid, but the effect of the demand response actions are higher the further out in the system the microgrid is placed. The peak shaving strategy exhibits a more smoothening effect on the voltage curves in general compared to the generation strategy, and the price based program makes the voltage levels fluctuate more than the other strategies, which can be seen during the hours the battery charges and discharges.

When the microgrid is connected to bus 10, all the strategies obtain almost similarly voltage profiles, and none of the strategies are able to restore the voltage levels over the critical limit. The effect of the PBP strategy exhibits small fluctuation from the other strategies for this microgrid placement.

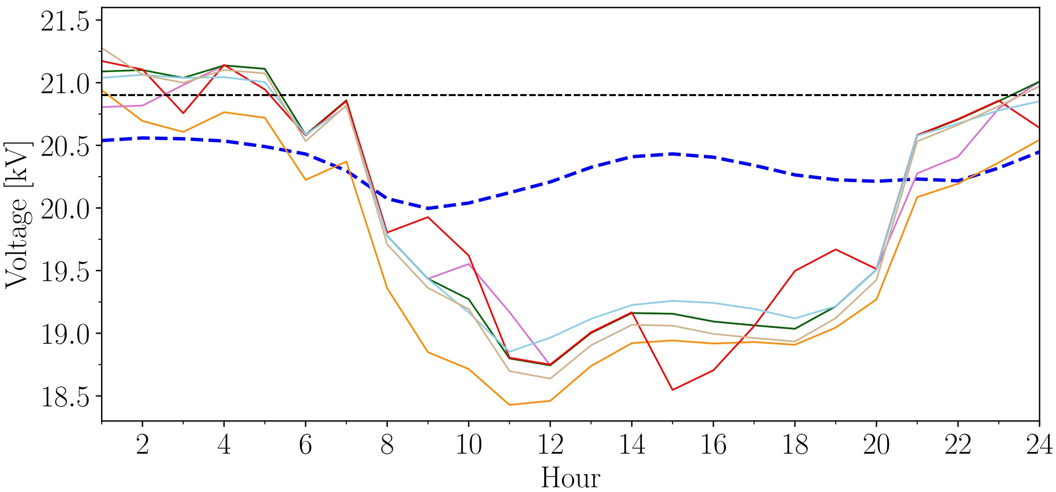
When the microgrid is connected to both bus 15 and 20, the peak shaving strategy manages to increase the voltage levels compared to the other strategies during the worst hours between hour 12 to 17. These are some of the hours where the peak shaving strategy is performed. In hour 11, the battery strategy result in slightly higher voltage profiles since the battery is able to discharge with a higher amount of active power compared to the peak shaving strategy during this hour. The voltage profile fluctuations seen for the PBP strategy obtain higher deviations when the microgrid is placed at bus 15 and 20. Thus, the demand response actions done by the price based program at hour 15 have such a high influence on the voltage that the voltage level becomes the new lowest point in this case when the microgrid is connected to bus 20. It is the second lowest obtained voltage level, only slightly higher than the voltage profile for the all regulation strategy at hour 11.



(a) Microgrid connected to bus 10



(b) Microgrid connected to bus 15



(c) Microgrid connected to bus 20

Figure (7.47) Voltage profiles on bus 22 for all strategies for the 1st of March

7.3.4 Line loading percentage

Figure 7.48 displays the loading percentage for line 4 and 13 with the different placements of the microgrid on the 1st of March. For comparison with the operation of the microgrid and the voltage curves for the same scenarios, the Figures 7.35, 7.37, 7.40, 7.43 and 7.47 can be used.

Figure 7.48a II illustrate the same effect as seen for the other days where a microgrid placement upstream a line will not affect that line in any great manner. For the other cases, the line loading, for both line 4 and 13, for all the strategies, except the all regulation strategy, manages to increase the line loading during hours with high penetration of produced active power from the microgrid compared to the base case. During hours with low penetration of produced active power in the microgrid, the line loading for all the strategies are increased compared to the base case. The same effect was seen on both the 4th and 7th of June.

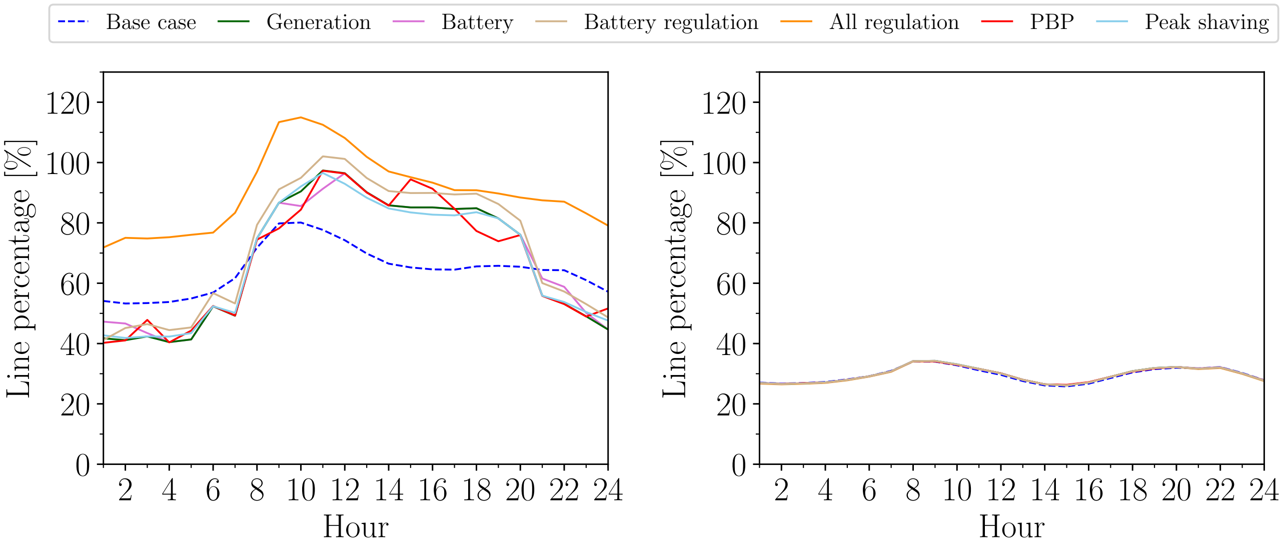
Figure 7.48 confirms that the all regulation strategy, where the active power from the DERs are converted to reactive, is not favorable for the line loading in this system. When the microgrid is connected to bus 20, a drop is seen in the loading percentage in hour 4 and 5 for the all regulation strategies. The reason for this can be seen in Figure 7.35 where the generation in the microgrid experience a small drop between hour 4 and 5. This illustrates the effect the amount of power through a line has on the line loading.

On this day, there are significant differences in the loading percentage caused by the different demand response strategies. The peak shaving strategy gives the lowest line loading in the stressed hours from hour 12 to 17 for both lines. Between hour 10 and 11, the battery strategy has slightly lower line loading than the other strategies, which can be seen in Figure 7.35 as hours where the battery discharges. Apart from this effects, only small differences separate the line loading curves for the generation strategy, the battery strategy and the peak shaving strategy. The PBP strategy has, equally to the other days, a tendency to make jumps in the line loading due to the charging and discharging of the battery. It is clearly visible that the price based program actions that happens in hour 15 and 16 cause higher peak loading percentage compared to other strategies. This action causes a peak loading percentage on line 4 and 13 respectively on 99.37 % and 63.10 % with the microgrid connected to bus 20, compared to 85.84 % and 48.33 % caused by the peak shaving strategy and the same placing of the microgrid.

Table 7.10 displays the line loading percentage for the generation strategy at hour 11 with the microgrid connected to the three different buses. The table aims to illustrate how the different line loading are influenced by the placement of the microgrid. Compared to the other strategies, the generation strategy do not follow any specific strategy. Thus, the strategy is more suitable for comparison between the different microgrid placements. Hour 11 is chosen based on the obtained high line loading for multiple of the strategies. The table disclose that the line loading for line 4 is not influenced in any great matter by the microgrid placement. The reason for the slight difference caused by the different placements for line 4 is due to higher power losses through the system when the microgrid is connected further out in the main radial. The line loading for line 13 is increased for a microgrid placement at bus 15 and 20 compared to bus 10. This effect can be seen through the high demand in the microgrid, which need to be supplied through line 13 when the microgrid is placed at bus 15 and 20.

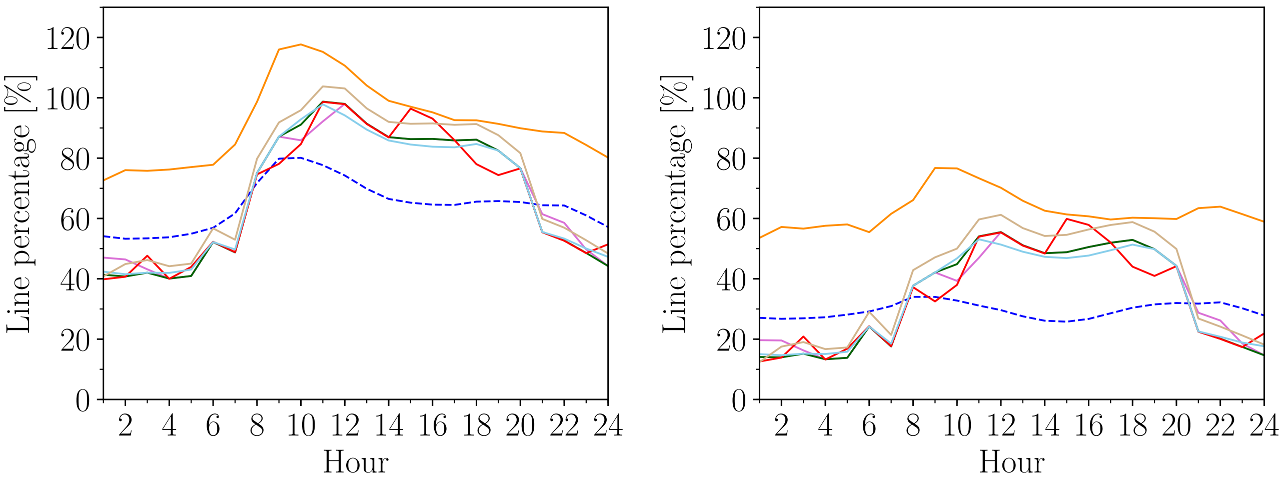
Table (7.30) Lowest line loading peaks for line 4 and 13 with different placings of the microgrid

Microgrid placement	Bus 10	Bus 15	Bus 20
Line loading line 4	97.37 %	98.74 %	100.52 %
Line loading line 13	31.62 %	54.08 %	56.03 %



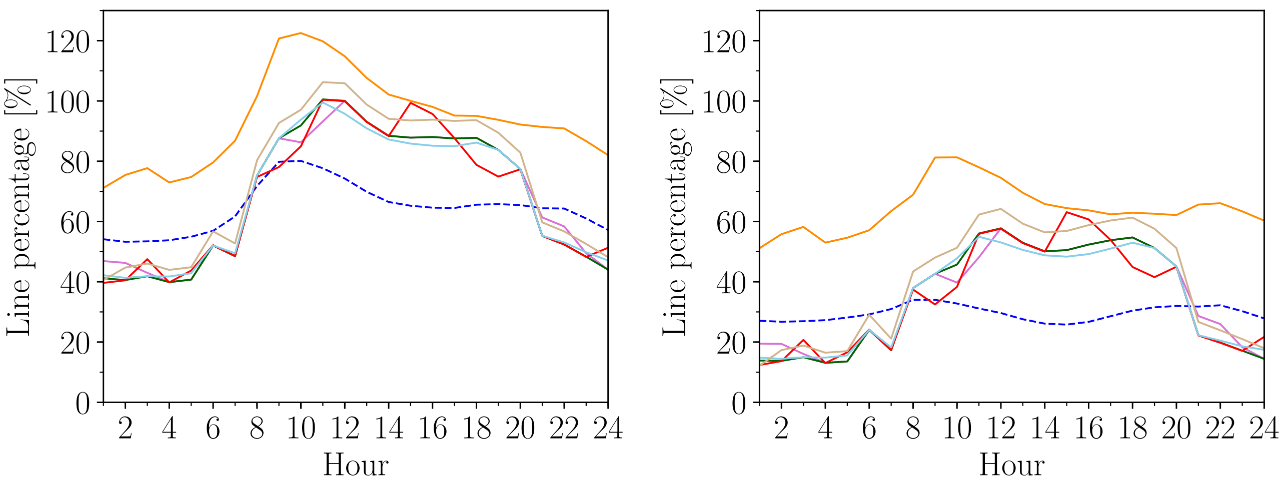
(I) Loading percentage on line 4 (II) Loading percentage on line 13

(a) Bus 10



(I) Loading percentage on line 4 (II) Loading percentage on line 13

(b) Bus 15



(I) Loading percentage on line 4 (II) Loading percentage on line 13

(c) Bus 20

Figure (7.48) Loading percentage for the 1st of March

7.4 Discussion

This section will discuss the obtained results from the simulations. The results will be compared and evaluated.

7.4.1 The effect of connecting a microgrid with different ancillary services

The different days with different placements of the microgrid have been presented in this chapter. Figure 7.49 presents three plots illustrating the voltage levels at bus 22 for each day where each plot includes all the tested strategies with the three different microgrid placements. Figure 7.50 presents the same illustrations only for bus 34 which is the battery bus. The figures are included to easier investigate the effect and differences between the different strategies, connection point of the microgrid and how a high penetration of active power in the microgrid affects the system. The discussion will be divided into two categories; The effect of voltage regulation strategies and the effect of demand response strategies.

The effect of voltage regulation strategies

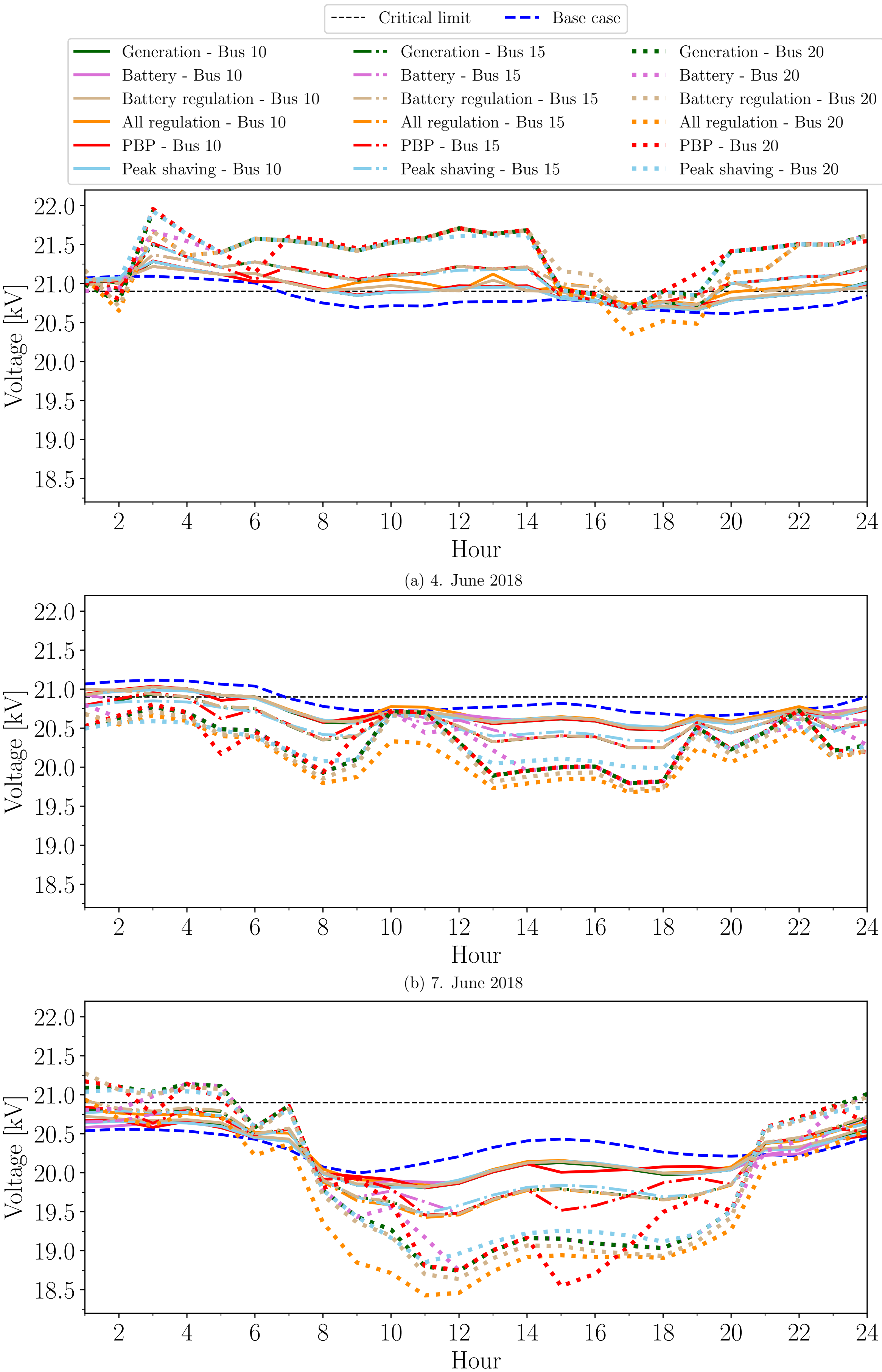
The first ting to investigate is how the active power from the DERs in the microgrid influence the weak distribution system. During the hours with high penetration of produced active power from the DERs in the microgrid, the generation strategy (dark green graphs in Figure 7.49) results in higher or near higher voltage profiles compared to the base case, depending on the microgrid placement. The highest change in voltage level for the generation strategy compared to the base case during high production hours, happens when the microgrid is placed at bus 20. This result can be explained by the short distance between the microgrid and the buses with voltage problems. The short distance will result in reduced power losses and voltage drops. When the microgrid is placed at bus 10 or 15, the change in voltage levels will be smaller much since the power needs to travel a longer distance and therefore losses will occur along the way. The opposite result can be illustrated during hours with low penetration of produced active power from the DERs. During these hours, the distribution system will see the microgrid as an additional load, and therefore provide active power to meet the demand in the microgrid as well. In this case the system would obtain better voltage profiles when the microgrid is placed at bus 10 compared to bus 20, since the active power drawn from the slack bus will be transferred a shorter distance, giving less losses.

When introducing voltage regulation with reactive power compensation, it is found that the regulation strategy is most effective when the compensation can be drawn from the stored energy in the battery. This is an expected result since the network avoids seeing the battery as a load when the battery injects reactive power to the system. By comparing the two regulation strategies, all regulation and battery regulation, the all regulation strategy gives the best voltage profiles when the microgrid is placed at bus 10 and a slightly better result at bus 15, while the battery regulation strategy gives the best result when the microgrid is placed at bus 20. When investigating the voltage profiles for all the three days when the microgrid is placed at bus 20, both regulation strategies degrades the voltage profiles in the system, and the generation and battery strategies are better.

The previously discussed effect is related to the R/X ratio seen from the microgrids point of view. The lines placed in the top of the network have a R/X ratio of approximately 0.5. The lines used in the center of the main radial have a R/X ratio of approximately 1, while the lines furthest down the main radial in the system have a R/X ratio close to 1.6. This result illustrates the effect the R/X ratio have on both the active and reactive power. The lower the ratio, the higher is the impact of reactive power on the voltage profiles, and thus the better is the resulting voltage profiles when performing reactive power compensating. For the cases where the ratio is high, the system will be more sensitive to active power resulting in a worsened effect if the produced active power is shifted to be reactive and/or if active power is needed by the battery to contribute with reactive power to the system. This result was as expected related to the presented theory for voltage drop in Section 5.4.7. The effect from the regulation strategies might have been better on bus 20 if the R/X ratio had been lower. A better regulation strategy for high R/X ratio is to compensate with active power instead of reactive.

Another important result obtained with the voltage regulation strategies is the poor effects some of the regulation strategies exhibited on the lines in the system, especially the all regulation strategy. The poor effect may be explained by the regulator converting all the produced active power to reactive power, making the system transfer more active power over the lines to compensate for the loss of active production. The same effect will happen for the battery regulation strategy when the battery need to store active power and convert it in order to regulate with reactive power. This effect can be drastic for the lines upstream of the microgrid, where high line loading percentages are obtained during regulation hours where the active power production in the microgrid is high.

Figure 7.50 illustrates the voltage profiles on the battery bus, bus 34 in the system, for all the strategies, placements of the microgrid and investigated days. The figure illustrate as expected that the microgrid will obtain better voltage profiles when the microgrid is placed at bus 10 in the distribution system. A voltage level on a bus is dependent on the voltages on the nearby buses, which is seen through equation 5.11. The microgrid voltages will therefore be worsened when the microgrid is placed further down in the system. Most of these voltage profiles are not acceptable from the microgrids point of view, and they would therefore not be considered acceptable for installation of a microgrid.

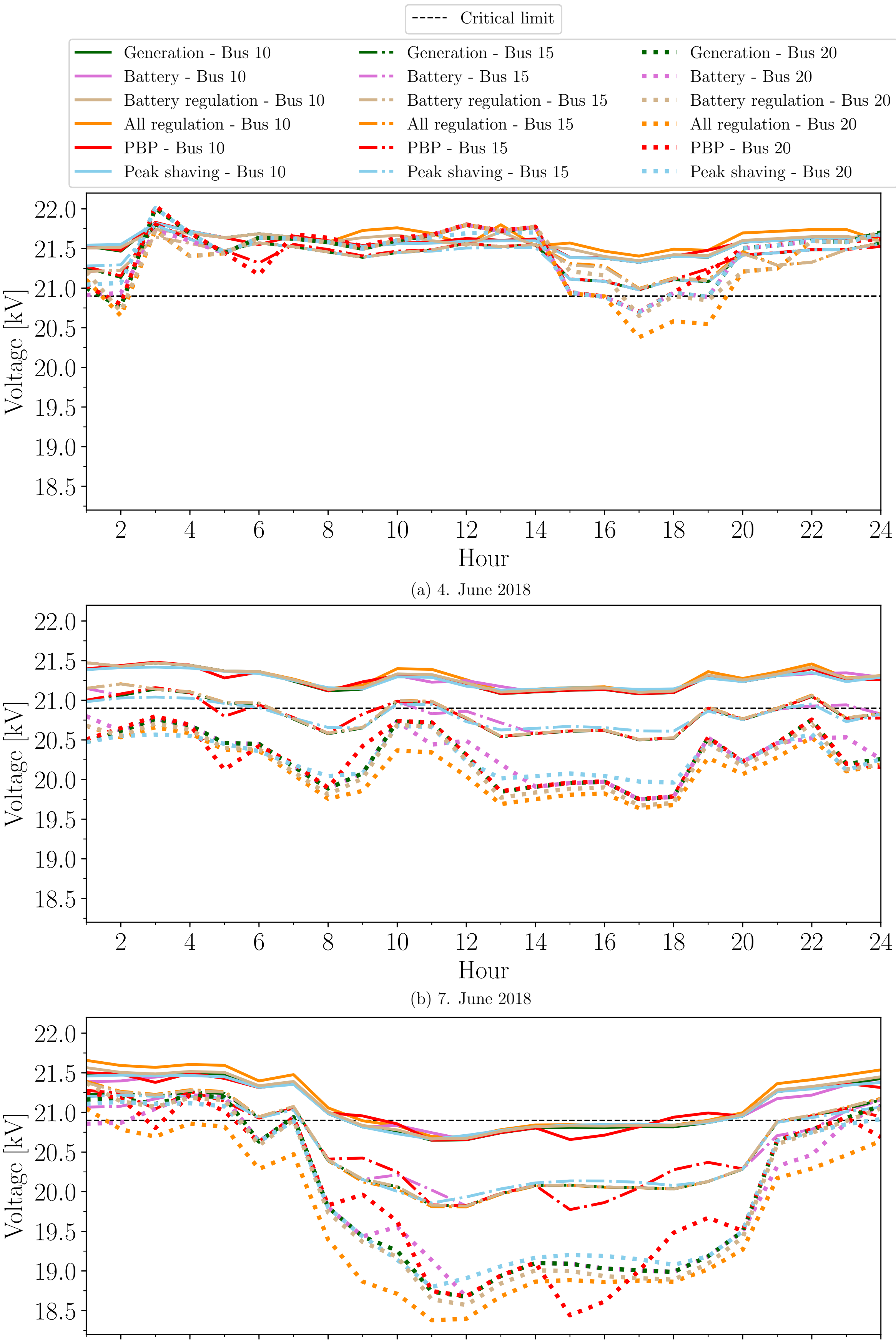


(a) 4. June 2018

(b) 7. June 2018

(c) 1. March 2018

Figure (7.49) Voltage profiles on bus 22 for all strategies



(a) 4. June 2018

(b) 7. June 2018

(c) 1. March 2018

Figure (7.50) Voltage profiles on bus 34 for all strategies

The effect of demand response strategies

The results illustrate that the peak shaving strategy has the opportunity to give smoother and better voltage profiles and lower line loading in the system compared to other strategies, especially for a microgrid placement near the problem buses. The peak shaving strategy will affect both the line loading and the voltage in the utility in a positive manner as long as the total load in the microgrid corresponds with the demand in the utility. It is observed that both the voltage and line loading are sensitive to changes in the electricity generation in the microgrid, and therefore often have per hour curves that correspond to the generation. Since the microgrid has a great amount of installed generation capacity compared to demand, the total load in the microgrid will be very influenced by the generation. This connection is the reason that the peak shaving strategy often works well in this developed test system. There was also one hour in the analysis where the worst voltage profiles in the distribution system did not occur at the same time as a peak load in the microgrid. Thus, the microgrid did not perform any peak shaving actions, and the voltage profiles were not improved.

One part of the network tariff that can be implemented so the microgrid also would take the load of the utility into account is the time of use pricing. Then, it will be more expensive to use electricity in the hour where the total load in the area is high. The microgrid would then probably have done some demand response actions in the hour with bad voltage levels where the peak shaving strategy did not take action. The problem with the implementation of this part is that it does not take local demand variations into account, so the price would be the same for the customers in the whole operation area for the DSO. Therefore, it would only be convenient for a local grid if it has challenges at the same time as the bigger region.

The real time pricing strategy appears unpredictable. Relatively small differences in the prices can cause huge differences in the power demand between two hours, especially when storage units with large capacities can respond to the price signals. A large amount of electrical vehicles with price based smart chargers in the same area also represents loads that can contribute to this huge power demand differences. The real time prices are decided on the global market and do not take local constraints into account. It might be a problem if real time pricing is implemented in an area with a lot of flexible loads and controllable storage units, like for instance microgrids, without considering possible local repercussions.

7.4.2 Strategies

The presented strategies provides different possible solutions to solve voltage and congestion problems in a weak distribution network. There are some issues related to the strategies that might not make them optimal for solving the addressed problems and improvements must be made in order to solve the problems in a more optimal manner. Since the cases where the microgrid is placed far down in the distribution system encountered worse situations for the regulation strategies with reactive power compensation, a better regulation strategy would be to use active power compensation to improve the voltage profiles. The battery strategy in the microgrid where the battery charges during hours with higher production than demand and discharges during hours with higher demand than production might not be the best strategy for the distribution system especially when the battery stores energy right after a hour with regulation, resulting in the voltage levels dropping below the critical limit. This situation can be avoided if the battery charging is postponed to an hour when the voltage profiles in the system are higher. A possible method is to implement another strategy for the battery where the voltage levels of the system must be above a set limit before the battery can store surplus energy in the microgrid. An all regulation strategy as proposed in this master's thesis could be damaging to the lines in the long run. This is something each individual DSO company needs investigate before implementing the strategy, to ensure that it will not cause capacity problems on the lines in the distribution system.

Another observation regarding both the regulation strategies was that they had the tendency to use all the available reactive power to perform the voltage regulation. During the hours where the voltages profiles were right below the limit and the voltage regulator was able to use already stored capacity, both voltage regulators often resulted in voltage profiles way above the limit. Thus, using unnecessary reactive power. A problem encountered when using reactive power compensation, especially for the all regulation strategy, was that if the produced reactive power from the regulator exceeded the reactive load demand for the downstream buses or exceeded the reactive load demand of the system, the reactive power was required to be transferred over long distances in the system, resulting in higher currents and therefore higher active and reactive losses. Another problem, as discussed in Section 5.4.7, is that the setpoint voltage at the slack bus will work against the setpoint voltage at the voltage regulator bus. For some hours a better strategy would be to calculate the setpoint voltage for the voltage regulator to try to minimize another voltage difference. The tendency is that the voltage regulator is poorer in the hours where the battery needs to store active power to compensate with reactive power.

For all the tested scenario days, the base case voltages appeared to be below the critical limit for multiple hours during the day without the implementation of any strategy. The regulation strategies would most likely, based on the trend, give better results if the scenario days had fewer hours were the voltage profiles in the network were below the critical voltage limit. Since the results illustrate that the regulation and battery strategies obtained good effect during the hours were already stored capacity could perform regulation or contribute with active power, it would be preferable for the regulation effect to be performed for fewer hours at a time, enabling charging of the battery in between the regulation hours.

Regarding the demand response strategies an interesting case would be to implement the strategies for the distribution system as well, to see how well the strategies could work for a larger system with more loads to be regulated. To implement a demand response strategy for a distribution system, it is necessary to be have a good regulatory strategy allowing the system operator to perform demand response programs as peak shaving on their customers and a guidance to how this should be implemented and performed by the DSO. The privacy policy regarding the customers needs to be followed and the data management must follow the law.

7.4.3 Possible sources of error

There are multiple possible sources of errors that might have occurred in the model. They are listed as follows;

- **Simplifications** - Errors due to some simplifications might affect the results. One simplification is related to the exluded imaginary part in the equation 5.14, might result in some errors related the total of voltage change the battery can contribute with regarding the amount of active and reactive power the battery.
- **The flexibility of the end user** - The chosen comfort temperature in the households is based on experience regarding normal indoor temperature and is therefore not a theoretical calculated range. The average household area is calculated so that the heat loss calculation match the conclusion of heat load shifting limits. The calculated average household area is much higher than the actual average household area in Norway.
- **Programming errors** - All the scripts used to calculate and represent the model in this thesis is conducted by self-developed codes written in python. The scripts are complex due to the complexity of the model system. They are made to apply for general cases, but are not tested for any other model and might therefore give other result for other implementations.
- **Calculation of load demand** - The load profiles for the base case, the connection of the microgrid with generation strategy, battery strategy and regulation strategy, are calculated as momentary values. The load profiles in the demand response model is calculated as average values equally as the FASIT-profiles. This might lead to small errors regarding the demand in the system between the cases.
- **Calculation of production** - The calculation of the production in the microgrid is based on theoretical methods including small assumptions which exclude optimal placing, variation in wind direction and the angle of the sun. This might lead to inaccuracies in the production profiles compared to a real case. The amount of total production in the microgrid also exceeds the maximum demand in the microgrid by quite a lot, which might not be the best solution in the strategy of developing a microgrid.
- **Energy storage** - In all the cases the battery is assumed to be loss free and able to be fully charged and discharged, which is made to simplify the model. In the price based program, an assumption of a battery efficiency is taken into account when calculating the energy price. For each day, the battery is also assumed to have an initial SoC value.
- **Heat loss calculations** - The heat loss calculations are done by thermodynamic definitions and an interpretation of how the FASIT-profiles are made. Constants are simply modified to obtain realistic values, which introduce inaccuracies in the calculation model. Aspects as thermal inertia is not considered in the development.
- **Lack of pattern analysis** - Since the model only investigates three different days with three different weather conditions, periodical patterns will not be obtained. The model will therefore only provide the effect the strategy can propose for similar scenario days. How the strategies might work on an overall yearly situation is not

investigated.

Chapter 8

Conclusion and further work

8.1 Conclusion

This master's thesis has through a literature study and the development of an extensive model investigated and enlightened different aspects regarding the integration of microgrids and the interaction between microgrids and DSOs. The most important aspects that are investigated are regulatory challenges regarding the implementation of microgrids, a possible strategy for interaction between a DSO and a microgrid and which ancillary services it can provide to help reducing voltage and capacity problems. The research has suggested a simple strategy for a possible interaction between a DSO and a microgrid based on the regulatory challenges. Six different strategies are developed and simulated in the developed model to illustrate possible interactions where the microgrid supports the main system. The strategies are based on the implementation of a microgrid without specific control strategies, with voltage regulation strategies and with demand response strategies. To obtain different cases that can be analyzed and compared in order to explore different scenarios, all the strategies are simulated on three different days with different weather and three different placings of the microgrid.

The key findings through the simulations are presented as follows;

- Providing voltage regulation with reactive power compensation from a microgrid does not necessarily improve the voltages in a distribution system. In a system including lines with a relatively high R/X ratio, regulation using active power can in many cases be a better strategy.
- Voltage regulation with reactive power compensation from a microgrid has the most negative impact on the voltages in the distribution grid when it is placed far out in a radial. When the microgrid is placed closer to the slack bus, the reactive power compensation strategy can in many cases have a better impact on the voltages than other strategies based on contribution of active power.
- Implementation of demand response programs based on the price of electricity and network tariffs in microgrids can improve both the voltage and the line loading in the distribution grid if the price signals correlate to the local problems. The price signals must also represent a great enough potential of financial savings for the microgrid to be an incentive to perform demand response strategies.

- The line loading in the distribution grid is dependent on the placement and the operation of the microgrid. Lines downstream of the microgrid are not significantly affected by the microgrid, while the line loading in lines upstream of the microgrid is affected by the power flow between the microgrid and the distribution grid.
- The contribution of active power has the most positive impact on the line loading when the loads mainly consume active power. The contribution of reactive power can have a big negative impact on lines if the reactive generation highly exceeds the consumption downstream of the respective line.
- The best placement of the microgrid is dependent on how much generation it is in the microgrid. When assuming that the microgrid only contributes with active power, a placement near the bus with the worst voltage is favorable when there is a generation surplus in the microgrid, while a placement closer to the slack bus is better when the microgrid appears as an additional load.

These results and conclusions have illustrated the effects of different strategies in different cases. It can not be concluded with an optimal microgrid placement or an optimal strategy from this work. That is because the effects are detected to be highly dependent on many variables regarding how the distribution grid and the microgrid are assembled and the expected weather. The result clearly illustrates the importance of a well defined planning phase, where all aspects are considered and explored.

The work in this thesis has produced both a simulation model and programs to simulate different strategies that can be reused, used for inspiration and developed further. The proposed regulation strategies can also be considered and used in the further development of how microgrids can be integrated into the Norwegian power system.

8.2 Further work

This master's thesis has performed a comprehensive study illustrating the regulatory problems with integration of microgrids through an investigation of possible solution strategies. Due to the limited time and the lack of real life models with an actual problem, there have been certain boundaries regarding what the work could include. There are different possible directions this thesis can go in regards to further work and improvements of the model. Some possible directions and suggestions are listed as follows;

- This master's thesis only investigates three different days and may by that be misleading in respect to the loading and weather conditions experienced during longer periods, as months or years. To produce more reliable data and results enabling firmer indications the simulations should be expanded to investigate a higher number of days. A greater database of results will increase the credibility of the obtained conclusions.
- An implementation of the interaction between multiple microgrids and distributed generation should be examined. To further illustrate the strategies for helping the distribution system, it is possible to integrate multiple microgrids and DGs into the distribution system to obtain a larger interaction plan and research how this effect will influence the voltage and capacity problems in the distribution system.
- There are other possible ancillary service strategies a microgrid can provide regarding supporting the distribution system. One possible solution can be to implement voltage regulation with active power compensation when the microgrid is placed far down in the main radial.
- The model strategy on a real power system with actual system problems should be investigated. The model in this thesis only aims to illustrate the effect the different strategies have on a weak distribution system with the calculated data for the microgrid generation and the system load. The result might, therefore, apply better for another case where the problems are smaller and a better planning phase regarding the microgrid has been conducted.
- In the model, the microgrid was somewhat randomly connected to three different buses in the system. For a preparation phase, an investigation of the most optimal placement of the microgrid would be interesting to research. Both regarding where the microgrid contributes with the best effect to the system voltage and where the microgrid will minimize the loading on the system lines. The total losses and costs over the lines can also be investigated to obtain the most optimal solution regarding losses, costs and capacity in the system.
- Regarding the flexibility in the network multiple different strategies are possible to implement to take advantage of consumer flexibility in the network. The first possible solution is to implement the demand response programs for the consumers in the distribution system as well. Another available flexibility is the electrical vehicle potential in Norway. A strategy can be to investigate this flexibility potential and implement vehicle-to-grid solutions for solving the voltage, congestion and capacity problems in a distribution system.
- Other demand response strategies such as time of use pricing can be implemented to

the same or a similar model to compare how the microgrid will operate the flexible loads differently. It would be interesting to develop a scenario with a probable new network tariff model together with real time energy pricing. It can then be obtained which part is going to be the most important part in different cases regarding the decision of operation. It can also be used to examine if the tariff model is appropriate from the DSO point of view if it is implemented to one or more systems with a considerable amount of flexible loads.

- How microgrids possibly can take part in power markets can be investigated deeper, and afterwards strategies can be made and implemented in a simulation system to see how they possibly can affect the utility grid.
- This thesis emphasized the importance of investigating regulatory boundaries regarding interaction strategies between a DSO company and a microgrid, and the possibility of obtaining a good strategy plan for this interaction. Important and interesting further work would be to investigate the possible interaction to a greater extent and examine different possible strategies and agreements that can be obtained for solving different problems.

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Appendix A

Appendix: Data

A.1 Load data

Table (A.1) Overview over load data during high peak hours on a weekday (hour 1-12)

Name	AB	01	02	03	04	05	06	07	08	09	10	11	12
Residential	A	-0.056	-0.058	-0.059	-0.061	-0.063	-0.068	-0.068	-0.080	-0.070	-0.066	-0.062	-0.065
Residential	B	2.536	2.442	2.423	2.412	2.458	2.558	2.837	3.038	2.987	2.913	2.887	2.809
Industry 1	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Industry 1	B	107.133	106.377	112.671	125.561	123.883	149.508	210.079	281.420	301.317	304.861	306.550	305.595
Industry 2	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Industry 2	B	111.846	107.133	106.377	112.671	125.561	123.883	210.079	281.420	301.317	304.861	305.595	305.595
Industry 3	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Industry 3	B	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861
Retail	A	-2.612	-2.617	-2.594	-2.581	-2.696	-2.782	-2.786	-2.751	-2.867	-3.604	-4.008	-3.938
Retail	B	110.838	112.498	110.461	110.690	110.832	113.092	117.935	128.397	144.894	164.127	170.017	167.751
Office	A	-0.846	-0.472	-0.333	0.667	1.941	1.612	2.740	2.459	-3.175	-4.386	-4.770	-5.197
Office	B	111.846	107.133	106.377	112.671	125.561	123.883	149.508	210.079	281.420	301.317	304.861	306.550
Hotel	A	-4.106	-4.058	-4.236	-4.330	-4.532	-4.617	-4.234	-4.617	-5.064	-4.488	-4.283	-3.877
Hotel	B	216.687	209.124	201.458	198.723	199.205	203.251	218.231	244.470	262.273	266.783	267.072	265.913
Hospital	A	-31.718	-31.907	-32.174	-32.463	-32.419	-33.301	-32.433	-39.244	-34.096	-34.919	-32.243	-31.967
Hospital	B	1050.539	1043.606	1040.771	1038.470	1043.435	1050.765	1145.913	1420.601	1621.464	1618.141	1683.880	1603.700
School	A	-2.406	-2.275	-2.520	-2.359	-2.263	-1.573	-0.432	-1.002	-0.808	-1.223	-1.285	-1.267
School	B	90.975	92.555	93.319	97.401	100.160	107.593	118.490	127.714	152.261	152.257	146.396	140.209

Table (A.2) Overview over load data during high peak hours on a weekday (hour 13-24)

Name	AB	13	14	15	16	17	18	19	20	21	22	23	24
Residential	A	-0.061	-0.060	-0.060	-0.060	-0.059	-0.062	-0.061	-0.056	-0.058	-0.054	-0.055	-0.056
Residential	B	2.715	2.668	2.685	2.904	3.201	3.369	3.491	3.536	3.470	3.401	3.191	2.799
Industry 1	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Industry 1	B	303.247	297.228	284.303	241.682	208.777	185.799	157.850	144.596	129.745	118.621	114.933	111.846
Industry 2	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Industry 2	B	305.595	305.595	305.595	305.595	305.595	305.595	305.595	305.595	305.595	305.595	305.595	284.303
Industry 3	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Industry 3	B	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861	304.861
Retail	A	-3.910	-3.873	-3.651	-3.415	-3.589	-3.228	-2.871	-3.149	-2.724	-2.948	-2.639	-2.761
Retail	B	165.096	164.520	164.238	162.386	161.509	152.737	142.092	121.101	114.631	111.380	110.273	109.250
Office	A	-5.173	-5.239	-4.945	-4.526	-1.359	-0.581	-0.176	-1.250	-1.718	-1.181	-1.039	-0.971
Office	B	305.595	303.247	297.228	284.303	241.682	208.777	185.799	157.850	144.596	129.745	118.621	114.933
Hotel	A	-3.787	-3.839	-3.995	-3.668	-3.956	-4.294	-4.744	-4.942	-4.934	-5.009	-4.798	-4.293
Hotel	B	262.562	261.495	261.050	261.827	264.649	272.076	279.040	279.096	274.564	265.588	250.640	234.789
Hospital	A	-34.731	-32.266	-37.343	-34.895	-33.017	-34.646	-34.131	-34.149	-34.001	-33.953	-32.634	-32.445
Hospital	B	1526.940	1513.810	1442.782	1296.273	1211.546	1179.073	1186.771	1152.486	1109.456	1083.735	1058.074	1046.175
School	A	-1.341	-1.290	-2.398	-3.000	-3.109	-3.291	-3.337	-3.221	-3.126	-2.915	-2.693	-2.611
School	B	140.976	137.878	120.907	106.039	100.785	97.829	100.798	102.293	99.948	96.100	91.335	91.078

A.2 Generation data

Table (A.3) Temperature, global radiation and wind speed for a weather station at Mære in Nord-Trøndelag for June 4, 2018.

Hour	**Temperature [°C]**	**Global irradiation**	**Wind speed in 2m [m/s]**
01	9.4	0	2.9
02	8.8	0	2.3
03	8.4	1	4.8
04	7.7	3	3.9
05	7.8	14	3.7
06	7.2	51	3.9
07	7.4	70	4.4
08	7.9	245	4.6
09	8.2	320	5.2
10	9.0	392	5.3
11	9.0	467	4.8
12	9.5	504	6.0
13	8.8	423	5.8
14	8.3	466	5.8
15	8.7	530	2.9
16	8.6	481	2.9
17	8.3	362	2.9
18	7.4	229	3.5
19	7.1	181	3.5
20	6.2	114	5.9
21	6.1	76	5.5
22	5.6	69	6.3
23	4.9	6	6.3
24	4.4	1	6.8

Table (A.4) Temperature, global radiation and wind speed for a weather station at Mære in Nord-Trøndelag for June 7, 2018.

Hour	Temperature [°C]	Global irradiation	Wind speed in 2m [m/s]
01	9.1	0	1.0
02	9.2	0	1.7
03	9.5	1	2.2
04	9.4	1	2.1
05	8.7	3	1.7
06	8.7	5	1.7
07	8.6	9	1.8
08	9.1	24	2.0
09	9.4	62	2.8
10	9.3	73	3.7
11	9.3	81	3.7
12	9.2	86	3.1
13	8.9	195	1.0
14	9.3	206	0.5
15	9.5	186	0.8
16	9.3	131	1.7
17	9.1	78	1.2
18	8.7	64	0.3
19	8.4	56	3.2
20	8.7	76	2.3
21	8.5	17	2.8
22	7.9	9	3.2
23	7.5	3	1.7
24	7.4	0	1.3

Table (A.5) Temperature, global radiation and wind speed for a weather station at Mære in Nord-Trøndelag for Marc 1, 2018.

Hour	**Temperature [°C]**	**Global irradiation**	**Wind speed in 2m [m/s]**
01	-17.1	0	4.7
02	-17.4	0	4.4
03	-17.7	0	4.2
04	-18.3	0	4.7
05	-19.3	0	5.1
06	-19.1	0	3.7
07	-19.5	0	4.5
08	-18.6	5	3.6
09	-18.6	45	3.8
10	-17.1	148	3.5
11	-14.7	217	2.4
12	-12.0	262	1.4
13	-9.2	276	0.7
14	-6.7	258	0.1
15	-6.2	211	0.2
16	-5.9	139	0.2
17	-7.2	60	0.6
18	-9.4	5	1.6
19	-10.6	0	2.2
20	-12.1	0	2.8
21	-12.5	0	4.2
22	-13.9	0	4.8
23	-14.7	0	4.9
24	-14.6	0	4.6

Appendix B

Algorithms

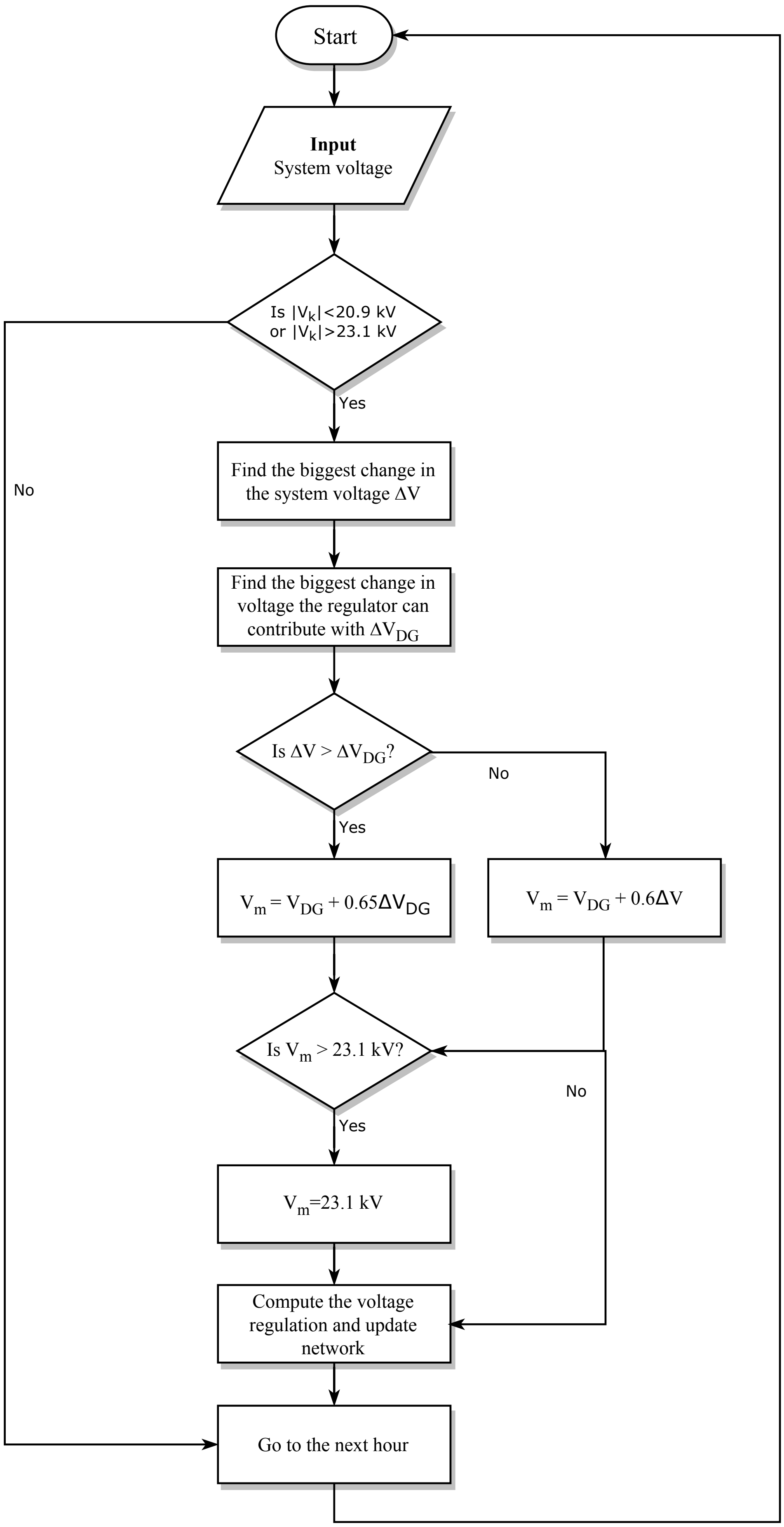


Figure (B.1) Voltage regulation algorithm

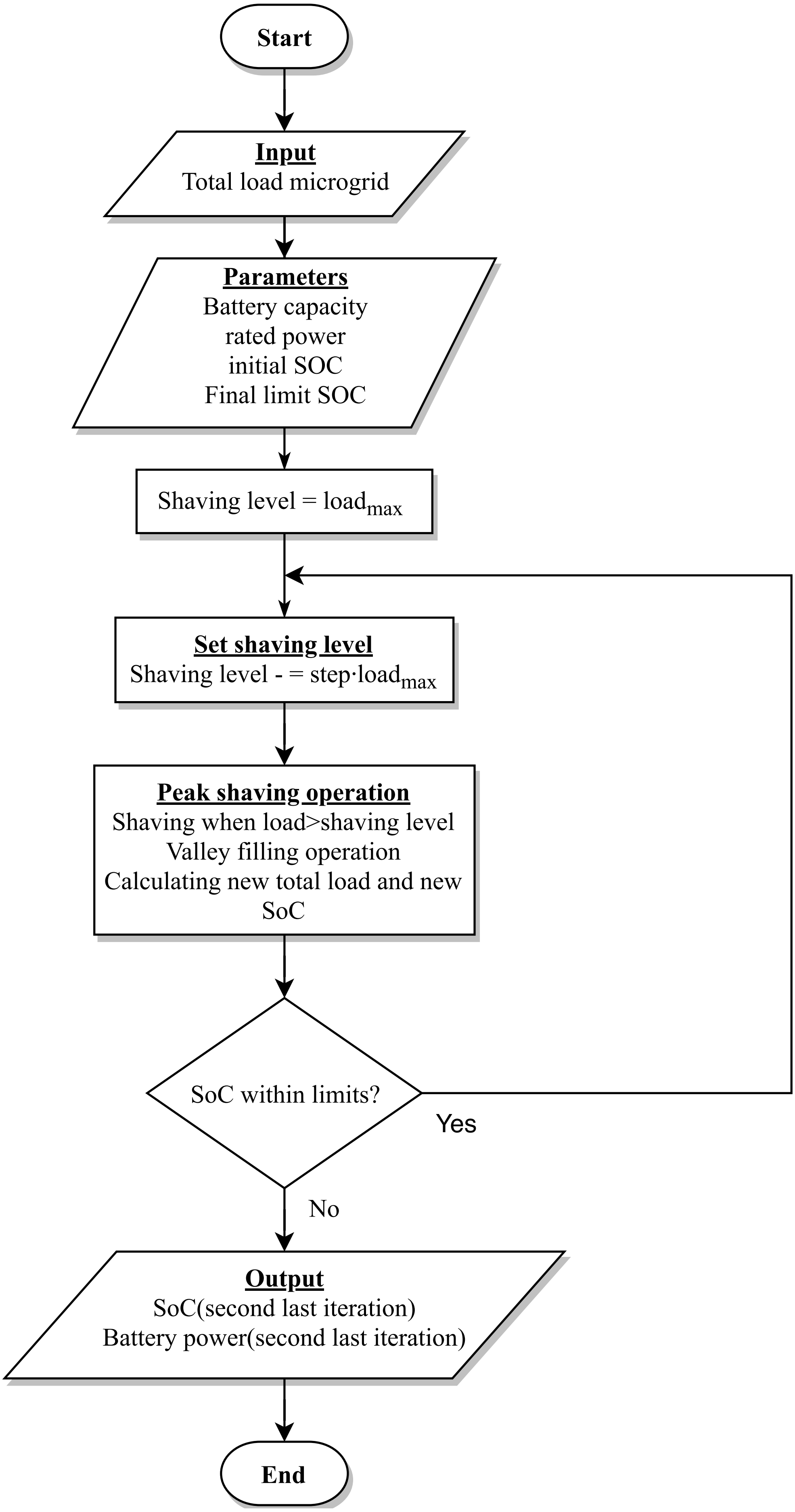


Figure (B.2) Algorithm for battery peak shaving operation

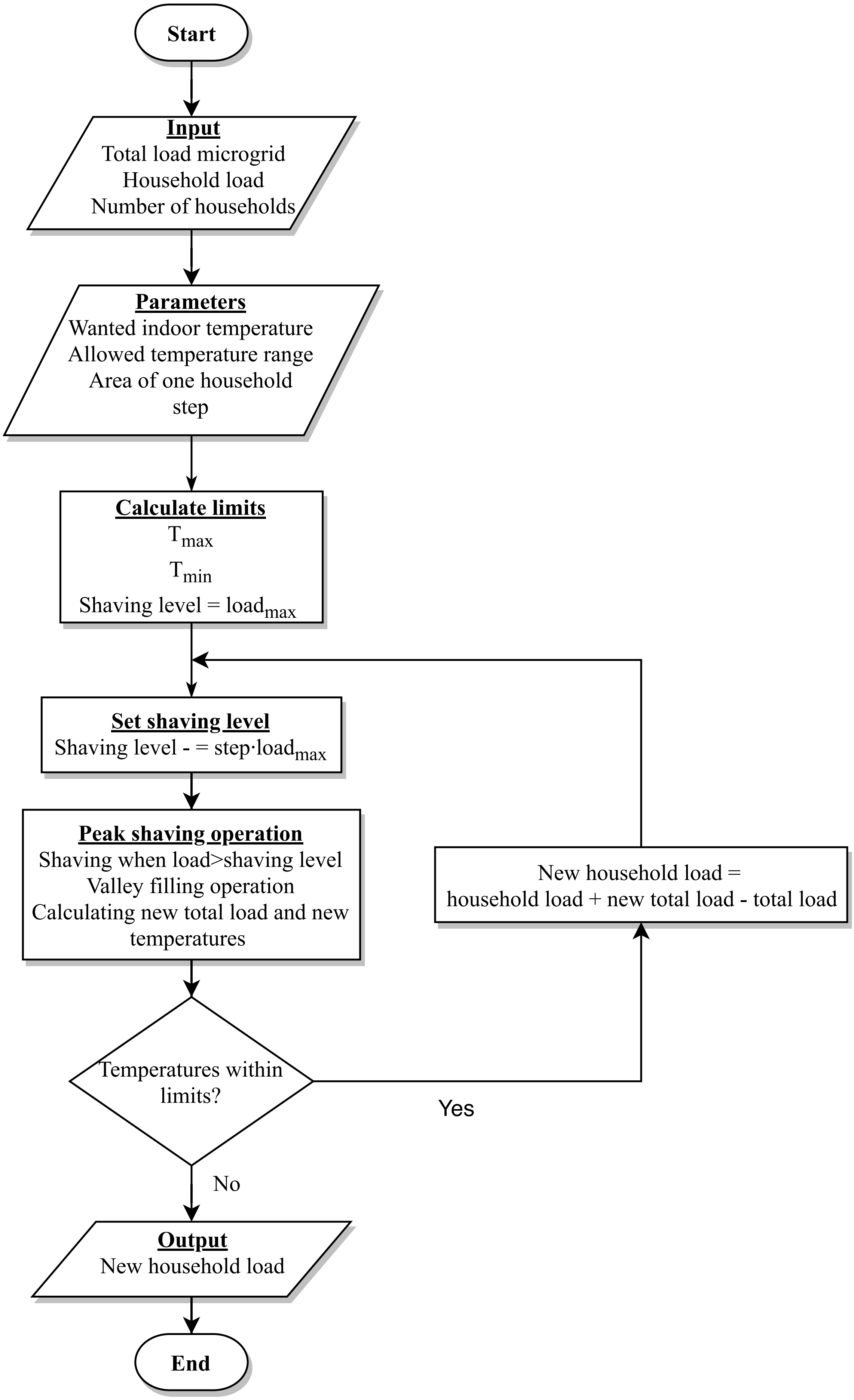


Figure (B.3) Algorithm for households peak shaving operation

Appendix C

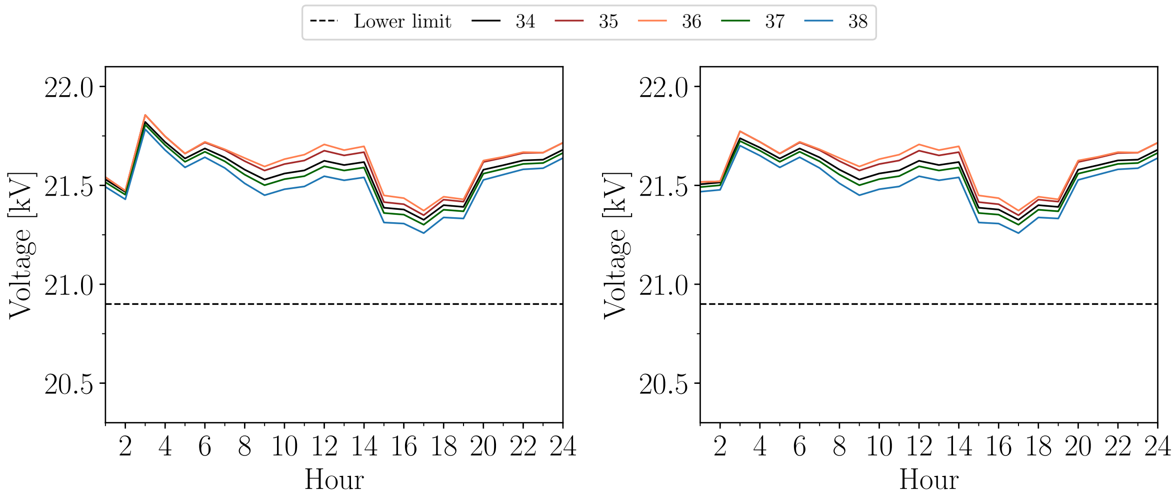
Appendix: Results

Table (C.1) Percentage increase in voltage on bus 22 for 4th of June with microgrid connected on bus 10. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	-0.137	-0.394	0.892	0.575	0.334	0.580	0.721	0.777	0.741	0.835	0.910	1.001
Increase in base case voltage compared to case with production and battery [%]	-0.226	-0.220	0.593	0.474	0.334	0.580	0.721	0.777	0.741	0.835	0.910	1.001
Increase in base case voltage compared to voltage regulation with battery [%]	-0.226	-0.220	0.593	0.474	0.334	0.580	0.721	0.777	1.159	1.251	1.013	0.690
Increase in base case voltage compared to voltage regulation with all units [%]	-0.226	-0.220	0.593	0.474	0.334	0.580	0.721	0.777	1.542	1.646	1.393	0.690
Increase in voltage with battery compared to voltage regulation with battery [%]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.414	0.413	0.102	-0.308
Increase in voltage with battery compared to voltage regulation with all units [%]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.795	0.805	0.479	-0.308

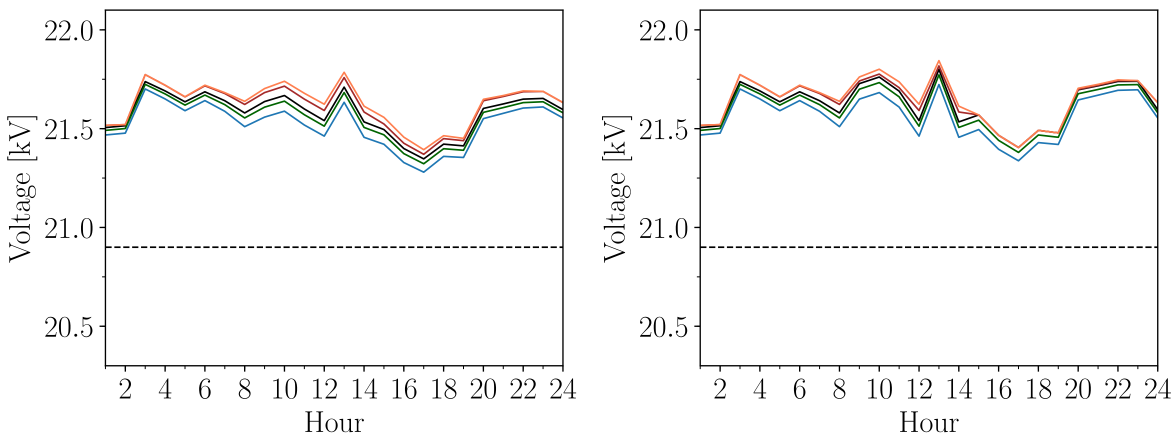
Table (C.2) Percentage increase in voltage on bus 22 for 4th of June with microgrid connected on bus 10. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	0.909	0.961	0.041	0.024	-0.101	0.193	0.168	0.848	0.853	0.878	0.820	0.829
Increase in base case voltage compared to case with production and battery [%]	0.909	0.961	0.041	0.024	-0.101	0.193	0.168	0.848	0.853	0.878	0.820	0.829
Increase in base case voltage compared to voltage regulation with battery [%]	1.322	0.650	0.457	0.116	-0.011	0.286	0.262	0.949	0.953	0.979	0.920	0.518
Increase in base case voltage compared to voltage regulation with all units [%]	1.700	0.650	0.764	0.393	0.227	0.577	0.537	1.346	1.340	1.357	1.285	0.518
Increase in voltage with battery compared to voltage regulation with battery [%]	0.410	-0.308	0.415	0.092	0.090	0.093	0.093	0.100	0.100	0.100	0.099	-0.308
Increase in voltage with battery compared to voltage regulation with all units [%]	0.784	-0.308	0.723	0.369	0.329	0.383	0.368	0.494	0.483	0.474	0.461	-0.308



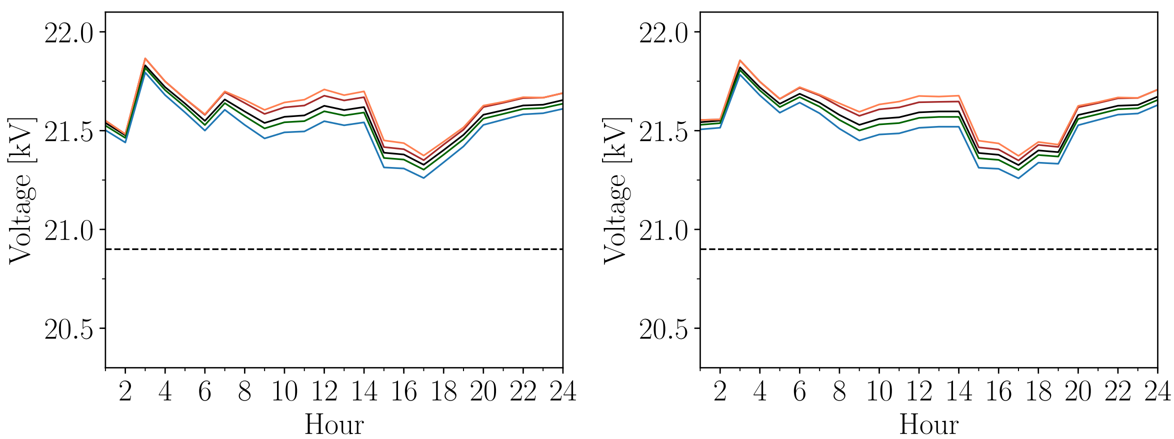
(a) Without battery

(b) With battery



(c) Regulation with only battery

(d) Regulation with all generation units



(e) Price based program

(f) Peak shaving program

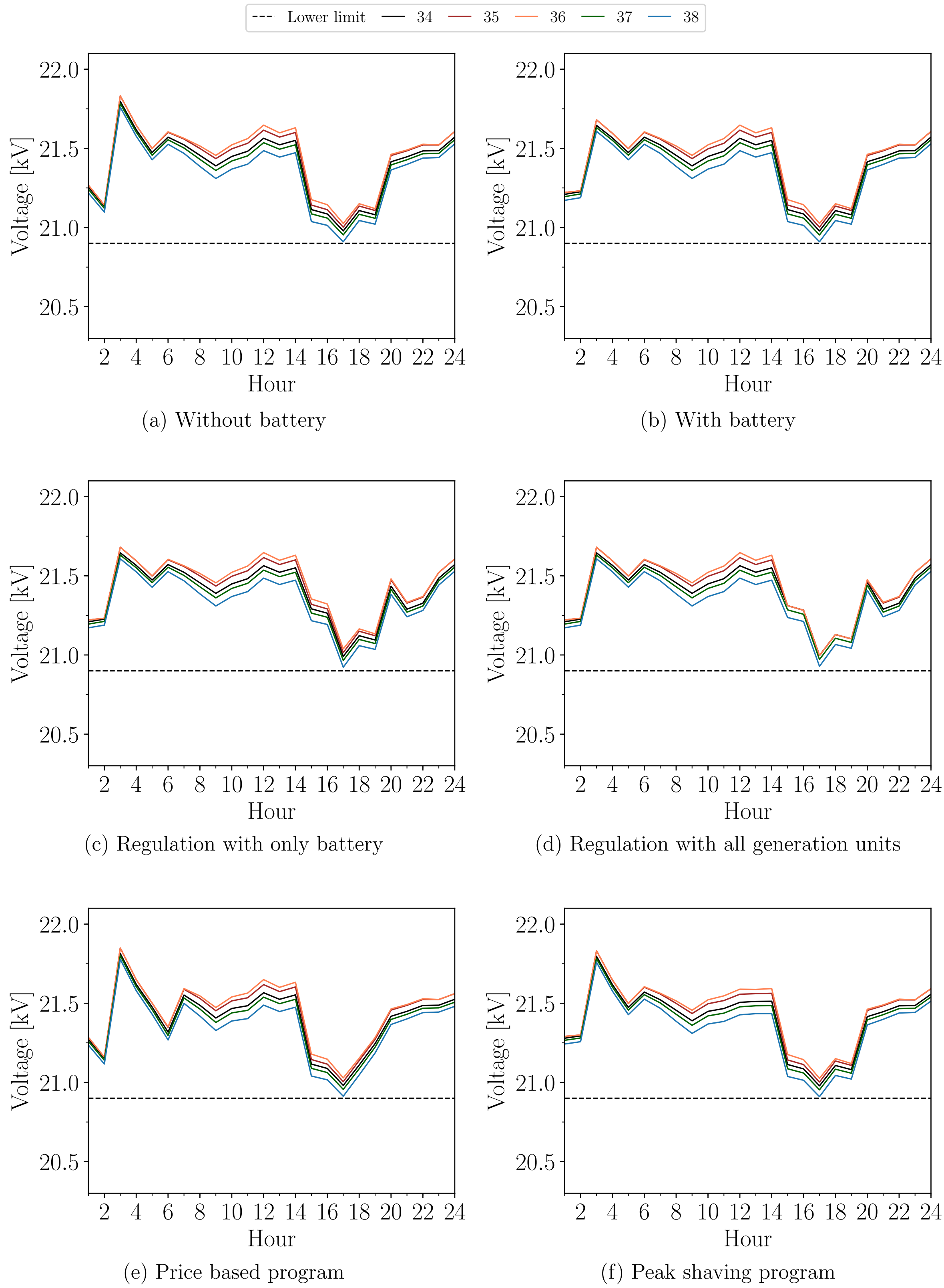
Figure (C.1) Voltage profiles for the microgrid buses with microgrid connected on bus 10 on the 4th of June

Table (C.3) Percentage increase in voltage on bus 22 for 4th of June with microgrid connected on bus 15. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	-0.246	-0.805	1.937	1.275	0.769	1.290	1.599	1.732	1.667	1.861	2.019	2.203
Increase in base case voltage compared to case with production and battery [%]	-0.438	-0.427	1.310	1.061	0.769	1.290	1.599	1.732	1.667	1.861	2.019	2.203
Increase in base case voltage compared to voltage regulation with battery [%]	-0.438	-0.427	1.310	1.061	0.769	1.290	1.599	1.732	1.667	1.861	2.019	2.203
Increase in base case voltage compared to voltage regulation with all units [%]	-0.438	-0.427	1.310	1.061	0.769	1.290	1.599	1.732	1.667	1.861	2.019	2.203
Increase in voltage with battery compared to voltage regulation with battery [%]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Increase in voltage with battery compared to voltage regulation with all units [%]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table (C.4) Percentage increase in voltage on bus 22 for 4th of June with microgrid connected on bus 15. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	2.011	2.120	0.178	0.138	-0.133	0.493	0.439	1.875	1.880	1.931	1.805	1.818
Increase in base case voltage compared to case with production and battery [%]	2.011	2.120	0.178	0.138	-0.133	0.493	0.439	1.875	1.880	1.931	1.805	1.818
Increase in base case voltage compared to voltage regulation with battery [%]	2.011	2.120	0.925	0.889	-0.087	0.549	0.493	1.953	1.209	1.264	1.805	1.818
Increase in base case voltage compared to voltage regulation with all units [%]	2.011	2.120	0.965	0.925	-0.109	0.529	0.473	2.015	1.209	1.264	1.805	1.818
Increase in voltage with battery compared to voltage regulation with battery [%]	0.000	0.000	0.746	0.750	0.046	0.056	0.053	0.077	-0.659	-0.655	0.000	0.000
Increase in voltage with battery compared to voltage regulation with all units [%]	0.000	0.000	0.786	0.786	0.024	0.035	0.033	0.137	-0.659	-0.655	0.000	0.000



(a) Without battery

(b) With battery

(c) Regulation with only battery

(d) Regulation with all generation units

(e) Price based program

(f) Peak shaving program

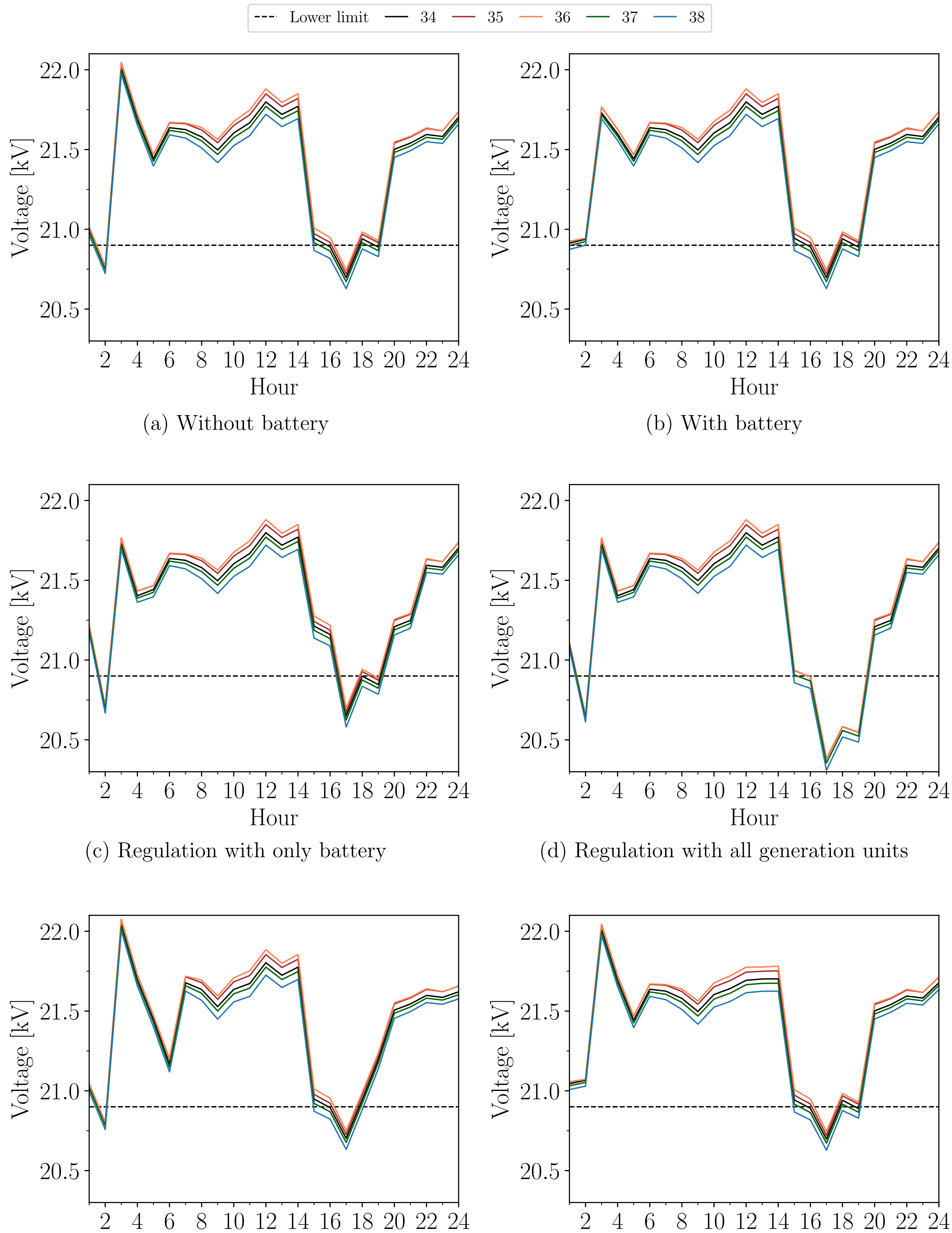
Figure (C.2) Voltage profiles for the microgrid buses with microgrid connected on bus 15 on the 4th of June

Table (C.5) Percentage increase in voltage on bus 22 for 4th of June with microgrid connected on bus 20. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	-0.394	-1.542	3.953	2.662	1.670	2.701	3.327	3.620	3.514	3.891	4.200	4.548
Increase in base case voltage compared to case with production and battery [%]	-0.788	-0.765	2.725	2.239	1.670	2.701	3.327	3.620	3.514	3.891	4.200	4.548
Increase in base case voltage compared to voltage regulation with battery [%]	0.477	-1.821	2.725	1.382	1.670	2.701	3.327	3.620	3.514	3.891	4.200	4.548
Increase in base case voltage compared to voltage regulation with all units [%]	-0.015	-2.091	2.725	1.382	1.670	2.701	3.327	3.620	3.514	3.891	4.200	4.548
Increase in voltage with battery compared to voltage regulation with battery [%]	1.275	-1.065	0.000	-0.838	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Increase in voltage with battery compared to voltage regulation with all units [%]	0.779	-1.337	0.000	-0.838	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table (C.6) Percentage increase in voltage on bus 22 for 4th of June with microgrid connected on bus 20. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	4.174	4.386	0.560	0.473	-0.079	1.169	1.054	3.870	3.871	3.963	3.713	3.732
Increase in base case voltage compared to case with production and battery [%]	4.174	4.386	0.560	0.473	-0.079	1.169	1.054	3.870	3.871	3.963	3.713	3.732
Increase in base case voltage compared to voltage regulation with battery [%]	4.174	4.386	1.738	1.656	-0.325	0.955	0.832	2.550	2.557	3.963	3.713	3.732
Increase in base case voltage compared to voltage regulation with all units [%]	4.174	4.386	0.334	0.321	-1.677	-0.641	-0.679	2.550	2.557	3.963	3.713	3.732
Increase in voltage with battery compared to voltage regulation with battery [%]	0.000	0.000	1.172	1.178	-0.246	-0.211	-0.220	-1.271	-1.265	0.000	0.000	0.000
Increase in voltage with battery compared to voltage regulation with all units [%]	0.000	0.000	-0.225	-0.151	-1.600	-1.788	-1.716	-1.271	-1.265	0.000	0.000	0.000



(a) Without battery

(b) With battery

(c) Regulation with only battery

(d) Regulation with all generation units

(e) Price based program

(f) Peak shaving program

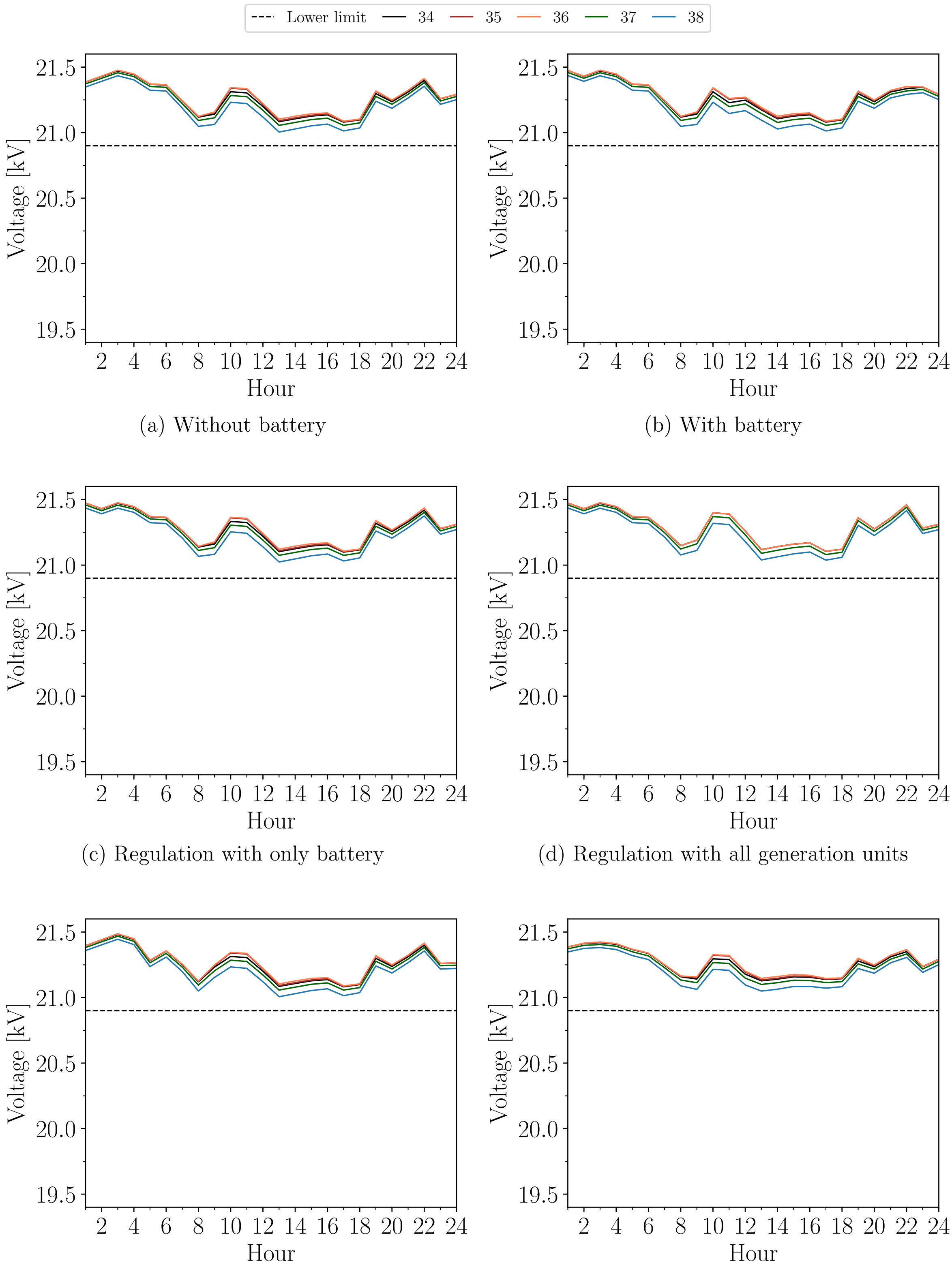
Figure (C.3) Voltage profiles for the microgrid buses with microgrid connected on bus 20 on the 4th of June

Table (C.7) Percentage increase in voltage on bus 22 for 7th of June with microgrid connected on bus 10. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	-0.652	-0.546	-0.414	-0.484	-0.668	-0.657	-0.799	-0.991	-0.765	-0.105	-0.122	-0.571
Increase in base case voltage compared to case with production and battery [%]	-0.333	-0.546	-0.414	-0.484	-0.668	-0.657	-0.799	-0.991	-0.765	-0.105	-0.404	-0.388
Increase in base case voltage compared to voltage regulation with battery [%]	-0.333	-0.546	-0.414	-0.484	-0.668	-0.657	-0.719	-0.912	-0.683	-0.015	-0.032	-0.486
Increase in base case voltage compared to voltage regulation with all units [%]	-0.333	-0.546	-0.414	-0.484	-0.668	-0.657	-0.689	-0.867	-0.561	0.255	0.240	-0.319
Increase in voltage with battery compared to voltage regulation with battery [%]	0.000	0.000	0.000	0.000	0.000	0.000	0.082	0.080	0.083	0.091	0.374	-0.099
Increase in voltage with battery compared to voltage regulation with all units [%]	0.000	0.000	0.000	0.000	0.000	0.000	0.111	0.125	0.206	0.361	0.646	0.068

Table (C.8) Percentage increase in voltage on bus 22 for 7th of June with microgrid connected on bus 10. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	-1.032	-0.991	-0.966	-0.912	-1.057	-0.999	-0.233	-0.543	-0.338	-0.070	-0.664	-0.714
Increase in base case voltage compared to case with production and battery [%]	-0.694	-0.991	-0.966	-0.912	-1.057	-0.999	-0.233	-0.543	-0.338	-0.305	-0.332	-0.714
Increase in base case voltage compared to voltage regulation with battery [%]	-0.953	-0.912	-0.886	-0.832	-0.979	-0.920	-0.145	-0.459	-0.252	0.019	-0.582	-0.633
Increase in base case voltage compared to voltage regulation with all units [%]	-0.890	-0.845	-0.826	-0.769	-0.954	-0.899	0.035	-0.375	-0.137	0.188	-0.560	-0.633
Increase in voltage with battery compared to voltage regulation with battery [%]	-0.261	0.080	0.080	0.081	0.079	0.080	0.088	0.084	0.087	0.325	-0.251	0.082
Increase in voltage with battery compared to voltage regulation with all units [%]	-0.198	0.147	0.141	0.144	0.104	0.101	0.268	0.168	0.202	0.495	-0.229	0.082



(a) Without battery

(b) With battery

(c) Regulation with only battery

(d) Regulation with all generation units

(e) Price based program

(f) Peak shaving program

Figure (C.4) Voltage profiles for the microgrid buses with microgrid connected on bus 10 on the 7th of June

Table (C.9) Percentage increase in voltage on bus 22 for 7th of June with microgrid connected on bus 15. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	-1.367	-1.134	-0.847	-0.996	-1.392	-1.369	-1.670	-2.073	-1.564	-0.130	-0.164	-1.137
Increase in base case voltage compared to case with production and battery [%]	-0.670	-1.134	-0.847	-0.996	-1.392	-1.369	-1.670	-2.073	-1.564	-0.130	-0.772	-0.739
Increase in base case voltage compared to voltage regulation with battery [%]	-0.670	-0.542	-0.847	-0.963	-1.365	-1.343	-1.652	-2.061	-1.542	-0.080	-0.115	-1.105
Increase in base case voltage compared to voltage regulation with all units [%]	-0.670	-0.535	-0.847	-0.955	-1.362	-1.340	-1.652	-2.068	-1.566	-0.120	-0.158	-1.133
Increase in voltage with battery compared to voltage regulation with battery [%]	0.000	0.599	0.000	0.034	0.027	0.026	0.019	0.012	0.022	0.050	0.662	-0.369
Increase in voltage with battery compared to voltage regulation with all units [%]	0.000	0.606	0.000	0.042	0.030	0.029	0.019	0.005	-0.002	0.010	0.618	-0.398

Table (C.10) Percentage increase in voltage on bus 22 for 7th of June with microgrid connected on bus 15. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	-2.152	-2.062	-2.010	-1.896	-2.224	-2.103	-0.428	-1.112	-0.670	-0.093	-1.390	-1.500
Increase in base case voltage compared to case with production and battery [%]	-1.407	-2.062	-2.010	-1.896	-2.224	-2.103	-0.428	-1.112	-0.670	-0.602	-0.663	-1.500
Increase in base case voltage compared to voltage regulation with battery [%]	-2.140	-2.048	-1.995	-1.881	-2.218	-2.096	-0.390	-1.089	-0.639	-0.050	-1.372	-1.481
Increase in base case voltage compared to voltage regulation with all units [%]	-2.151	-2.059	-2.003	-1.889	-2.222	-2.099	-0.406	-1.095	-0.641	-0.045	-1.372	-1.481
Increase in voltage with battery compared to voltage regulation with battery [%]	-0.744	0.014	0.015	0.015	0.006	0.007	0.038	0.023	0.032	0.555	-0.714	0.019
Increase in voltage with battery compared to voltage regulation with all units [%]	-0.755	0.003	0.007	0.007	0.002	0.004	0.022	0.018	0.030	0.559	-0.714	0.019

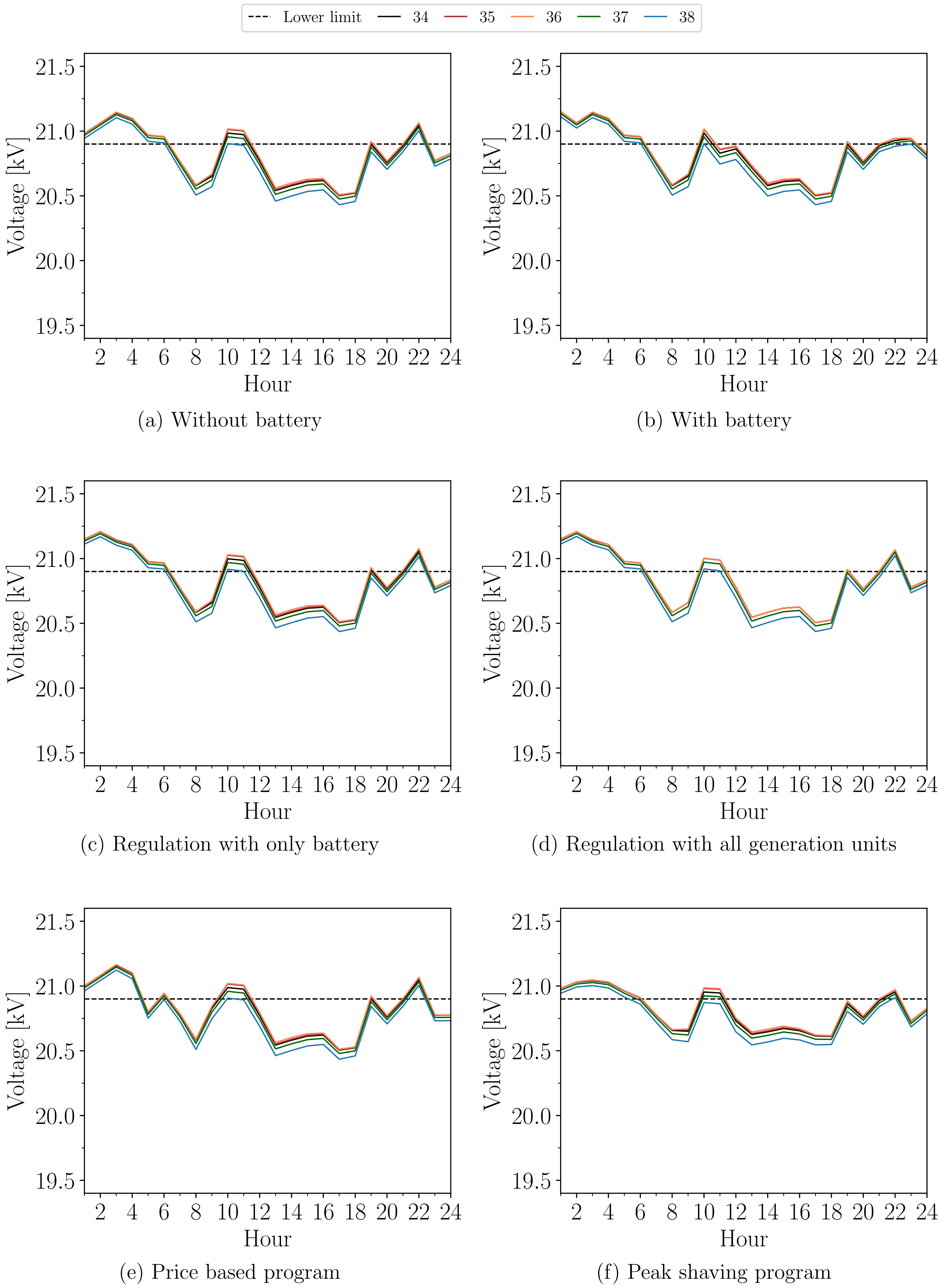


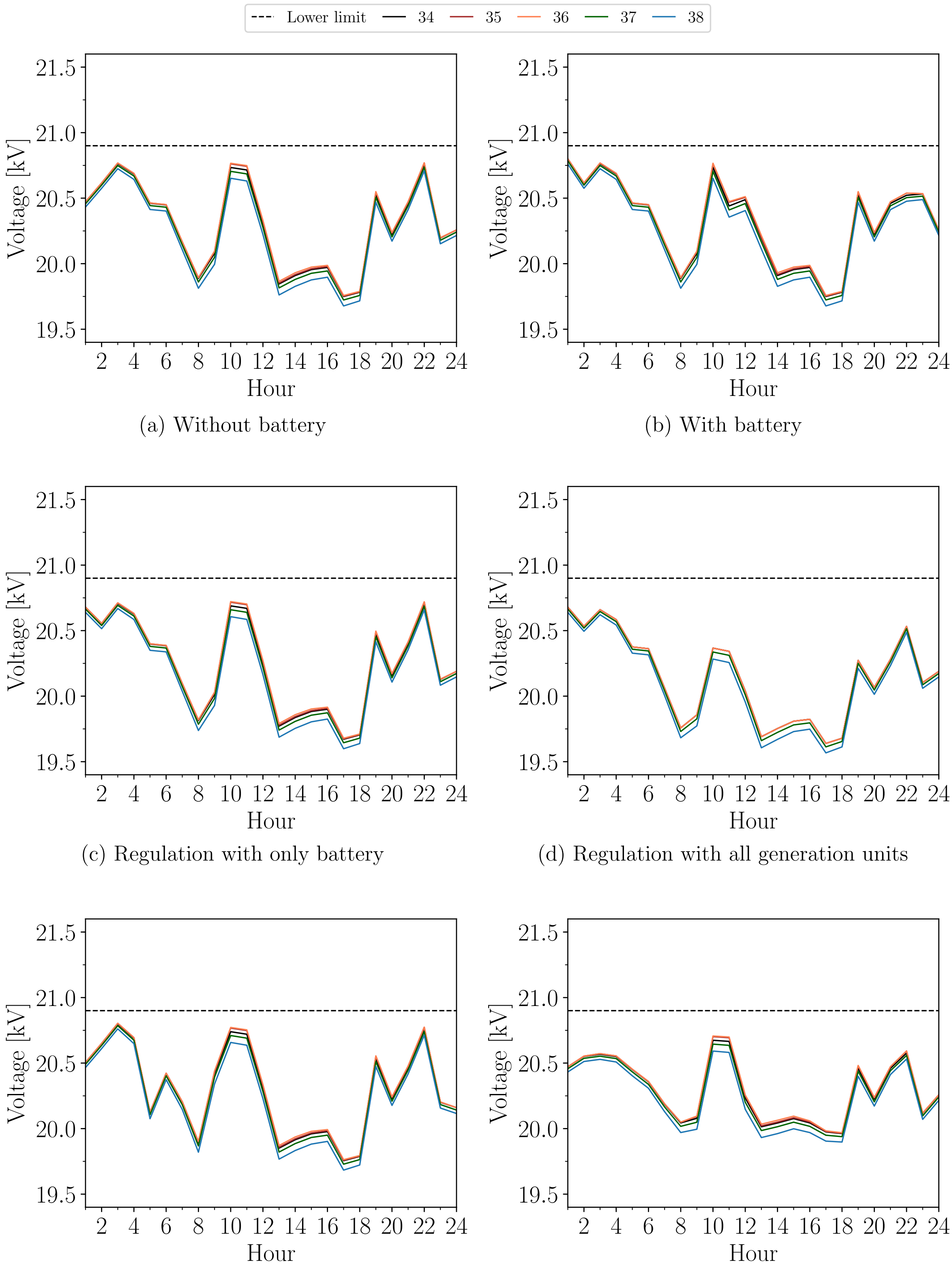
Figure (C.5) Voltage profiles for the microgrid buses with microgrid connected on bus 15 on the 7th of June

Table (C.11) Percentage increase in voltage on bus 22 for 7th of June with microgrid connected on bus 20. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	-2.711	-2.227	-1.632	-1.933	-2.742	-2.695	-3.296	-4.094	-2.994	-0.045	-0.110	-2.102
Increase in base case voltage compared to case with production and battery [%]	-1.262	-2.227	-1.632	-1.933	-2.742	-2.695	-3.296	-4.094	-2.994	-0.045	-1.344	-1.284
Increase in base case voltage compared to voltage regulation with battery [%]	-1.829	-2.528	-1.913	-2.223	-3.058	-3.013	-3.641	-4.467	-3.326	-0.278	-0.344	-2.399
Increase in base case voltage compared to voltage regulation with all units [%]	-1.829	-2.627	-2.146	-2.432	-3.166	-3.124	-3.801	-4.741	-4.102	-1.890	-1.984	-3.431
Increase in voltage with battery compared to voltage regulation with battery [%]	-0.573	-0.308	-0.285	-0.295	-0.325	-0.326	-0.357	-0.388	-0.342	-0.233	1.014	-1.130
Increase in voltage with battery compared to voltage regulation with all units [%]	-0.573	-0.408	-0.522	-0.509	-0.436	-0.440	-0.523	-0.675	-1.142	-1.845	-0.648	-2.174

Table (C.12) Percentage increase in voltage on bus 22 for 7th of June with microgrid connected on bus 20. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	-4.236	-4.050	-3.949	-3.719	-4.425	-4.183	-0.700	-2.132	-1.230	-0.058	-2.740	-2.977
Increase in base case voltage compared to case with production and battery [%]	-2.669	-4.050	-3.949	-3.719	-4.425	-4.183	-0.700	-2.132	-1.230	-1.096	-1.230	-2.977
Increase in base case voltage compared to voltage regulation with battery [%]	-4.607	-4.413	-4.309	-4.077	-4.819	-4.575	-0.975	-2.460	-1.528	-0.316	-3.084	-3.319
Increase in base case voltage compared to voltage regulation with all units [%]	-5.007	-4.829	-4.677	-4.459	-4.976	-4.701	-1.988	-2.927	-2.135	-1.170	-3.200	-3.319
Increase in voltage with battery compared to voltage regulation with battery [%]	-1.992	-0.378	-0.374	-0.372	-0.412	-0.409	-0.277	-0.335	-0.301	0.789	-1.877	-0.352
Increase in voltage with battery compared to voltage regulation with all units [%]	-2.403	-0.812	-0.757	-0.768	-0.576	-0.541	-1.297	-0.812	-0.916	-0.074	-1.995	-0.352



(a) Without battery

(b) With battery

(c) Regulation with only battery

(d) Regulation with all generation units

(e) Price based program

(f) Peak shaving program

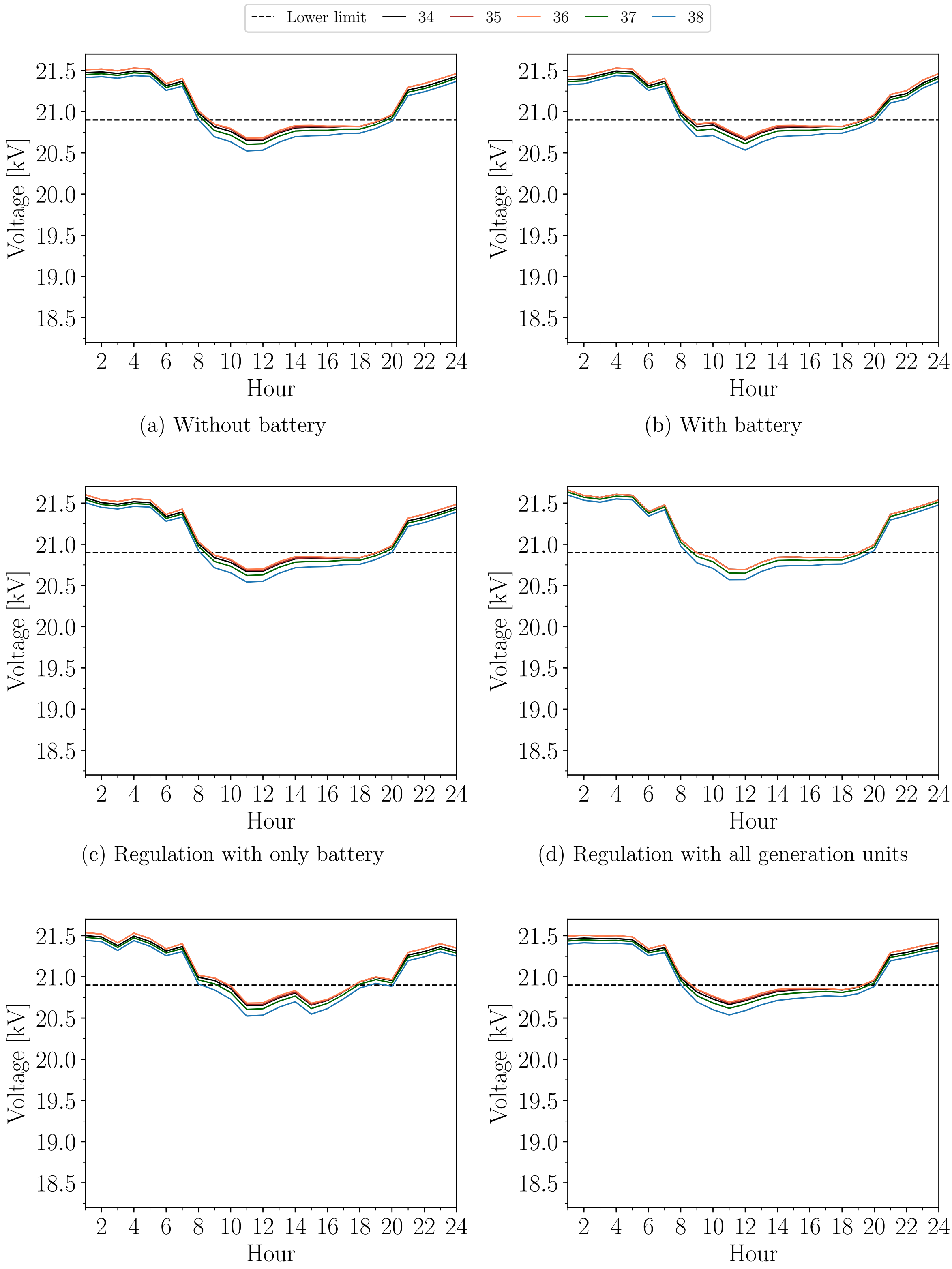
Figure (C.6) Voltage profiles for the microgrid buses with microgrid connected on bus 20 on the 7th of June

Table (C.13) Percentage increase in voltage on bus 22 for 1st of March with microgrid connected on bus 10. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	0.547	0.539	0.474	0.612	0.634	0.095	0.563	-0.444	-0.783	-1.010	-1.576	-1.702
Increase in base case voltage compared to case with production and battery [%]	0.220	0.212	0.409	0.612	0.634	0.095	0.563	-0.444	-0.783	-0.706	-1.198	-1.702
Increase in base case voltage compared to voltage regulation with battery [%]	0.907	0.637	0.572	0.711	0.734	0.188	0.661	-0.356	-0.697	-0.927	-1.500	-1.628
Increase in base case voltage compared to voltage regulation with all units [%]	1.297	1.003	0.921	1.089	1.111	0.445	1.032	-0.137	-0.445	-0.702	-1.378	-1.544
Increase in voltage with battery compared to voltage regulation with battery [%]	0.685	0.424	0.162	0.098	0.099	0.093	0.098	0.088	0.087	-0.222	-0.305	0.075
Increase in voltage with battery compared to voltage regulation with all units [%]	1.075	0.789	0.510	0.473	0.474	0.350	0.467	0.309	0.340	0.005	-0.182	0.161

Table (C.14) Percentage increase in voltage on bus 22 for 1st of March with microgrid connected on bus 10. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	-1.546	-1.459	-1.481	-1.508	-1.460	-1.407	-1.183	-0.864	0.303	0.472	0.528	0.562
Increase in base case voltage compared to case with production and battery [%]	-1.546	-1.459	-1.481	-1.508	-1.460	-1.407	-1.183	-0.864	-0.043	0.128	0.459	0.562
Increase in base case voltage compared to voltage regulation with battery [%]	-1.471	-1.383	-1.405	-1.433	-1.385	-1.331	-1.105	-0.783	0.399	0.570	0.626	0.660
Increase in base case voltage compared to voltage regulation with all units [%]	-1.384	-1.301	-1.338	-1.389	-1.365	-1.316	-1.058	-0.680	0.736	0.935	0.995	1.032
Increase in voltage with battery compared to voltage regulation with battery [%]	0.076	0.077	0.077	0.076	0.076	0.076	0.079	0.083	0.442	0.441	0.166	0.098
Increase in voltage with battery compared to voltage regulation with all units [%]	0.165	0.160	0.145	0.121	0.095	0.092	0.127	0.186	0.780	0.806	0.533	0.468



(a) Without battery

(b) With battery

(c) Regulation with only battery

(d) Regulation with all generation units

(e) Price based program

(f) Peak shaving program

Figure (C.7) Voltage profiles for the microgrid buses with microgrid connected on bus 10 on the 1st of March

Table (C.15) Percentage increase in voltage on bus 22 for 1st of March with microgrid connected on bus 15. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	1.253	1.232	1.095	1.388	1.435	0.285	1.293	-0.850	-1.545	-2.040	-3.311	-3.604
Increase in base case voltage compared to case with production and battery [%]	0.556	0.536	0.957	1.388	1.435	0.285	1.293	-0.850	-1.545	-1.370	-2.462	-3.604
Increase in base case voltage compared to voltage regulation with battery [%]	1.876	1.300	1.160	1.457	1.503	0.331	1.356	-0.829	-1.530	-2.033	-3.328	-3.627
Increase in base case voltage compared to voltage regulation with all units [%]	1.899	1.274	1.133	1.432	1.474	0.291	1.281	-0.954	-1.775	-2.264	-3.454	-3.703
Increase in voltage with battery compared to voltage regulation with battery [%]	1.313	0.759	0.201	0.068	0.068	0.046	0.062	0.021	0.015	-0.672	-0.888	-0.024
Increase in voltage with battery compared to voltage regulation with all units [%]	1.335	0.734	0.175	0.044	0.039	0.006	-0.012	-0.105	-0.233	-0.906	-1.017	-0.103

Table (C.16) Percentage increase in voltage on bus 22 for 1st of March with microgrid connected on bus 15. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	-3.258	-3.069	-3.123	-3.195	-3.108	-3.001	-2.505	-1.795	0.750	1.110	1.221	1.286
Increase in base case voltage compared to case with production and battery [%]	-3.258	-3.069	-3.123	-3.195	-3.108	-3.001	-2.505	-1.795	0.005	0.372	1.075	1.286
Increase in base case voltage compared to voltage regulation with battery [%]	-3.272	-3.078	-3.133	-3.210	-3.126	-3.019	-2.516	-1.792	0.803	1.168	1.283	1.352
Increase in base case voltage compared to voltage regulation with all units [%]	-3.336	-3.129	-3.173	-3.235	-3.136	-3.028	-2.540	-1.840	0.696	1.062	1.205	1.302
Increase in voltage with battery compared to voltage regulation with battery [%]	-0.014	-0.010	-0.011	-0.015	-0.018	-0.019	-0.011	0.003	0.798	0.793	0.206	0.065
Increase in voltage with battery compared to voltage regulation with all units [%]	-0.080	-0.062	-0.052	-0.041	-0.029	-0.028	-0.036	-0.046	0.691	0.688	0.128	0.016

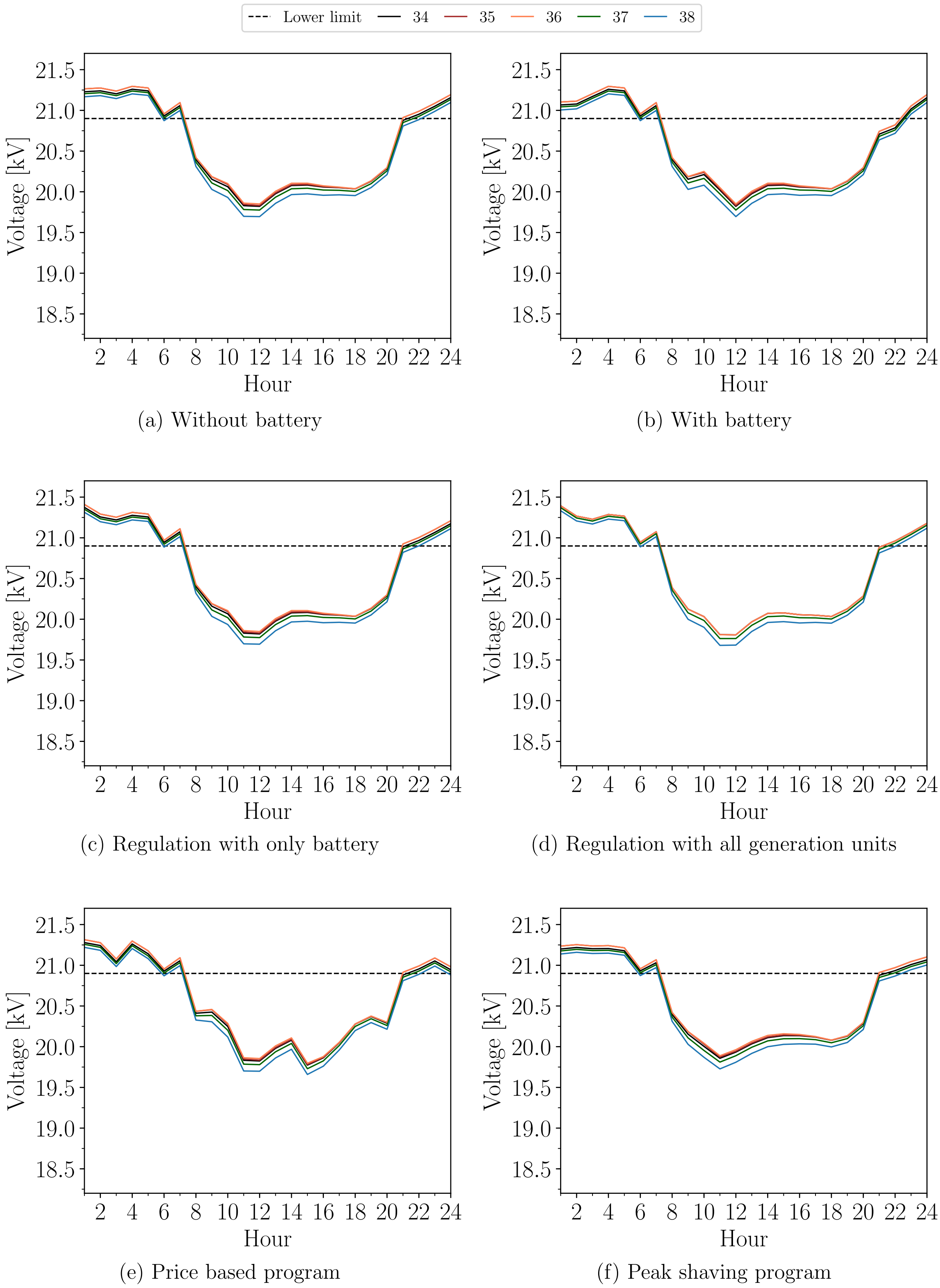


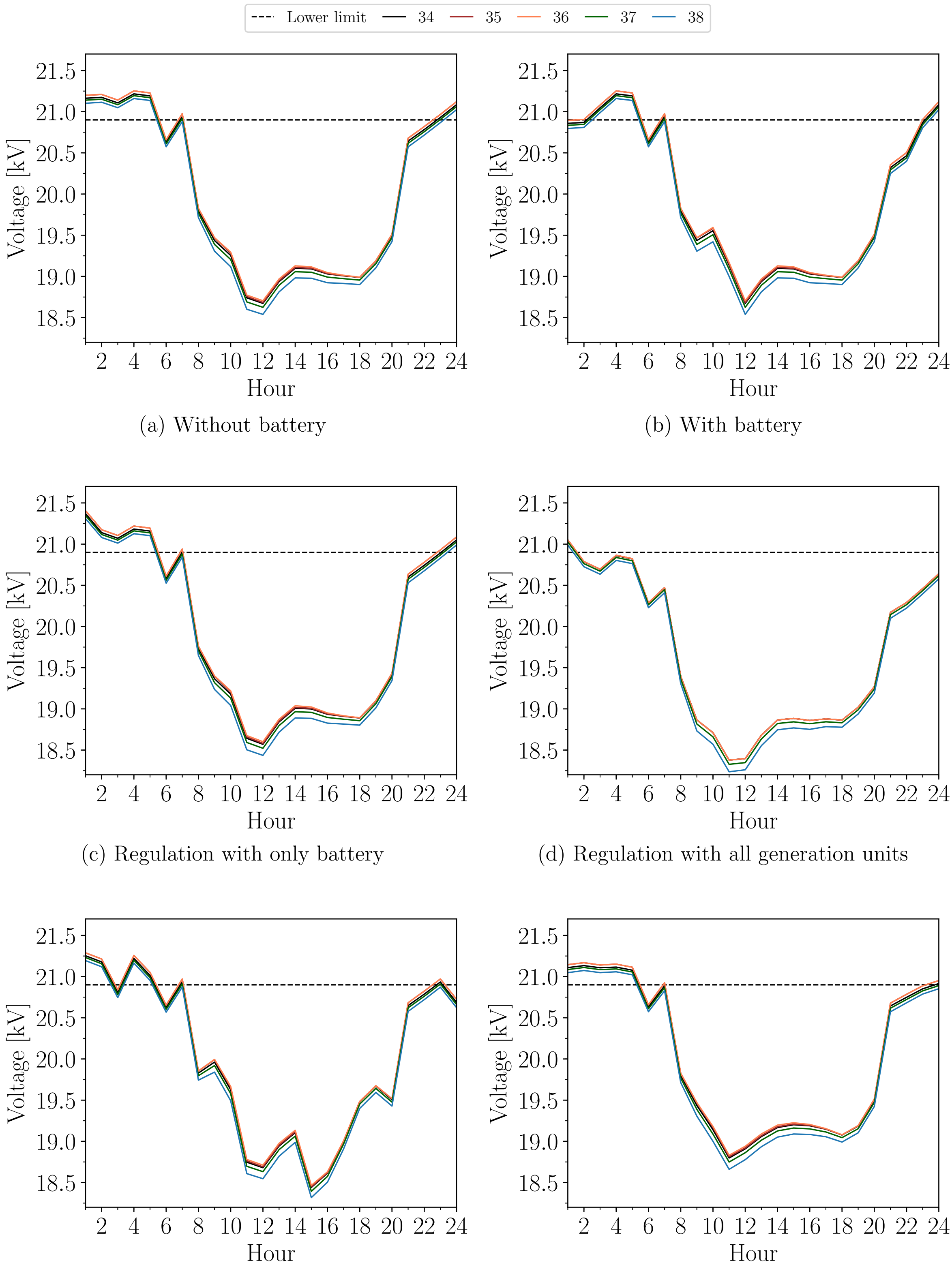
Figure (C.8) Voltage profiles for the microgrid buses with microgrid connected on bus 15 on the 1st of March

Table (C.17) Percentage increase in voltage on bus 22 for 1st of March with microgrid connected on bus 20. Hour 1-12

Hours:	1	2	3	4	5	6	7	8	9	10	11	12
Increase in base case voltage compared to case with production [%]	2.683	2.636	2.365	2.938	3.028	0.751	2.764	-1.479	-2.808	-3.830	-6.576	-7.245
Increase in base case voltage compared to case with production and battery [%]	1.301	1.256	2.091	2.938	3.028	0.751	2.764	-1.479	-2.808	-2.429	-4.735	-7.245
Increase in base case voltage compared to voltage regulation with battery [%]	3.599	2.455	2.175	2.762	2.850	0.500	2.566	-1.819	-3.174	-4.225	-7.076	-7.769
Increase in base case voltage compared to voltage regulation with all units [%]	1.958	0.660	0.267	1.118	1.123	-1.011	0.358	-3.559	-5.739	-6.612	-8.417	-8.645
Increase in voltage with battery compared to voltage regulation with battery [%]	2.269	1.184	0.082	-0.171	-0.173	-0.249	-0.192	-0.345	-0.377	-1.841	-2.457	-0.564
Increase in voltage with battery compared to voltage regulation with all units [%]	0.649	-0.588	-1.786	-1.768	-1.849	-1.749	-2.341	-2.111	-3.016	-4.288	-3.865	-1.509

Table (C.18) Percentage increase in voltage on bus 22 for 1st of March with microgrid connected on bus 20. Hour 13-24

Hour:	13	14	15	16	17	18	19	20	21	22	23	24
Increase in base case voltage compared to case with production [%]	-6.507	-6.114	-6.244	-6.427	-6.279	-6.062	-4.997	-3.487	1.713	2.417	2.624	2.743
Increase in base case voltage compared to case with production and battery [%]	-6.507	-6.114	-6.244	-6.427	-6.279	-6.062	-4.997	-3.487	0.223	0.954	2.337	2.743
Increase in base case voltage compared to voltage regulation with battery [%]	-6.990	-6.576	-6.711	-6.910	-6.774	-6.563	-5.461	-3.895	1.485	2.207	2.426	2.558
Increase in base case voltage compared to voltage regulation with all units [%]	-7.806	-7.291	-7.287	-7.287	-6.932	-6.690	-5.835	-4.666	-0.715	-0.113	0.213	0.473
Increase in voltage with battery compared to voltage regulation with battery [%]	-0.516	-0.491	-0.498	-0.517	-0.529	-0.533	-0.489	-0.423	1.259	1.241	0.087	-0.180
Increase in voltage with battery compared to voltage regulation with all units [%]	-1.389	-1.254	-1.113	-0.919	-0.697	-0.669	-0.882	-1.222	-0.936	-1.057	-2.076	-2.209



(a) Without battery

(b) With battery

(c) Regulation with only battery

(d) Regulation with all generation units

(e) Price based program

(f) Peak shaving program

Figure (C.9) Voltage profiles for the microgrid buses with microgrid connected on bus 20 on the 1st of March

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