Cape Peninsula
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ANCILLARY SERVICES CAPABILITY OF GRID-CONNECTED RENEWABLE ENERGY SYSTEMS

by

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Thesis submitted in partial fulfilment of the requirements for the degree

Master of Engineering in Energy

in the Faculty of Engineering

at the Cape Peninsula University of Technology

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Bellville
November 2023

DECLARATION

I, Jesse Nathan Fritz, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

8/11/2023

Signed **Date**

ABSTRACT

Renewable energy sources are rapidly expanding their share in the global electricity mix, driven by the need to reduce carbon emissions and enhance energy security. However, the variability and uncertainty of renewables pose significant challenges for the reliable and efficient operation of power grids, which require stable and balanced supply-demand dynamics. Ancillary services, which are the supplementary services that support the basic functions of the grid, have emerged as a critical means to address these challenges and optimize the integration of renewables.

This thesis aims to investigate the potential and challenges of renewable-based ancillary services, with a focus on photovoltaic (PV) and wind power systems. The study employs a multi-disciplinary approach that combines technical, economic, and regulatory aspects, and incorporates both quantitative and qualitative methods.

The thesis starts by reviewing the literature on renewable ancillary services, and identifying the main types, requirements, and benefits of these services. Then, it presents a detailed analysis of the technical characteristics and performance of PV and wind power systems in providing ancillary services, based on simulation models and case studies. The analysis covers a range of ancillary services, including frequency regulation, voltage control, and ramping support, and evaluates the effectiveness and limitations of renewables-based solutions.

Finally, the thesis draws conclusions and recommendations for future research and practice in the field of renewable ancillary services. The study highlights the importance of holistic and integrated approaches that consider the technical, economic, and regulatory aspects of renewables integration, as well as the need for coordinated efforts among different stakeholders. The thesis also identifies the challenges and opportunities for further improving the reliability and sustainability of power grids with renewables-based ancillary services.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Dr Atanda Raji for his invaluable guidance, support, and encouragement throughout my research journey. His expertise, constructive feedback, and patience have been instrumental in shaping my ideas and improving the quality of my work.

I am also indebted to the faculty members and staff of Cape Peninsula University of Technology for their professional and friendly assistance, who have provided significant help, such as technical support, administrative support, and research collaboration.

My sincere thanks also go to my family and friends for their unwavering love, encouragement, and understanding during the ups and downs of my academic pursuit. Their support and inspiration have been a constant source of motivation and joy.

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GLOSSARY

AC - Alternate Current
AGC - Automatic Generation Control
AS - Ancillary Services
CSP - Concentrated Solar Power
DC - Direct Current
DFIG - Double-fed Induction Generators
DG - Distributed Generation
DERs - Distributed Energy Resources
DSP - Digital Signal Processor
DSTATCOM - Distributed Static Synchronous Condenser
FACTS - Flexible Alternating Current Transmission Systems
FSIG - Fixed Speed Induction Generators
IESP - Integrated Energy Service Provider
HV - High Voltage
IG - Induction Generation
LV - Low Voltage
MMPT - Maximum Power Point Tracking
MFGCI - Multifunctional Grid-connected Inverter
MV - Medium Voltage
PCC - Point of Common Coupling
PILC - Paper Insulated Lead Covered
PV - Photovoltaic
PWM - Pulse Width Modulation
RE - Renewable Energy
RIES - Renewable Integrated Energy System
RDGs - Renewable Distributed Generators
SCIG - Squirrel Cage Induction Generation
SG - Synchronous Generators
SGMP - Synchronous Generators Multi-pole
STATCOM - Static Synchronous Condenser
SVCs - Static VAR Compensators
UPQC - Unified Power Quality Conditioner
VSM - Virtual Synchronous Machine
WP - Wind Power
WRSG - Wounded Rotor Synchronous Generators

CHAPTER 1 Research background

1.1 Introduction

Renewable electrical ancillary services refer to the support services that are provided to the main grid system to ensure reliable and stable operation of the power system (Holttinen, 2012). These services are required to balance the supply and demand of electricity in real-time. As the share of renewable energy sources in the power mix increases, the need for ancillary services also increases (Lin et al., 2021). These services can be provided by conventional power plants or by specially designed systems connected to renewable energy sources, such as wind or solar farms. The main types of ancillary services include frequency control, voltage control, and reserve power. These services help to ensure the stability and reliability of the power system, even as the generation mix changes and the demand for electricity fluctuates (Olek and Wierzbowski, 2013; Kashyap, 2013).

1.2 Problem statement

The integration of renewable energy sources into the grid can bring challenges in terms of grid stability, reliability and efficiency. The increasing penetration of these renewable energy sources has led to new challenges for ancillary services (Gong et al., 2022). The lack of predictability and controllability of renewable energy sources such as wind and solar requires the provision of ancillary services, such as frequency regulation and voltage control, to maintain grid stability (Holttinen, 2012). The problem is to find an effective and efficient way to provide these ancillary services using renewable energy sources while also ensuring grid reliability and stability. The importance of grid-tied ancillary services in renewable energy integration has been highlighted by many researchers (Bartolucci et al., 2019).

1.3 Research design and methodology

The research design and methodology for renewable ancillary services include the following steps:

- Problem Statement: Identifying the potential of renewable energy sources for providing ancillary services to the grid.

- Literature Review: A comprehensive literature review to gain an understanding of the current state of research in the field of renewable ancillary services. Grid-tied renewable energy systems such as wind turbines and solar panels can provide ancillary services to the grid. Ancillary services are essential services that help grid operators maintain the stability and reliability of the power grid. Some examples of ancillary services include frequency regulation, voltage support, and reactive power control.

- Data Collection: Collecting relevant data on renewable energy sources, their capabilities for providing ancillary services, and current practices in the use of these services. This could include both primary data (e.g. through surveys, interviews, case studies) and secondary data (e.g. from industry reports and academic articles).

- Methodology: Develop a model of the renewable energy system that includes the necessary components such as wind turbines, solar panels, inverters, and energy storage systems (if any). The model should also include the necessary control systems and communication protocols to provide the ancillary services required. Choosing an appropriate methodology for the research, such as a case study, simulation-based analysis, or econometric analysis, based on the data availability and research objectives. There are various simulation tools available that can help simulate grid-tied renewable energy systems, such as MATLAB/Simulink, PSCAD and PowerFactory.

- Data Analysis: Analyse the data using appropriate statistical and/or econometric techniques to answer the research questions and test the hypotheses. Validate the model by comparing the simulation results with actual field measurements Analyze the simulation results to determine if the renewable energy system is capable of providing the required ancillary services. Make necessary adjustments to the model and control systems as needed. Analyse the simulation results to determine if the renewable energy system is capable of providing the required ancillary services. Make necessary adjustments to the model and control systems as needed.

- Results: Present the results of the research in a clear and concise manner, using tables, graphs, and other visual aids where appropriate.

- Conclusion: Summarize the key findings and draw conclusions based on the results, discussing the implications for policymakers, industry, and academia.

1.4 Delineation of the research

Research on electrical ancillary services typically focuses on the design, implementation and evaluation of various methods to provide support services to the power grid. The objective is to maintain the stability and reliability of the electrical system by ensuring that supply matches demand in real-time.

The research covers topics such as the economic and technical aspects of ancillary services, the role of different participants in providing these services, the impact of renewable energy sources on the provision of ancillary services, and the use of new technologies such as energy storage and demand response.

Another area of research is on the regulatory framework for ancillary services and its impact on market efficiency, competition, and the deployment of new technologies. The design of market mechanisms and pricing strategies for ancillary services is also an important aspect of the research.

Overall, the research on electrical ancillary services aims to provide practical solutions to improve the functioning and reliability of the power grid while balancing economic and environmental objectives.

The research will cover the full scope and outline of the dissertation. An understanding of the causes and impacts of poor power quality on grids.

1.5 Significance of the research

Researching renewable energy ancillary services is significant because:

It helps to integrate renewable energy sources into the grid, making it more stable and reliable.

- It contributes to the transition towards a more sustainable energy system, reducing dependence on non-renewable energy sources and reducing greenhouse gas emissions.
- It can lead to cost savings and increased efficiency in the energy sector.
- It can help to improve the economic viability of renewable energy projects, making it more attractive for investment.
- It provides new business and employment opportunities in the renewable energy sector.
- In summary, researching renewable energy ancillary services is crucial for the development of a cleaner, more efficient, and sustainable energy system.

1.6 Expected outcomes, results and contributions of the research

The study of the ancillary services capability of grid-connected renewable energy systems is an area of active research. The expected outcomes of this research include a better understanding of the technical and economic aspects of integrating renewable energy sources into the power grid to provide ancillary services. The expected outcomes will also include:

- Advancement in understanding of renewable energy systems and their integration into power grids.
- Development of new and improved technologies for renewable energy ancillary services.
- Increased reliability and stability of renewable energy systems.
- Improved economic viability of renewable energy systems.
- Better integration of renewable energy sources into power grids, leading to increased use of renewable energy.

The results of this research are expected to lead to a more sustainable and reliable power system that is capable of meeting the growing demand for electricity while reducing greenhouse gas emissions. The results will also include:

- Increased understanding of the technical and economic aspects of renewable energy ancillary services.

- New and improved methods for providing ancillary services to support renewable energy systems.
- Improved efficiency and reduced costs of renewable energy systems.
- Better grid management and integration of renewable energy sources.

Research in this area is expected to result in the development of advanced control and optimization techniques for renewable energy systems to provide ancillary services such as frequency regulation, voltage support, and spinning reserves. Furthermore, this research is expected to contribute to the development of policies and regulations that facilitate the integration of renewable energy sources into the power grid as providers of ancillary services. The contributions will also include:

- Improved access to clean and sustainable energy sources.
- Reduction in greenhouse gas emissions and other pollutants.
- Stimulation of economic growth and job creation through investment in renewable energy technology and services.
- Increased energy security through reduced dependence on non-renewable sources.
- Contribution to global efforts to address climate change.

1.7 **Delimitations of the Research**

The study of the ancillary services capability of grid-connected renewable energy systems is a complex and interdisciplinary field that involves multiple technical, economic, and regulatory factors. Therefore, the research in this area has several delimitations that need to be considered.

Firstly, the research is limited by the availability of data on renewable energy systems and their performance in providing ancillary services. This may be due to the lack of standardized measurement and reporting protocols for these systems. Also focusing on a particular type of renewable energy technology or ancillary service.

Secondly, the research may be limited by the availability of appropriate modelling and simulation tools that can accurately represent the behaviour of renewable energy systems under different operating conditions.

Thirdly, the research may be limited by the existing regulatory frameworks that govern the provision of ancillary services in the power system, which may not be designed to accommodate the unique characteristics of renewable energy sources.

Finally, the research may be limited by the variability and intermittency of renewable energy sources, which can make it challenging to provide reliable and consistent ancillary services. These delimitations highlight the need for further research to overcome the technical, economic, and regulatory challenges associated with the integration of renewable energy sources into the power grid as providers of ancillary services.

1.8 Research aims

Research aims for ancillary services capability of grid-connected renewable energy systems include:

1) Assessing the technical feasibility of providing ancillary services from renewable energy sources such as wind or solar. This would involve evaluating the ability of these systems to respond quickly to changes in grid loads and voltage, as well as their ability to provide other essential grid services such as reactive power and voltage control.
2) Assessing the environmental benefits of integrating renewable energy sources into ancillary services markets. This would involve evaluating the potential reduction in greenhouse gas emissions associated with the displacement of conventional fossil-fuel-based generators, as well as the potential for renewable energy sources to reduce other environmental impacts such as air pollution and water use.
3) Assessing the financial benefits: Examine existing market mechanisms and regulatory frameworks for compensating grid-connected renewable energy systems that provide ancillary services. Propose enhancements or new models that encourage the active participation of renewable energy producers in providing these services while ensuring fair compensation.
4) Developing new models and algorithms for optimizing the provision of ancillary services from renewable energy sources. This would involve using advanced analytics and machine learning techniques to develop

more sophisticated models for predicting the behaviour of renewable energy systems and optimizing their performance in providing ancillary services to the grid.

1.9 Research Objectives

The research objectives of the ancillary services capability of grid-connected renewable energy systems are as follows:

1) Overall, the research objectives aim to promote the integration of renewable energy sources into the grid as providers of ancillary services, which can improve the reliability, flexibility, and sustainability of the electricity system.
2) To investigate the current status of grid-connected renewable energy systems and their ability to provide ancillary services to the grid.
3) To identify the technical and operational challenges associated with integrating renewable energy sources into the grid and providing ancillary services.
4) To develop models and algorithms that optimize the provision of ancillary services by renewable energy sources, considering factors such as variability, uncertainty, and grid stability.
5) To evaluate the potential of renewable energy systems to provide different types of ancillary services, including voltage control, frequency regulation, and reactive power support.
6) To analyze the environmental benefits and impacts of using renewable energy sources for ancillary services provision, including greenhouse gas emissions, land use, and biodiversity.

1.10 Overview of study

1.10.1 Chapter one

This chapter introduces the research topic by first outlining the background of the research. It also covers the statement of the research problem, clearly stating the aim of research, the research objectives and hypothesis. Further to this, the research design and methodology is summarised, the outcomes of the research and delimitations provided as well.

1.10.2 Chapter two

This chapter introduces the literature review and integration of renewable energy sources, such as wind and solar power, into the electricity grid has presented new challenges for maintaining grid stability and reliability. One way to address these challenges is through the provision of ancillary services, which are additional grid support services beyond the basic provision of energy. Ancillary services include services such as frequency regulation, voltage control, and reactive power support, which are essential for maintaining grid stability and ensuring the reliable operation of the electricity grid.

1.10.3 Chapter three

This chapter discusses power grid systems networks that facilitate the generation, transmission, and distribution of electricity from power plants to consumers. The grid is divided into three main components: generation, transmission, and distribution. The generation component includes power plants and other sources of electricity, while the transmission component includes high-voltage transmission lines that transport electricity over long distances. The distribution component includes low-voltage lines that deliver electricity to homes, businesses, and other consumers.

1.10.4 Chapter four

This chapter discusses renewable energy sources that are replenished naturally and can be harnessed to generate electricity. The renewable energy sources included are solar, wind, hydro, geothermal, and biomass. Renewable energy sources are gaining popularity due to their low greenhouse gas emissions, lower operating costs, and the potential to reduce reliance on fossil fuels.

1.10.5 Chapter five

This chapter discusses PV systems are devices that convert sunlight directly into electricity using solar cells. The PV systems are commonly used for power generation in residential, commercial, and industrial applications. PV systems are an important and growing component of the energy mix, and their development and deployment will play a crucial role in the transition to a more sustainable and low-carbon energy system.

1.10.6 Chapter six

This chapter discusses wind energy systems harnessing the power of the wind to generate electricity. Wind turbines are the primary components of wind energy systems, and they convert the kinetic energy of the wind into electrical energy. Wind turbines can range in size from small turbines used for residential or community-scale applications to large utility-scale turbines used for commercial and industrial applications.

1.10.7 Chapter seven

The chapter discusses the methodology used for the simulations, which involved modelling the power grid and simulating different scenarios with varying levels of renewable energy penetration. The simulations were carried out using specialized software that takes into account the technical constraints of the power grid and the behaviour of renewable energy resources. The aim of this chapter is the simulation design to investigate the potential of grid-tied PV systems to provide ancillary services to the power grid.

1.10.8 Chapter eight

This chapter will discuss the results and conclusion of the simulations showing that renewable energy resources can provide ancillary services to the grid with comparable or even better performance than conventional power plants. The simulations also highlight the benefits of integrating renewable resources into the power grid, such as reduced emissions, improved grid reliability, and lower costs.

1.10.9 Chapter nine

In this chapter, we explored the conclusion and the contributions of the literature review of grid-connected renewable energy sources to various ancillary services. These services specifies versatility and their ability to swiftly respond to grid dynamics, provide reactive power compensation and voltage control.

CHAPTER 2 Literature review: Renewable ancillary services

The literature review of renewable electrical ancillary services would examine the existing research on the use of renewable energy sources to provide grid stability and support services, such as frequency regulation and capacity firming. The literature would examine the current state of technology, the economic benefits and challenges of using renewable energy sources for ancillary services, and the regulatory framework and policies that are in place or proposed. The study by Camal et al. (2020) explores forecast trajectories for the production of a renewable virtual power plant capable of providing ancillary services. The literature would likely also explore the technical requirements for integrating renewable energy sources into the grid to provide ancillary services, as well as the potential impact of increased renewable energy penetration on the stability and reliability of the grid.

2.1 Introduction

Renewable energy ancillary services refer to the support services that are provided to the electrical grid to ensure its stability and reliability, specifically when incorporating a significant amount of renewable energy sources like wind and solar power (Ehnberg et al., 2019; Zeng et al., 2018). These services include regulation of frequency, voltage control, and spinning reserve, which help balance the power grid and maintain its stability even with fluctuating and uncertain renewable energy generation (Hirth and Ziegenhagen, 2015). Ancillary services play a crucial role in the integration of renewable energy into the grid and in ensuring the grid's ability to meet the demands of electricity consumers (Rebello et al., 2019). Kahrl et al. (2021) evaluate the economic aspects and key issues related to the participation of variable renewable energy sources in ancillary services markets in the United States. Olek and Wierzbowski (2013) investigate the provision of ancillary services by renewable energy sources, examining their potential contribution and benefits.

2.2 Types of Ancillary services

Ancillary services in the electrical power system refer to the various services provided to support the reliable and efficient operation of the power grid (Ehnberg et al., 2019). According to recent research, these services encompass a range of activities such as frequency regulation, voltage control, and reactive power support, among others (Prakash et al., 2022). There are a variety of ancillary services defined, and the ancillary services provided in different jurisdictions are not necessarily the same (Rebours, 2007). Figure 2-1 indicates the different supports of electrical ancillary services include (Holttinen, 2012).

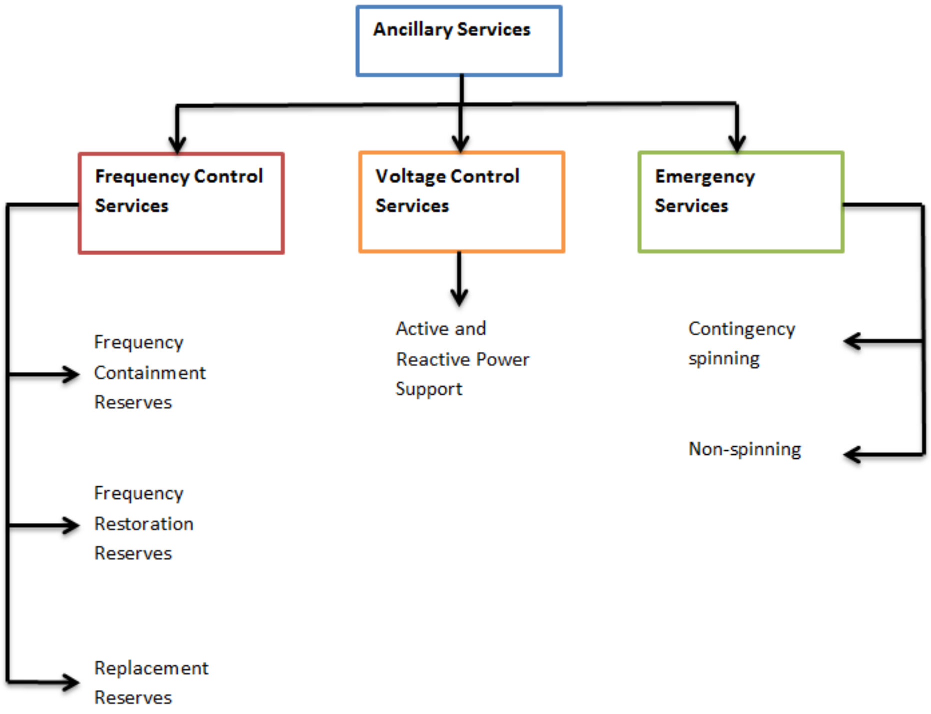

Figure 2-1: Types of Ancillary services (Prakash et al., 2022)

Figure 2-2 depicts the operational procedure of an Integrated Energy Service Provider (IESP) and its interaction with the markets. In essence, the IESP procures energy from both the electric energy and natural gas markets to meet the demands of users and offer ancillary services. This is achieved by optimizing the scheduling of devices within the Renewable Integrated Energy System (RIES) (Lai et al., 2022).

Specifically, the IESP purchases electricity from the electric energy market at real-time prices, providing it to users based on a time-of-use tariff. Additionally, other energy services are supplied to users at fixed prices, while natural gas is procured at predetermined rates. Moreover, to maximize its benefits, the IESP participates in the ancillary service market whenever the prices are favorable and its equipment is not in use (Lai et al., 2022).

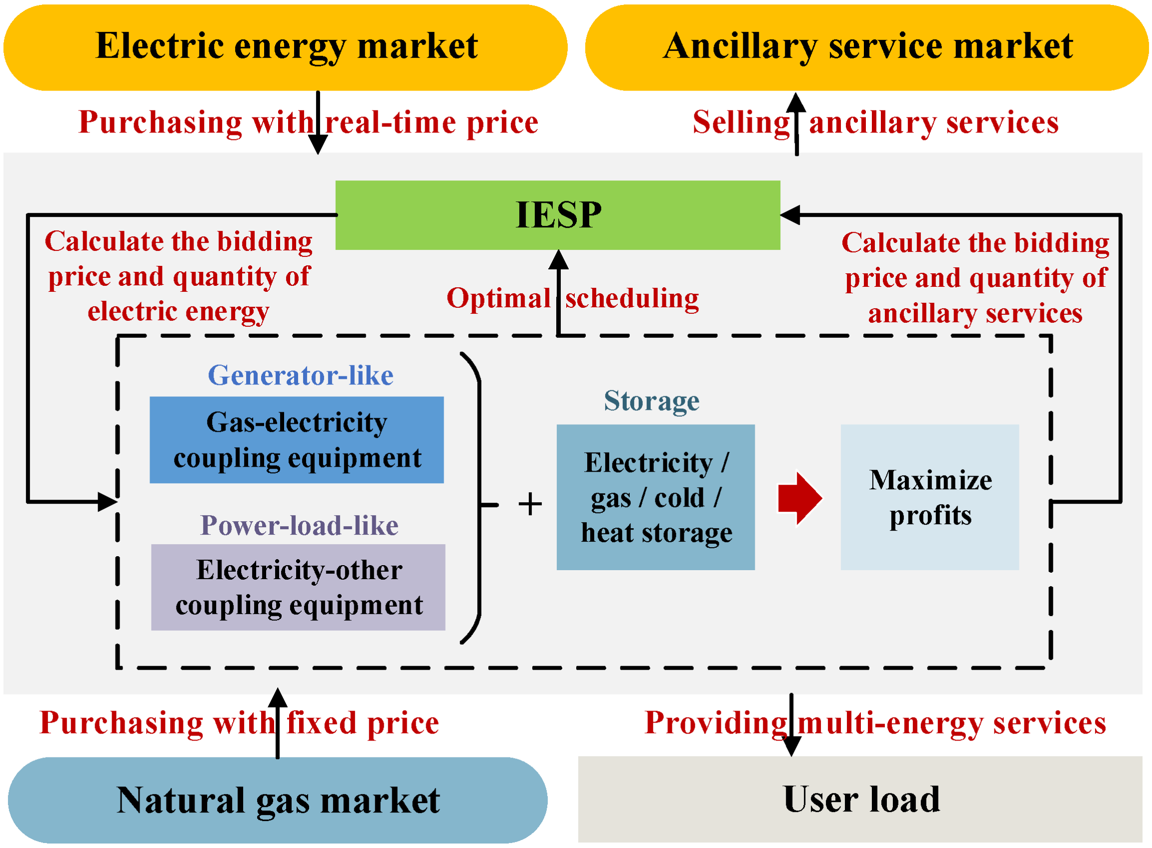

Figure 2-2: Operation of the IESP (Lai et al., 2022)

2.2.1 Frequency control

Ancillary services that help regulate the frequency of the power grid by providing additional or reducing generation or consumption. Frequency control services on the grid refer to a set of measures and technologies used to maintain the stability and reliability of the electrical power system by ensuring that the frequency of the electricity being generated and supplied to the grid remains constant (Camal et al., 2017).

These developments are expected to enhance the accuracy and responsiveness of frequency control systems, thereby improving the stability and reliability of power supply. This is critical for the proper functioning of the power system, as frequency variations can result in damage to equipment and disruption of power supply to consumers (Ehnberg et al., 2019).

The amplitude vs. Frequency Characteristics of controlled inverter is shown in Figure 2-3 are typically provided by grid-connected inverters, using techniques such as load shedding, ramping of generator outputs, or adjustment of spinning reserves, to balance the supply and demand of electricity in real-time. According to Zeng et al. (2019), frequency control play a vital role in maintaining power quality and reliability in power systems.

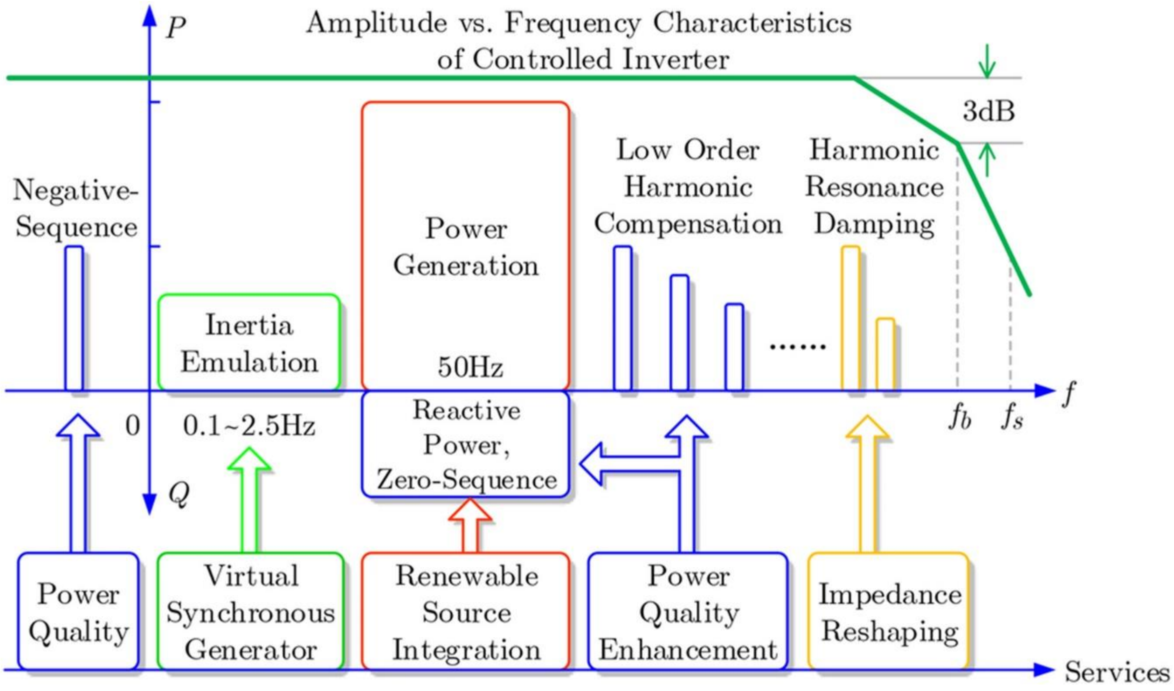

Figure 2-3: Functions of grid-connected inverter in frequency domain (Zeng et al., 2018)

2.2.2 Voltage control

Ancillary services that help regulate the voltage of the power grid by providing reactive power to the grid or by absorbing it (Bhattacharya, 2001). Voltage control services refer to the active management of voltage levels on the electrical grid. This is done to ensure that the voltage stays within a certain range, which is necessary for maintaining the stability and reliability of the power system (Prakash et al., 2022). Prakash et al. (2022) present a comprehensive review of battery energy storage systems for ancillary services in distribution grids, discussing the current status, challenges, and future directions. The goal is to balance supply and demand and maintain the voltage at an optimal level, thereby avoiding over- or under-voltage conditions and reducing the risk of power outages (Holttinen, 2012). Voltage control services play a critical role in ensuring that the electrical grid operates efficiently and effectively (Idoko et al, 2018). The integration of energy storage systems into power grids can provide valuable voltage controlled services (Prakash et al., 2022).

2.2.3 Emergency services

Ancillary services that provide backup capacity to the power grid to ensure system reliability in Emergency services on the electrical grid refer to the critical support provided to restore and maintain power supply in case of outages or disruptions (Holttinen, 2012). One of the key challenges faced by emergency services in this regard is the need to balance the demand and supply of electrical power during emergency situations (Camal et al., 2022).

Additionally, Camal et al. (2022) propose a method for reliably providing ancillary services from aggregated variable renewable energy sources through the forecasting of extreme quantiles. These initiatives will help to ensure that emergency services have access to uninterrupted and sustainable power supply, even during times of crisis. Electrical ancillary services in power systems also includes (Ehnberg et al., 2019; Holttinen, 2012):

- Restoration teams: These teams are responsible for quickly repairing any damage to the grid and restoring power supply as soon as possible.
- Emergency response centres: These centres serve as command and control centres for managing emergencies and coordinating the response effort.
- Load balancing: Ancillary services that help balance the supply and demand of electricity in real-time by adjusting the output of different power sources.
- Black start capability: Ancillary services that enable the restart of a power system following a blackout, without relying on external sources of power.

Figure 2-4 indicates the power balance, gas balance, cold balance, and heat balance are respectively presented for the two scenarios. The positive bars in the figures represent the power of energy produced, the negative bars represent the power of energy consumed, and the curve represents the user’s energy load (Lai et al., 2022).

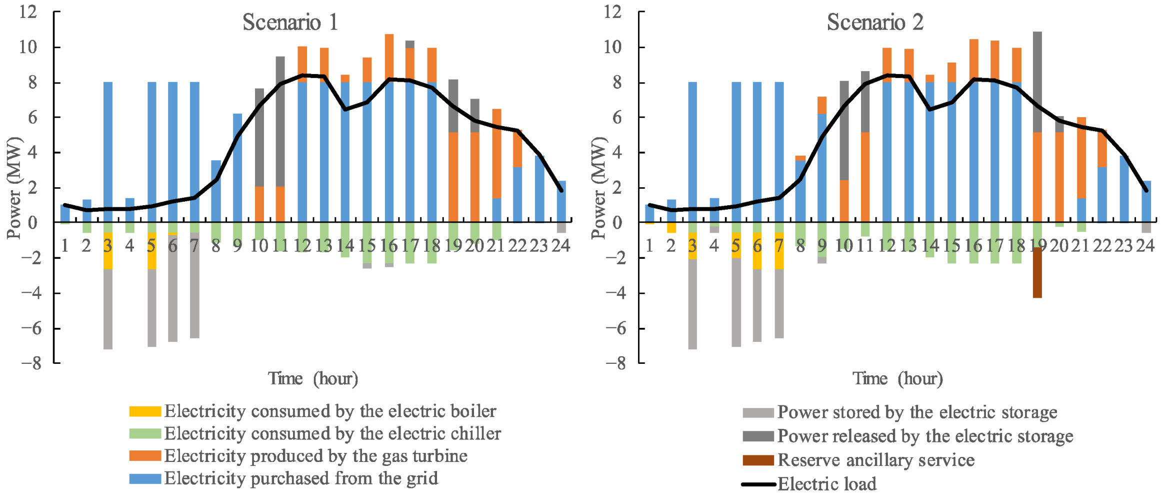

Figure 2-4: Power balance (Lai et al., 2022)

In summary, renewable ancillary services go beyond the core role of electricity generation and play a crucial role in grid management. The provision of ancillary services by renewables includes activities like voltage regulation, frequency control, and maintaining grid stability in the face of fluctuating generation. This concept is integral to the effective integration of renewable energy into the grid, addressing the intermittency and variability inherent to renewables. Moreover, understanding how renewables contribute to ancillary services is essential for optimizing grid operations and advancing the transition towards sustainable and resilient energy systems. This research area encompasses a diverse range of topics, from technical aspects and grid infrastructure to regulatory frameworks and market mechanisms, all aimed at harnessing the full potential of renewables in supporting modern electrical grids.

CHAPTER 3 Power grid systems

3.1 Introduction

Ancillary services are the services and functions provided by electric grids that facilitate and support the continuous flow of electricity to ensure that the supply will continually meet the demand (Idoko et al, 2018). A power grid system is a network of power stations, transmission lines, substations, and distribution networks that work together to supply electricity to homes, businesses, and other facilities. The power grid is an essential part of modern society, providing a reliable and constant source of electricity to power our homes, offices, and industry (Borowski, 2020).

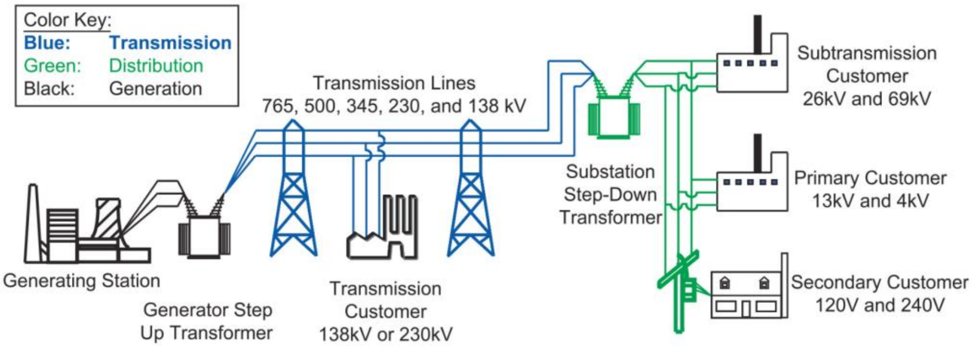

Figure 3-1: Energy sector with transmission system (Borowski, 2020)

There are two main types of power grids: the AC (alternating current) grid, which is the most common type, and the DC (direct current) grid, which is used in some specialized applications. The DC grid is used for most residential and commercial applications, while the AC grid is used primarily for high-voltage power transmission over long distances (Borowski, 2020).

The increasing integration of renewable energy sources into power grid systems has raised new challenges for their operation and management. Power demand can vary widely based on time of day, season, weather conditions, and other factors, making it difficult to maintain a constant supply of electricity. This can lead to power outages, voltage fluctuations, and other issues that can disrupt power supply and damage equipment (Elmasry and Wadi, 2022).

Another issue facing power grids is aging infrastructure. Many power grids were built decades ago and are in need of significant upgrades and modernization to meet the needs of today's energy demands. This includes replacing aging transmission lines, upgrading substations, and installing new equipment to improve grid resilience and reliability (Dehghani, 2021).

3.2 Power grid stability

Power grid stability is an essential aspect of the electrical power system. It refers to the ability of the grid to maintain a steady state of operation despite any disturbances or fluctuations in the system (Idoko et al, 2018). The stability of the power grid is crucial to ensure the reliable and safe delivery of electrical power to consumers (Kumar et al., 2022).

The schematic diagram of a multifunctional grid-connected inverter (MFGCI) is indicated in Figure 3-2a. This inverter is utilised to control certain parameters of the grid. Figure 3-2a shows the load current and utility voltage are denoted in the equation (3.1), (3.2), (3.3) and (3.4) (Zeng et al., 2018):

$$\boldsymbol{iL} = [\boldsymbol{iLa}, \boldsymbol{iLb}, \boldsymbol{iLc}]\boldsymbol{T} \tag{3.1}$$

And

$$\boldsymbol{u} = [\boldsymbol{ua}, \boldsymbol{ub}, \boldsymbol{uc}]\boldsymbol{T} \tag{3.2}$$

respectively.

The reference and output currents of the MFGCI are represented as:

$$\boldsymbol{iref} = [\boldsymbol{iref}, \boldsymbol{a}, \boldsymbol{iref}, \boldsymbol{b}, \boldsymbol{iref}, \boldsymbol{c}]\boldsymbol{T} \tag{3.3}$$

And

$$\boldsymbol{i} = [\boldsymbol{ia}, \boldsymbol{ib}, \boldsymbol{ic}]\boldsymbol{T}, \tag{3.4}$$

respectively.

Moreover, $\boldsymbol{Pref}$ and $\boldsymbol{Qref}$ stand for the reference active and reactive power, respectively.

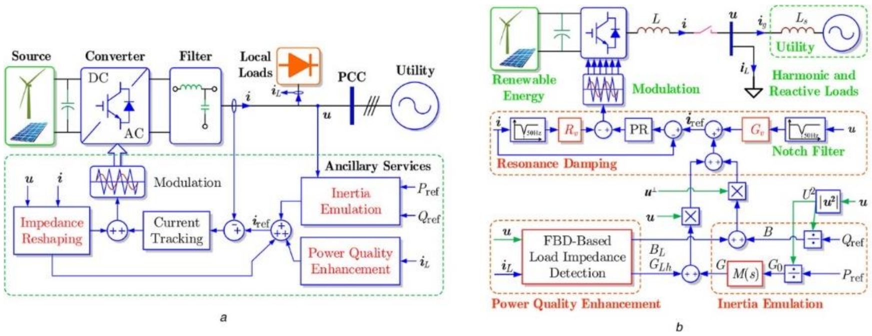

Figure 3-2: Configuration of grid-connected inverter with multiple ancillary services (Zeng et al., 2018)

(a) Schematic block diagram and (b) Detailed block diagram

To incorporate additional functionalities such as power quality enhancement, inertia emulation, and impedance reshaping, advanced control loops can be employed in the inverter. These control loops modify either the calculation of the reference current or the duty of modulation. Implementing these services on a Digital Signal Processor (DSP) based control board is straightforward. Further details regarding the realization of these supplementary functions or services are discussed in Figure 3-2b (Zeng et al., 2018).

The stability of the power grid is a critical factor in ensuring a reliable and secure power supply. According to recent research, power grid stability can be affected by a range of factors such as the integration of renewable energy sources, changes in load demand, and network faults (Kumar et al., 2022).

3.3 Types of Power Grid Stability

There are different types of power grid stability, including small-signal stability and transient stability. The two types of power grid stability: steady-state stability and dynamic stability (Elmasry and Wadi, 2022).

Steady-state stability refers to the ability of the grid to maintain a stable operating point under steady-state conditions. It is usually associated with the steady-state power transfer limit of the transmission lines. Presently, anti-islanding protection schemes mandate the swift disconnection and cessation of power generation by renewable distributed generators (RDGs) in response to grid faults caused by the loss of grid protection system (Chowdhurya, 2009; Teodorescu, 2014).

Dynamic stability, on the other hand, refers to the ability of the grid to maintain stability under dynamic conditions. This type of stability is essential during sudden disturbances in the system, such as short circuits or sudden changes in load. Ancillary services performed by distributed generation (DG) sources connected to the grid are discussed (Schafer et al., 2018; Triggianese, et al., 2007).

In summary, the power grid systems offers a comprehensive exploration of this critical aspect of modern society. It highlights the complexity of these systems, their evolving nature, and the imperative to balance reliability, sustainability, and technological advancements.

CHAPTER 4 Photovoltaic systems

4.1 Introduction

PV systems, also known as solar panels, are devices that convert sunlight into electrical energy. These systems are becoming increasingly popular as a source of clean, renewable energy for homes and businesses (Yao et al., 2022).

Solar energy refers to the energy that is derived from the sun's radiation. This energy can be harnessed through various technologies, such as photovoltaic systems, solar thermal systems, and concentrated solar power (CSP) systems. Solar power can also provide ancillary services to the grid when necessary. (Ehnberg et al., 2019; Yao et al., 2022).

The use of solar energy has been increasing rapidly over the past few decades due to its environmental benefits and decreasing costs. According to the International Energy Agency (2021), solar energy is expected to become the largest source of electricity by 2050, accounting for 37% of the total electricity generation.

4.2 Background

The origin of the first working photovoltaic process occurred in the nineteenth century, and Charles Fritts was one of the first to try to generate electricity using solar panels (Luque and Hegedus, 2003).

The upcoming of the photovoltaic age began in 1954 at Bell Laboratories (USA) and was discovered by coincidental by turning on a lamp to pn junction diodes to produce voltage. The following year researches produced 6% solar silicon batteries adjacent to silicon pn. Over the same year, numerous similar findings were informed around the United States and the earlier Soviet Union. Also during this period, the first photovoltaic application was used to power satellites for US space programs missions (Luque and Hegedus, 2003).

A typical PV system consists of solar panels, an inverter, and a mounting system. Solar panels are made up of photovoltaic cells, which use the photovoltaic effect to generate electrical energy from sunlight. The inverter converts the direct current (DC) energy produced by the solar panels into alternating current (AC) energy, which can be used to power electrical appliances and devices. The mounting system securely attaches the solar panels to the roof or ground, ensuring that they are properly angled to maximize their exposure to sunlight (Asadi et al., 2021; Rahimi and Hemmati, 2019).

4.3 Photovoltaic Operating Principles

Solar power is a renewable energy source that harnesses the energy from the sun and converts it into electricity. It works by using solar panels, made up of photovoltaic cells, to capture the sun's energy and convert it into direct current electricity. The DC electricity is then converted into alternating current electricity, which is the type of electricity that is used in homes and businesses (Vizoso et al., 2011).

Figure 3 below shows a simple equivalent circuit of a single PV photocell system. The circuit consists of a photodiode parallel to a diode and current source namely R_p and R_s (Vizoso et al., 2011).

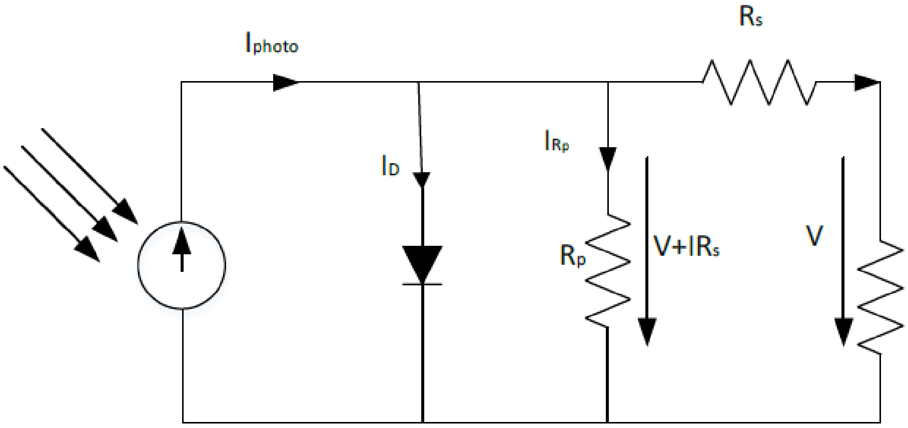

Figure 4-1: Equivalent circuit model for a PV cell (Bouziane et al., 2022)

Solar cell equation (4.1) describe the electrical behaviour of photovoltaic cells, which are the building blocks of solar panels (Bouziane et al., 2022). The most important solar cell equation is the Shockley equation, which describes the current-voltage (I-V) characteristics of a solar cell (McAllister, 2023):

$$I = I_0 * \left(e^{\frac{qV}{(nkT)}} - 1\right) \tag{4.1}$$

where:

I_0 is the reverse saturation current

q is the electron charge

V is the voltage across the cell

n is the ideality factor

k is the Boltzmann constant

T is the cell temperature in kelvin

4.4 Grid-tied Solar Systems

Grid-tied solar systems have gained popularity in recent years as a means of reducing electricity costs and carbon emissions. These systems are connected to the main power grid and can feed excess electricity generated by the solar panels back into the grid. The integration of energy storage systems such as batteries can help to enhance the reliability and flexibility of grid-tied solar systems (Asadi et al., 2021).

However, challenges remain related to the intermittency and variability of solar energy, which can impact the stability and reliability of the power grid. Therefore, new approaches such as forecasting techniques and demand response programs are being explored to mitigate the impact of these challenges (Chicco, 2009).

Figure 4-2 indicates a solar photovoltaic system that consists of PV modules, an inverter, a filter control mechanism, etc. These electronic power converters, as well as the operation of non-linear devices, inject harmonics into the network. PV systems can also be unstable due to cloud cover or shading effects in terms of grid connection (Calleja and Jimenez, 2004). The inverter produces excessive harmonic currents having contamination of the electrical systems making the grid system abnormal and other equipment’s are also affected (Teodorescu et al., 2014).

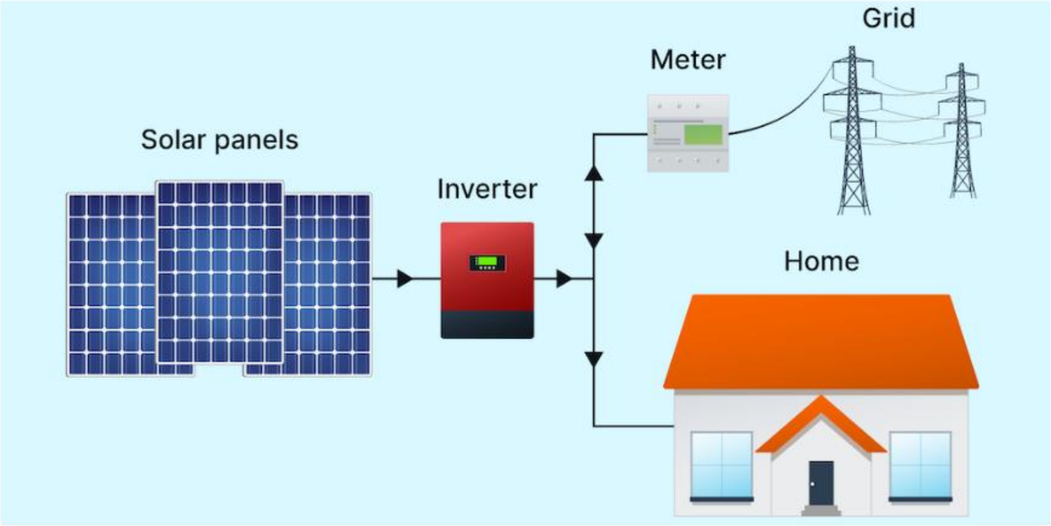

Figure 4-2: Grid tied PV system (Hyder, 2019)

4.5 Ancillary Services for Grid-tied Solar Systems

4.5.1 Introduction

A basic grid-connected PV inverter are not able to control the reactive and harmonic current drawn from non-linear loads (Bhattacharya, 2001). Vizoso et al. (2011) discuss a photovoltaic power unit that provides ancillary services for smart distribution networks. This controlling mechanism uses the PV system as an active filter to control the reactive and harmonic current by providing power to the network (Yao et al., 2022). Dong et al. (2019) discuss the provision of ancillary services by renewable hybrid generation in low-frequency AC systems to the grid.

Consideration should be made to the voltage profile and the control stream on the line. The inverter makes it simple to control real and reactive power output on demands, while hysteresis current control, used for the pulse width modulation (PWM) gating controlling, is simple and robust (Prakash et al., 2022).

4.5.2 Distributed static synchronous condenser

Distributed static synchronous condenser (DSTATCOM) are shunt-connected modified power devices particularly intended for power factor adjustment, current harmonics filtering and load balancing (Saleh et al., 2020).

Figure 4-3 indicates the micro grid that consists of several components, including a battery energy storage system, DSTATCOM, unbalanced load, linear inductive load, and nonlinear load. The presence of these diverse loads leads to compromised power quality, characterized by three-phase unbalanced currents, lagging power factor, and current harmonics. Additionally, the droop-controlled micro grid operates in islanding mode (Tan et al., 2022).

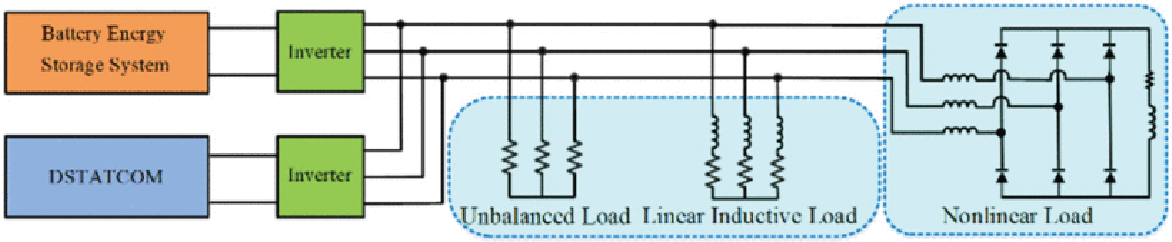

Figure 4-3: droop controlled micro grid with DSTATCOM and various loads (Tan et al., 2022)

4.5.3 Unified power quality conditioner

The PV system can use a Unified Power Quality Conditioner (UPQC) device that improves the power quality of an electrical network by providing compensation for voltage sags, voltage swells, and harmonics (Hosseinpour, 2009). The device functions as both a shunt and series active filter, effectively eliminating the voltage and current distortion present in the electrical grid. UPQC can improve the reliability and stability of the power system, enhance the performance of sensitive loads, and reduce the stress on the electrical equipment (Leon et al., 2011).

Figure 4-4 illustrates the connection of the two converters of UPQC in a back-to-back configuration, with one connected in series and the other in shunt to the power grid. This configuration enhances its suitability for voltage sag compensation by enabling internal energy exchange (Xu et al., 2016).

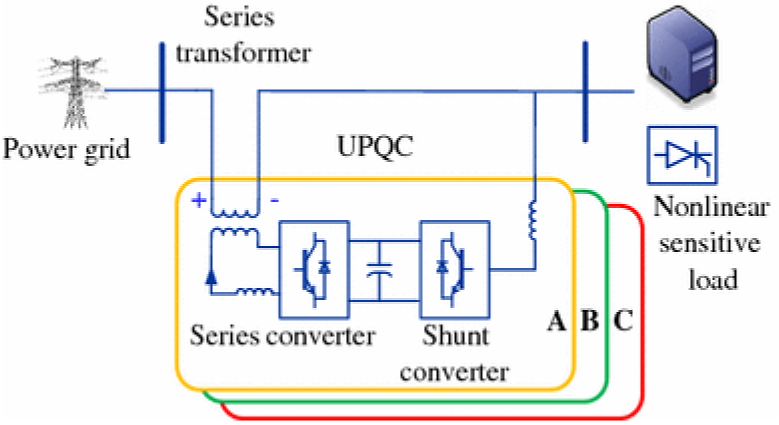

Figure 4-4: Structure of Unified Power Quality Conditioner (Xu et al., 2016)

4.5.4 Maximum power point tracking techniques

There are variations of maximum power due to solar radiation, ambient and solar cell temperature. Therefore, Maximum power point tracking techniques (MPPT) plays a vital role for modern PV systems to produce its maximum power as shown in Figure 4-5 (Femia, 2004). The MPPT relies on the temperature and irradiation conditions that change during the season of the year. Also when batteries are deeply discharged the MPPT can draw additional current to charge the battery (Motaleb, 2010).

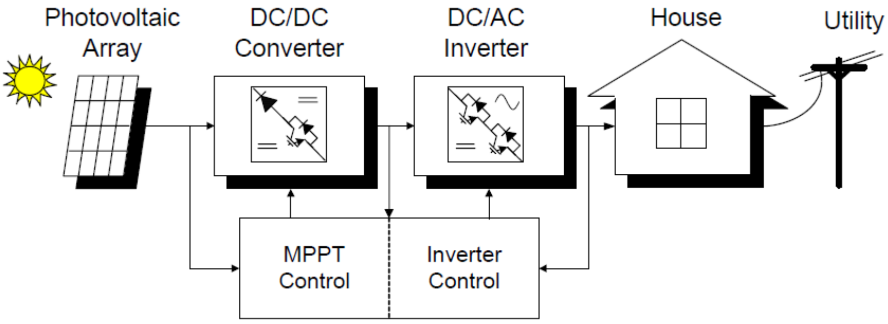

Figure 4-5: Maximum Power Point Tracking System (Motaleb, 2010)

4.5.5 Battery storage

Figure 4-6 illustrates how the production from photovoltaic units surpasses the energy consumption from 08:00 to 14:00, leading to a surplus of power that flows back into the substation. This surplus power causes overvoltage problems. Similarly, during the peak load period between 19:00 to 21:00, voltage issues occur. Figure 4 demonstrates that a Battery Energy Storage System is employed to address these problems by charging and discharging as needed, thereby mitigating overvoltage and under-voltage issues, respectively (Prakash et al., 2022).

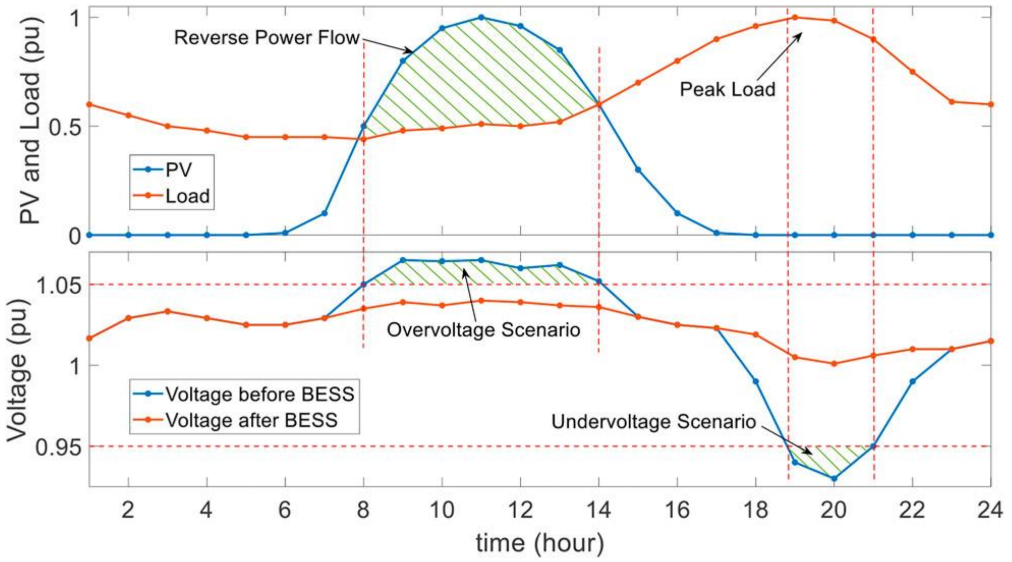

Figure 4-6: Typical application of BESS for mitigating overvoltage and under voltage issues (Prakash et al., 2022).

4.5.6 Voltage Q droop

Voltage Q droop is a technique used in PV systems to regulate the output voltage of a system. In a PV system, the output voltage of the system is determined by the amount of sunlight available and the electrical load connected to it (Idoko et al., 2018).

By using voltage Q droop, PV systems can maintain stable voltage levels even under changing load conditions. This is important in ensuring that the PV system can deliver consistent power output to the load and prevent any voltage fluctuations that may damage the load or the PV system (Tan et al., 2022).

P-Q-V Droop Control Method is well-suited for intricate line impedance systems, wherein both the line resistance and reactance hold equal importance, rendering neither negligible. Within such systems, the X/R ratio approaches unity, thereby rendering the P-f and Q-V droop techniques individually insufficient for governing the point of common coupling (PCC) voltage. Within this framework, alterations in voltage magnitude and phase angle difference concurrently impact both active and reactive power. Given the interplay between active and reactive power concerning voltage magnitude in such setups, the system can be mathematically depicted as expressed in equation (4.2) (Opiyo, 2018) :

$$\boldsymbol{V} = \boldsymbol{Vpcc} - (\boldsymbol{nL} * \boldsymbol{P}) - \boldsymbol{j}(\boldsymbol{mL} * \boldsymbol{Q}) \qquad (4.2)$$

Where $\mathbf{nL}$ and $\mathbf{mL}$ are the electric load droop coefficients while Vpcc is the voltage before compensation.

In summary, the additional functions and benefits that grid-tied solar power systems offer to support the stability, reliability, and efficiency of the electrical grid. This concept explores how grid-connected solar installations go beyond their primary role of generating electricity and provide essential services to the grid infrastructure. These services may include frequency regulation, voltage control, peak load reduction, grid reliability enhancement, grid management support, and compliance with regulatory standards and market mechanisms. Grid-tied solar systems play a crucial role in helping modern power grids accommodate renewable energy sources effectively, ensuring a sustainable and resilient energy future.

CHAPTER 5 Wind energy systems

5.1 Introduction

Wind energy is a form of solar energy that is generated by the wind through kinetic energy. Winds are formed from temperature shifts in the atmosphere from the sun, indiscretions surfaces and rotations from the earth. Wind turbines rotate at high wind speeds through a shaft using a gearbox to generate electricity (Dehghan et al., 2009). Du et al. (2016) proposed a method to examine the impact of grid connection of the DFIGs on power system electromechanical oscillation modes.

According to the International Energy Agency (IEA), wind energy has become the second largest source of new power generation capacity in the world, after solar energy (IEA, 2021). With its increasing cost competitiveness and environmental advantages, wind energy has become a promising solution for meeting the growing global energy demand and reducing greenhouse gas emissions (Sahinidis et al., 2020).

5.2 Background

The cumulative installed capacity of small wind turbines worldwide is estimated to be around 1.8 GW (Sheridan et al., 2022). Wind turbines have the capability to offer diverse ancillary services to the electrical grid. However, renewable generators like wind and solar have historically been restricted from providing substantial amounts of ancillary services, partly because of the fluctuating and unpredictable nature of their electricity generation. Rebello et al. (2020) explored ancillary services from wind turbines, particularly automatic generation control from a single type 4 turbine. Sheridan et al. (2022) validated wind resource and energy production simulations for small wind turbines in the United States.

5.3 Wind energy operating principles

Wind energy is the kinetic energy of wind harnessed and converted into electricity using wind turbines. Lee and Fields (2021) provided an overview of wind-energy-production prediction bias, losses, and uncertainties. The efficiency of this process depends on various factors such as wind speed, turbine design, and electrical system configuration.

The equation (5.1) for the wind power at location $\boldsymbol{A}$, perpendicular to the direction of blowing the wind is given by the formula (Dehghan et al., 2009):

$$\boldsymbol{P = \frac{1}{2} p A C_p v^3} \tag{5.1}$$

Here, $\boldsymbol{P}$ is the power, ρ is the air density, v is the wind speed and Cp is the power coefficient, which represents the proportion of wind that can be caught by the wind turbine.

5.4 Wind energy systems connected to the grid

Figure 5-1 depicts a simplified diagram illustrating various types of wind energy systems. From a design standpoint, certain generators are directly linked to the grid via a dedicated transformer, while others incorporate power electronics. Many designs also integrate power electronics to enhance control and operational range. Irrespective of the connection configuration, each turbine has an impact on the power quality of the transmission system (Li et al., 2022, Khadem et al., 2010).

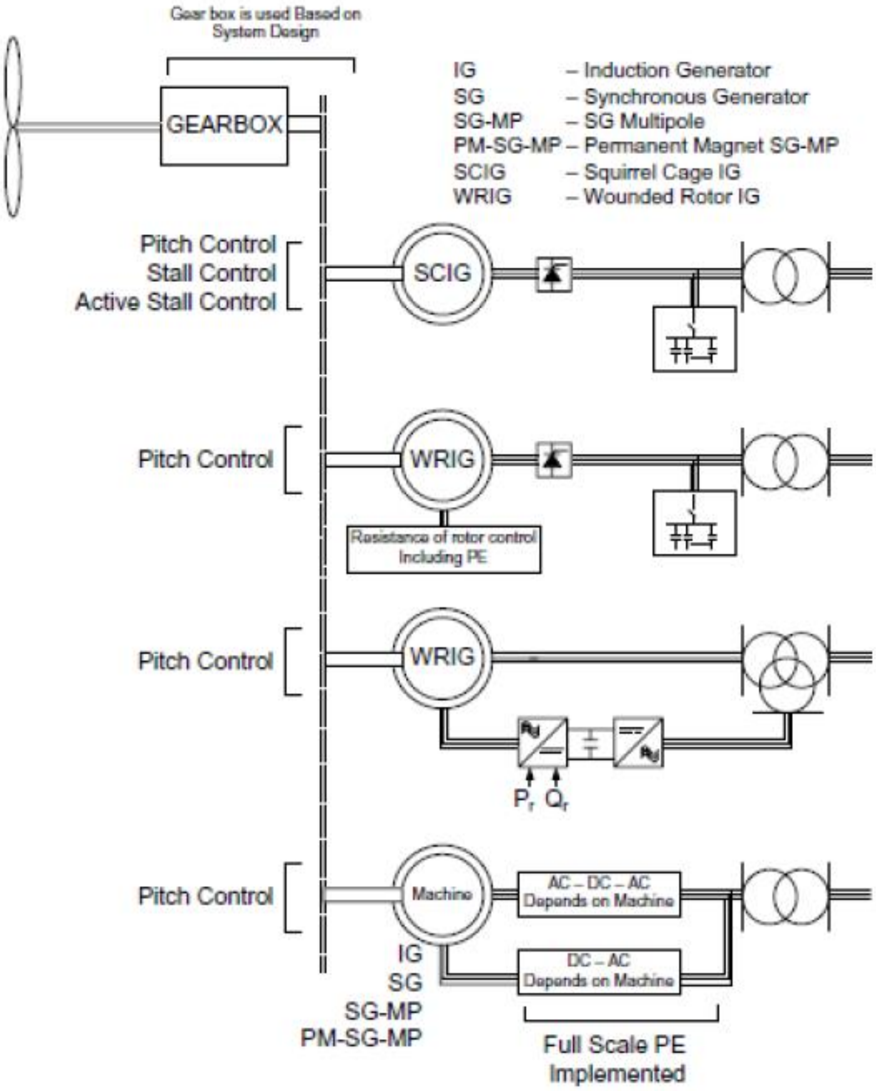

Figure 5-1: Different types of wind energy system (Khadem et al., 2010)

5.5 Ancillary Services for Grid-tied Wind Energy Systems

5.5.1 Introduction

Wind energy systems contributing ancillary services include the services needed to ensure the stability and reliability of the grid while incorporating wind energy into the mix. Rebello et al. (2019) explore the automatic generation control (AGC) capabilities of a single Type 4 wind turbine for providing ancillary services.

Wind energy systems are inherently variable, and the amount of power they generate can fluctuate depending on wind speed and other factors (Holttinen, 2012; Rebello et al., 2020). This variability can make it difficult to maintain the stability of the power grid, which requires a constant balance of supply and demand (Hodge and Lesieutre, 2010).

Energy storage systems, such as batteries, are used to store excess wind energy for use during periods of low wind speeds. Demand response programs allow customers to adjust their electricity usage based on grid conditions, reducing the need for ancillary services. Flexible generators, such as natural gas-fired power plants, are used to provide backup power when wind energy production is low (Carvalho, 2019).

5.5.2 Virtual synchronous machine

The virtual synchronous machine (VSM) method is mostly utilized for frequency control due to its ability to add virtual inertia to control power-electronic device-based systems (Dewenter et al., 2016).

Wind farms with fixed speed induction generators (FSIG) have to be phased out because they cannot offer the required voltage or frequency control (Li, 2022). An overview of the developed controllers for the converter of grid connected system has also been discussed according to the research conducted by Blaabjerg et al. (2006). These generators can also support the system during voltage sags (Wenle et al., 2022; Blaabjerg et al., 2006).

5.5.3 Static synchronous condenser

The utilization of Static synchronous condenser (STATCOM) has been previously documented in wind power applications for enhancing stability and addressing transient and flicker issues. However, the conventional STATCOM is limited to operating in leading and lagging modes (Khadem et al., 2010).

The STATCOM is typically composed of a voltage source converter (VSC) and a DC capacitor, which allows the device to produce or absorb reactive power as needed. The reactive power provided by the STATCOM is proportional to the square of the voltage at the point of connection, which means that it can respond quickly to changes in the grid voltage. The ability to provide reactive power in this way can help to stabilize the grid voltage and improve power quality (Khadem et al., 2010).

In summary, the supplementary functions and benefits that wind energy systems connected to the electrical grid offer to enhance grid performance. This concept encompasses the ways in which grid-tied wind installations go beyond their primary purpose of generating electricity and provide critical services to improve the stability, reliability, and efficiency of the power grid. These services may include frequency regulation, voltage support, power factor correction, reactive power control, and participation in demand response programs. Grid-tied wind energy systems play a pivotal role in helping modern power grids effectively integrate renewable energy sources, ensuring a sustainable and resilient energy future while supporting grid reliability and resilience.

CHAPTER 6 **Methodology**

6.1 **Introduction**

The simulation uses PowerFactory and models a small local grid that includes a solar PV energy system, step-down transformers, feeders, and consumer loads. The simulation includes a number of consumer loads, such as homes, businesses, and industrial facilities that draw power from the grid. These loads are modelled using power consumption profiles, which represent the amount of power they consume over time.

Quasi-dynamic simulation will be utilised and is a type of power system simulation used in PowerFactory, a software package commonly used for analysing and simulating electrical power systems. In quasi-dynamic simulation, the electrical network is modelled using time-varying parameters and dynamic models, but the simulation is carried out in a series of steady-state steps, rather than as a continuous time-domain simulation.

The simulation is used to test different scenarios, such as changes in the amount of power generated by the PV system, changes in the power consumption of consumer loads and changes in the configuration of the distribution network. The application of voltage Q droop will be implemented for one of the scenarios as well.

Overall, the simulation provides a valuable tool for understanding the behaviour of local grids that incorporate solar PV systems, step-down transformers, cables, and consumer loads, and can help to monitor their performance and increase their efficiency.

6.2 **Base Case**

By simulating the behaviour of the grid under the base case scenario, the model can provide a baseline for comparison with other scenarios that involve changes or disturbances to the system. Overall, the base case of a grid simulation model provides a starting point for understanding how the system typically behaves, and will help to identify areas where improvements or changes may be needed to ensure reliable and efficient operation.
A few standard component models are chosen from PowerFactory library in displaying the framework for the examinations.

6.3 Network components

6.3.1 Busbars

The network consisted of ten busbars with their respective voltages that are used in the simulation to model to distribute power in electrical circuits. The busbars voltages are modelled as ideal conductors that have zero resistance and parameters as shown in Table 6.1.

Table 6.1: Busbar parameters

Name	Nom.L-L Volt.
	kV
HV Busbar	132
LV Hospital Busbar	0.4
MV Commercial Busbar	11
LV Residential Busbar	0.4
LV Comercial Busbar	0.4
Secondary Busbar	11
MV Residential Busbar	11
Primary Substation Busbar	11
LV Industrial Busbar	0.4
Mixed Load Busbar	11

6.3.2 Transformers

Simulating the transformers involves creating a mathematical model that represents the behaviour of the transformer. The model can be used to predict the transformer's response to different input conditions, such as changes in voltage and load. The parameters of the transformers are shown in Table 6.2 that includes the type, HV (High Voltage), LV (Low Voltage) and apparent power.

Table 6.2: Transformers parameters

Name	Type	HV-Side	LV-Side	Snom(act.)
	TypTr2			MVA
HV Transformer	10 MVA 132/11 Standard	HV Busbar	Primary Substation Busbar	10
MV Transformer 1	2 MVA 11/0.4 kV	MV Residential Busbar	LV Residential Busbar	2
MV Transformer 2	2 MVA 11/0.4 kV	MV Commercial Busbar	LV Commercial Busbar	2
MV Transformer 4	2 MVA 11/0.4 kV	Mixed Load Busbar	LV Hospital Busbar	2

MV Transformer 3	2 MVA 11/0.4 kV	Mixed Load Busbar	LV Industrial Busbar	2

6.3.3 Cables

Simulating cables for load flow analysis involves modelling the cable as an electrical circuit and calculating the electrical parameters of the circuit. These parameters include the type, length, derating factor, Earth resistivity and nominal current the cables shown in Table 6.3.

Table 6.3: Cable parameters

Name	Type	Length	Derating F.	Earth resistivity	Inom(act.)
		km		Ohm*m	kA
Line 1	300 Al 3C PILC 11kV	0.6	1	100	0.34
Line 2	120 Al 3C PILC 11 kV	0.3	1	100	0.205
Line 4	120 Al 3C PILC 11 kV	1	1	100	0.205
Line 3	120 Al 3C PILC 11 kV	0.4	1	100	0.205

6.4 Modelling of Consumer Load data

General loads were populated in the same way with the real power, reactive power and per unit voltages for load flow analysis. The load profiles used in this model represents weekly load curves of typical consumers on a single feeder. The data makes use of 30-minute average data that have active and reactive power values. The energy consumption for a period of a week between 01/04/2018 - 08/04/2018 will be used starting from Saturday to Friday. The data will consist of a residential, industrial, commercial and hospital load profiles.

This approach allows for a compromise between the accuracy of dynamic simulation and the computational speed of steady-state simulation. In quasi-dynamic simulation, the electrical network is partitioned into smaller sections, and the system is analysed in a step-by-step fashion, with each step representing a short time interval during which the electrical network is assumed to be in a quasi-steady-state condition.

The quasi-dynamic simulation approach is often used in power system planning and design studies, as it allows for the evaluation of the long-term behaviour of the power system under different operating conditions and scenarios. It can also be used for the analysis of transient stability, voltage stability, and other dynamic phenomena in the power system.

6.4.1 Residential weekly load profile

When designing a residential load, it's important to consider factors such as occupancy patterns, appliances, and heating and cooling loads, as outlined by Sharma and Singh (2014).

Figure 6-1 indicates the load profile following a Residential weekly load profile:

- Morning: Energy demand is low during the early hours of the morning when most occupants are sleeping. Energy consumption may start to increase as occupants wake up and begin to use appliances such as electric kettles, coffee makers, and toasters for breakfast.
- Daytime: Energy demand may increase during the day as occupants leave for work or school. Energy consumption may be low during this period, with occasional use of appliances such as refrigerators, electric water heaters, and air conditioning systems.
- Evening: Energy demand may start to increase in the evening as occupants return home and start using appliances such as televisions, computers, and lighting. Energy consumption may peak during the dinner period when occupants use cooking appliances such as ovens and microwaves.
- Night-time: Energy demand may start to decrease in the late evening as occupants start to wind down and prepare for bed. Energy consumption may be low during this period, with occasional use of appliances such as televisions, computers, and lighting.

Overall, the residential load profile may be characterized by a peak in energy demand during the evening period, with lower energy consumption during the morning and night-time periods. The populated residential loading is shown in Figure 6-1 with peak loads over 0.8 MVA and reactive power between 0.2 and 0.26 Mvar.

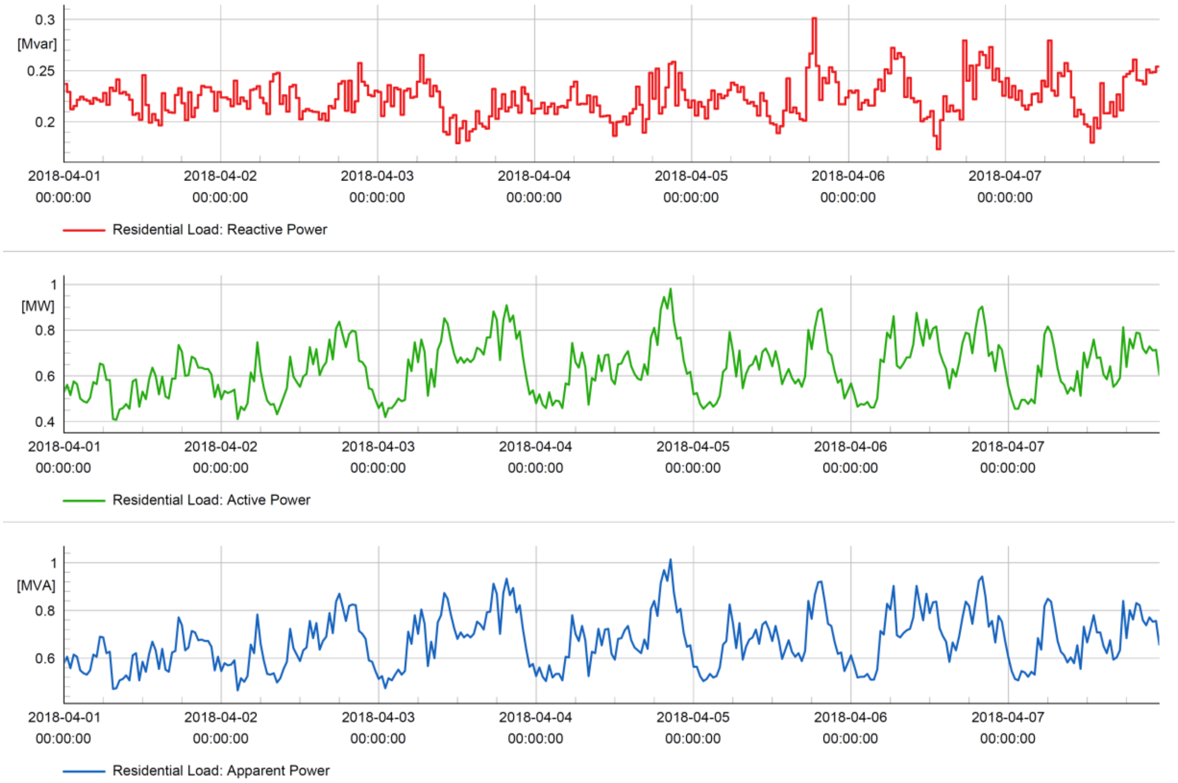

Figure 6-1: Residential Load simulation

6.4.2 Industrial weekly load profile

When designing an industrial load, it's important to consider factors such as load profile, equipment types, and power quality (Sharma and Singh, 2014). A general industrial load profile for the day can vary depending on the specific industry and the processes involved.

Figure 6-2 indicates a typical industrial load profile:

- Early morning: As workers arrive and begin their tasks, the industrial load starts to increase. Machines are powered on, heating and cooling systems are activated, and lights are turned on. The load may reach its peak during this time as production begins.
- Morning: The load generally remains high during this time as production continues. However, there may be some fluctuations depending on the type of industry and the specific processes involved.
- Lunchtime: The load may decrease slightly during this time as some machines are turned off for lunch breaks, and workers may use less energy.
- Afternoon: The load generally remains high during this time as production continues, but there may be some fluctuations depending on the type of industry and the specific processes involved.

- Weekends: The factory will be closed until the next week.

An industrial load profile refers to the pattern of electricity consumption by an industrial facility over a certain period of time, typically measured in hours, days, weeks, or months. The specific profile of electricity usage by an industrial facility can be seen in the output graph in Figure 6-2 with constant peak loads between 0.9 and 1.2 MVA also reactive power between 0.1 and 0.25 Mvar.

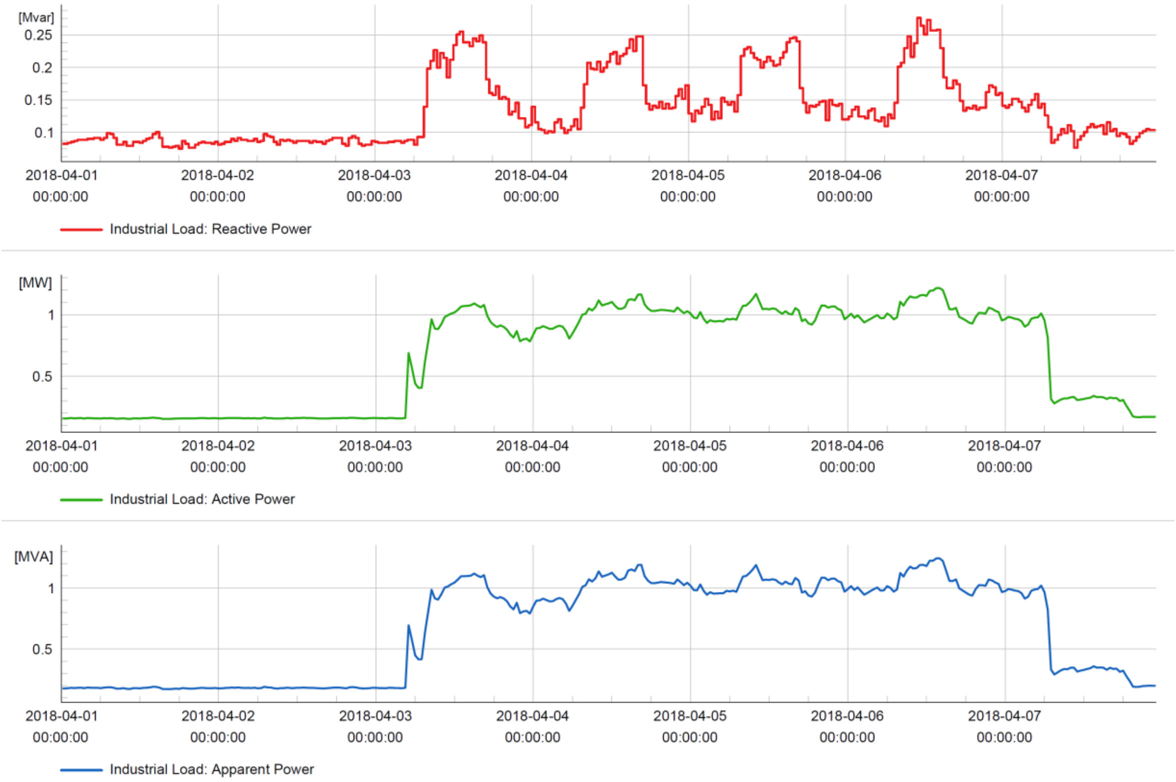

Figure 6-2: Industrial load simulation

6.4.3 Commercial weekly load profile

A general Commercial load profile for the day can vary depending on factors such as location, store size, customer traffic, and season (Sharma and Singh, 2014).

Figure 6-3 indicates typical patterns, load profile for a Commercial:

- Early morning: During the first few hours after opening, the store is relatively quiet, with few customers in the aisles. At this time, the load is relatively low as only the essential equipment such as refrigerators, lights, and cash registers are running.

- Mid-morning to noon: As the morning progresses, more customers begin to arrive, and the store becomes busier. This is usually the peak shopping period, with high customer traffic and increased demand for cooling and lighting. The load on refrigerators, freezers, air conditioning, and lighting, in particular, can increase significantly during this time.
- Afternoon to early evening: After the lunch rush, the store may experience a temporary lull in customer traffic. However, as the day progresses, more customers arrive, especially after work hours. The load on refrigeration and lighting typically remains high during this period, although the demand for air conditioning may decrease as the outdoor temperature drops.
- Late evening: As the store approaches closing time, the load begins to decrease as customers finish their shopping and leave the premises. Most stores typically close between 8 pm and 10 pm, depending on the location and store policies. After closing time, the load gradually decreases as the essential equipment is powered down, and the store becomes quieter.
- Overnight: During the night, the store is closed, and the load is minimal, with only a few essential systems such as security, refrigeration, and lighting running.

Figure 6-3 shows the reactive, active and apparent load duration curve of a Commercial for the duration of a week with four distinct peak loads over 1 MVA and reactive power between 0.2 and 0.3 Mvar.

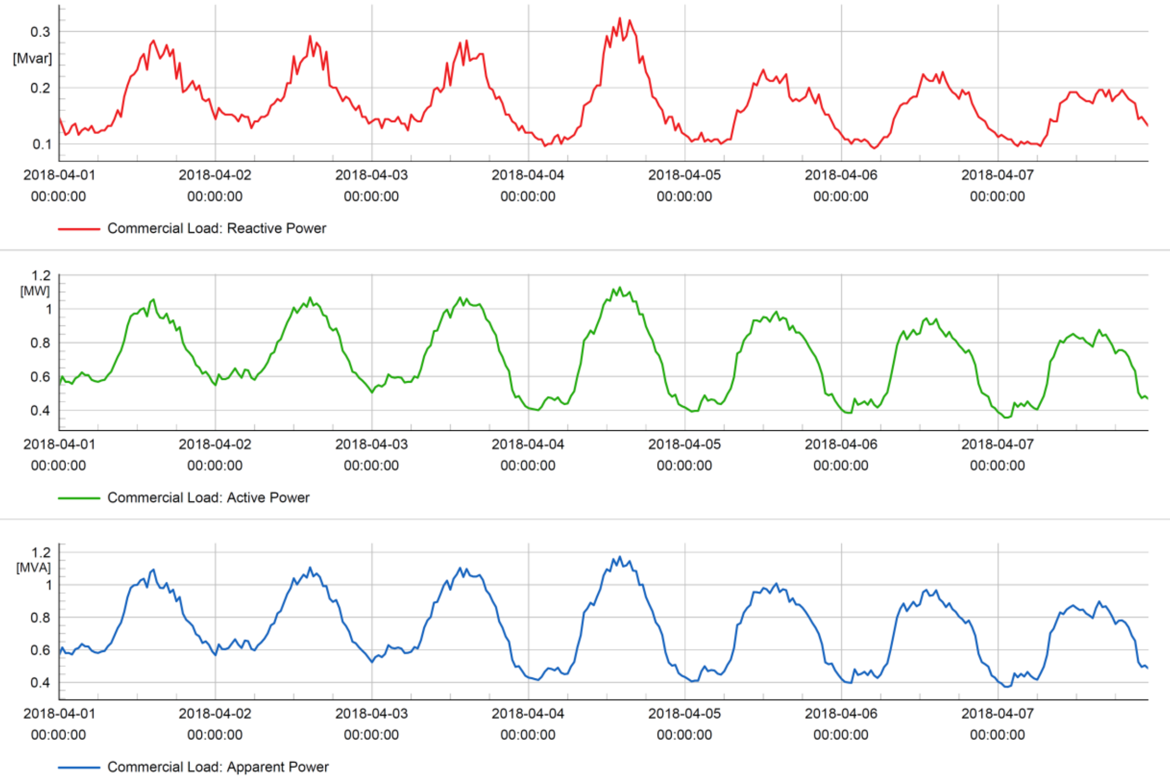

Figure 6-3: Commercial load simulation

6.4.4 Hospital weekly load profile

When designing a hospital load, it's important to consider factors such as peak demand, critical loads, and backup power systems (Sharma and Singh, 2014).

Figure 6-4 indicates a weekly hospital load with some general considerations:

- Patients based on the size of the hospital and the area it serves. This could be determined by researching the demographics of the surrounding community.
- Hospital has basic facilities such as operating rooms, patient rooms, emergency department, laboratory, and radiology. The number and size of each facility can be determined based on the hospital's size and the expected patient load.
- Sufficient number of medical professionals to handle the patient load. This could be based on the number of patients and the number of medical professionals required to treat them.
- Basic medical equipment such as diagnostic machines, hospital beds, and other medical supplies. The number and size of equipment can be determined based on the expected patient load.

Figure 6-4 given below shows the load duration curve of a hospital over the period of seven days indicating three distinct peak loads over at 1.4 MVA.

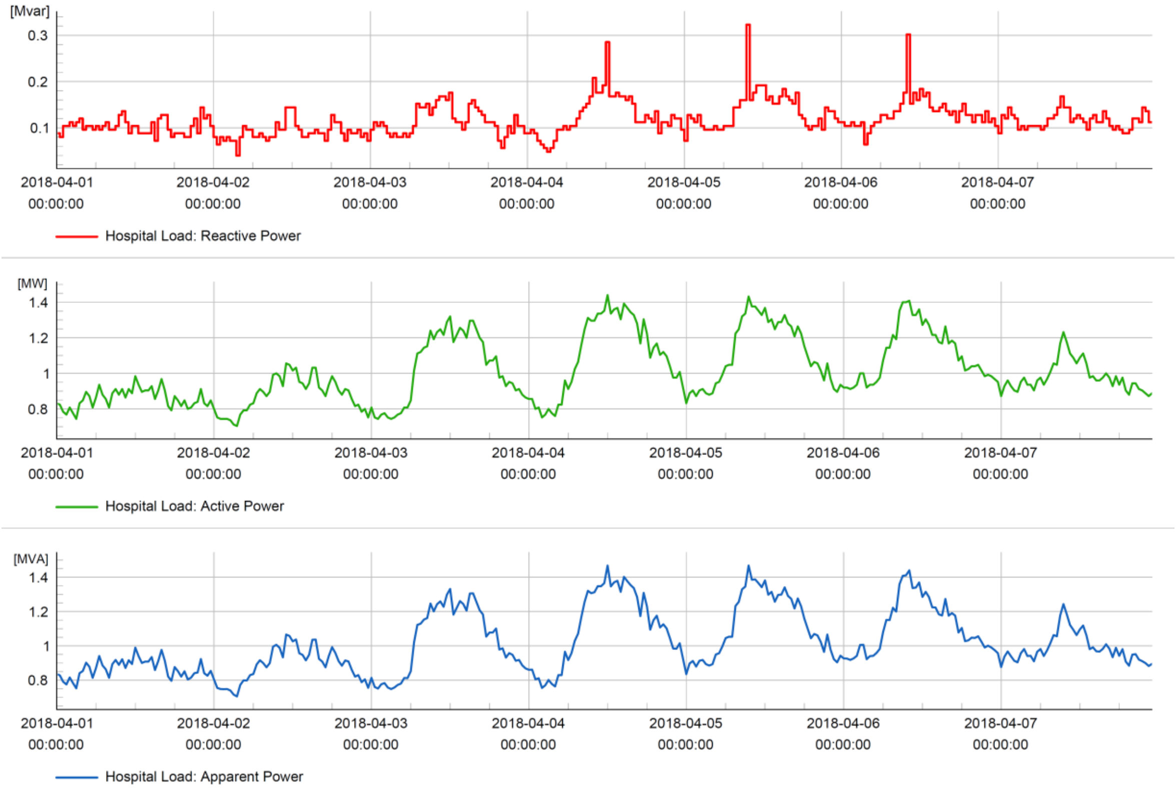

Figure 6-4: Hospital load simulation

6.5 External Grid

The external grid is represented by its equivalent circuit and parameters, such as its short-circuit levels, load flow characteristics, and fault behaviour. The external grid modelling is essential for the accurate simulation of large-scale power systems, especially in cases where the power system under study is a substation or a distribution network connected to the transmission grid. Figure 6-5 indicates the total output load of the Grid that has four distinct peak loads over 4 MW.

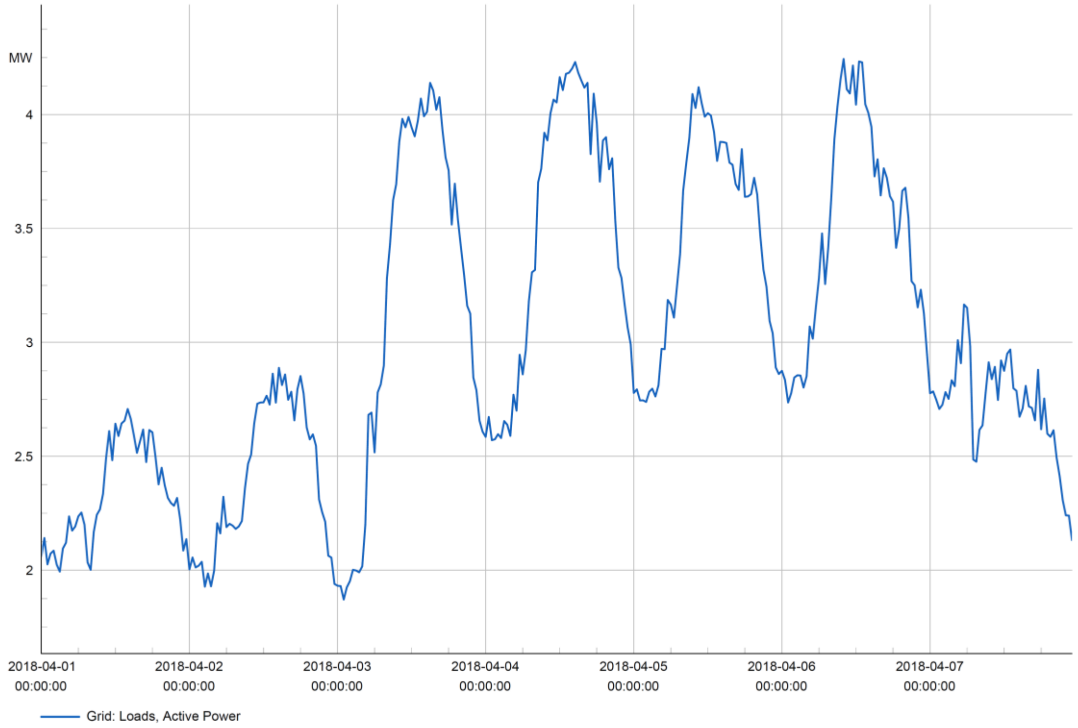

Figure 6-5: Grid output load simulation

6.6 Distribution grid model

Figure 6-6 indicates the base case simulation model with the External grid, cables, busbars, transformers and various operating loads conditions. The modelled data consists of a residential, industrial, commercial and hospital load profiles. This includes assessing the system's ability to handle varying load demand and the integration of Distributed Energy Resources (DERs).

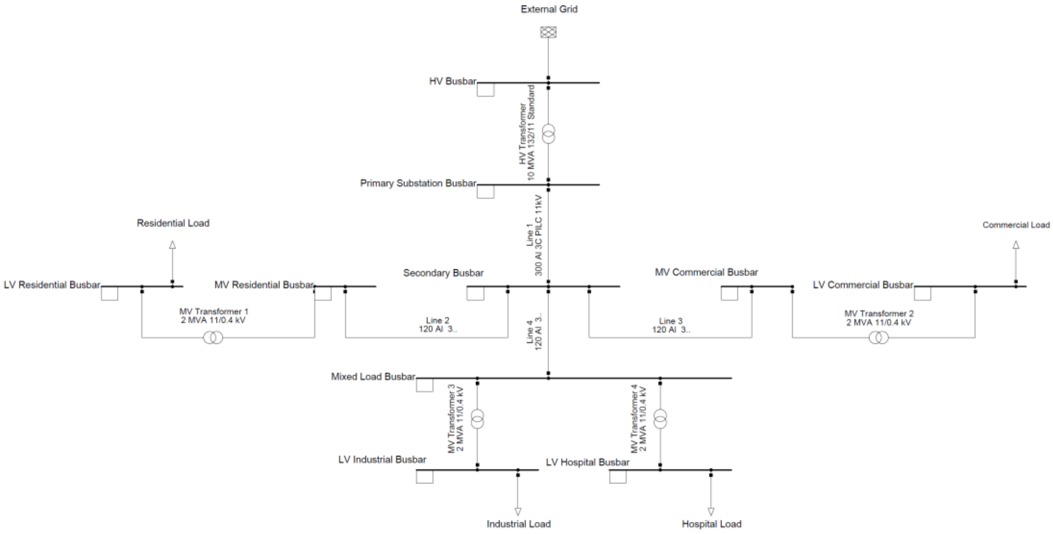

Figure 6-6: Base case simulation model

6.7 Modelling of PV Energy System

6.7.1 PV Parameters

Modelling a PV system simulation involves creating a computer-based model that simulates the behaviour of a PV system. The PV system typically consists of PV panels, an inverter, and other components such as batteries, charge controllers, and monitoring systems. The simulation model can be used to analyse the performance of the PV system under different operating conditions, such as varying solar irradiance levels and temperature conditions. Table 6.4 indicates the parameters of each PV system.

Table 6.4: PV system parameters

Name	Type	Terminal	Model	Par.no.	Pan.no.	App. Pow.	Pow. Fact.	Tilt Angle	Efficiency Factor
	TypPv panel					kVA		deg	%
PV System - Industrial	YL280P-35b	LV Industrial Busbar	Solar Calculation	100	52	1000	0.8	30	95
PV System - Commercial	YL280P-35b	LV Commercial Busbar	Solar Calculation	100	55	1000	0.8	30	95
PV System - Residential	YL280P-35b	LV Residential Busbar	Solar Calculation	100	49	1000	0.8	30	95

PV System - Hospital	YL280 P-35b	LV Hospital Busbar	Solar Calculation	100	60	1000	0.8	30	95

6.7.2 PV system output

Figure 6-7 shows the PV system simulation model includes mathematical equations that describe the physical behaviour of the components. Figure 6-7 also indicates the active, apparent and reactive power value that can be automatically calculated, given the data of the solar panel type, the arrangement of the solar array, and optionally irradiance data, with the option Solar Calculation for the week.

Figure 6-7: PV output curves

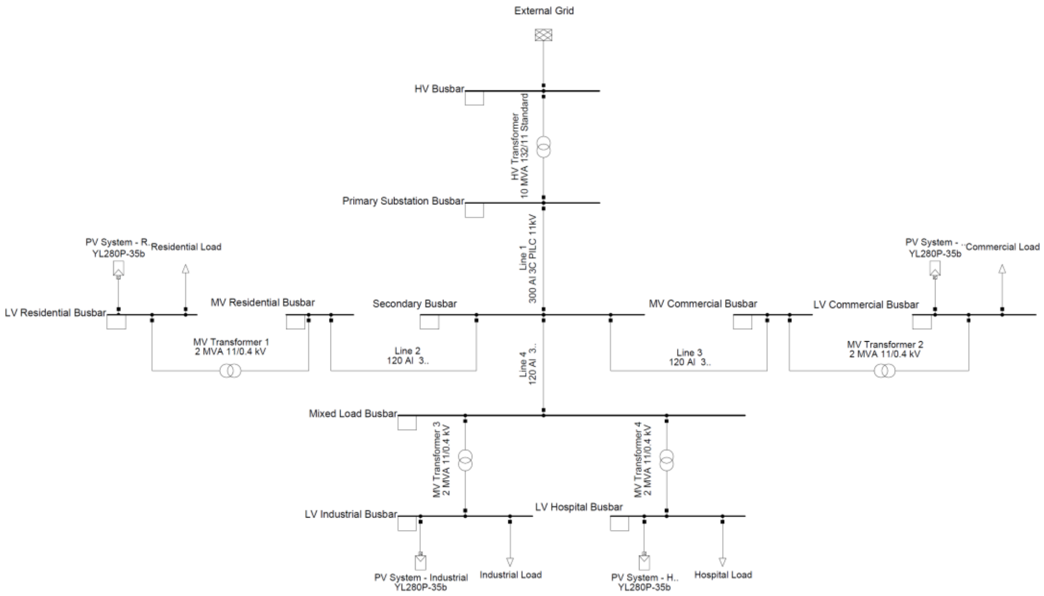

Figure 6-8: PV system

CHAPTER 7 Results

7.1 Introduction

This chapter analyses the results obtained from the network model simulated in PowerFactory. Simulating PV systems to determine their potential for providing ancillary services is a complex and challenging task that requires a deep understanding of both power systems and PV technology. However, it is also an area of research that is becoming increasingly important as more renewable energy sources are integrated into the power grid.

7.2 Base case

The normal operating conditions of the simulation model outputs will be addressed. The base case refers to a scenario where all the parameters and inputs of the model are set to their baseline values, which are typically based on historical data or assumptions about the system being modelled.

By comparing the results of the base case to the results of different scenarios with modified parameters or inputs, analysts can assess the potential effects of changes on the system being modelled. The base case is an essential component of any simulation model, as it provides a benchmark for evaluating the accuracy and usefulness of the model's predictions.

7.2.1 Bus voltages

Figure 7-1 below indicates the base case HV, MV and LV busbar voltages for maximum and minimum values that are all below 1 p.u. Operating at a voltage lower than the rated voltage can have various implications for the performance and safety of the electrical system. It can affect the efficiency of the equipment, cause voltage drop, and affect the quality of power supplied to the loads. Therefore, it is important to monitor and maintain the busbar voltages within their rated values to ensure the reliable and safe operation of the electrical system.

Figure A - 3 shown in Appendix A indicates the weekly voltage bus profile of the different consumers and busbars depending on their power consumption patterns and needs.

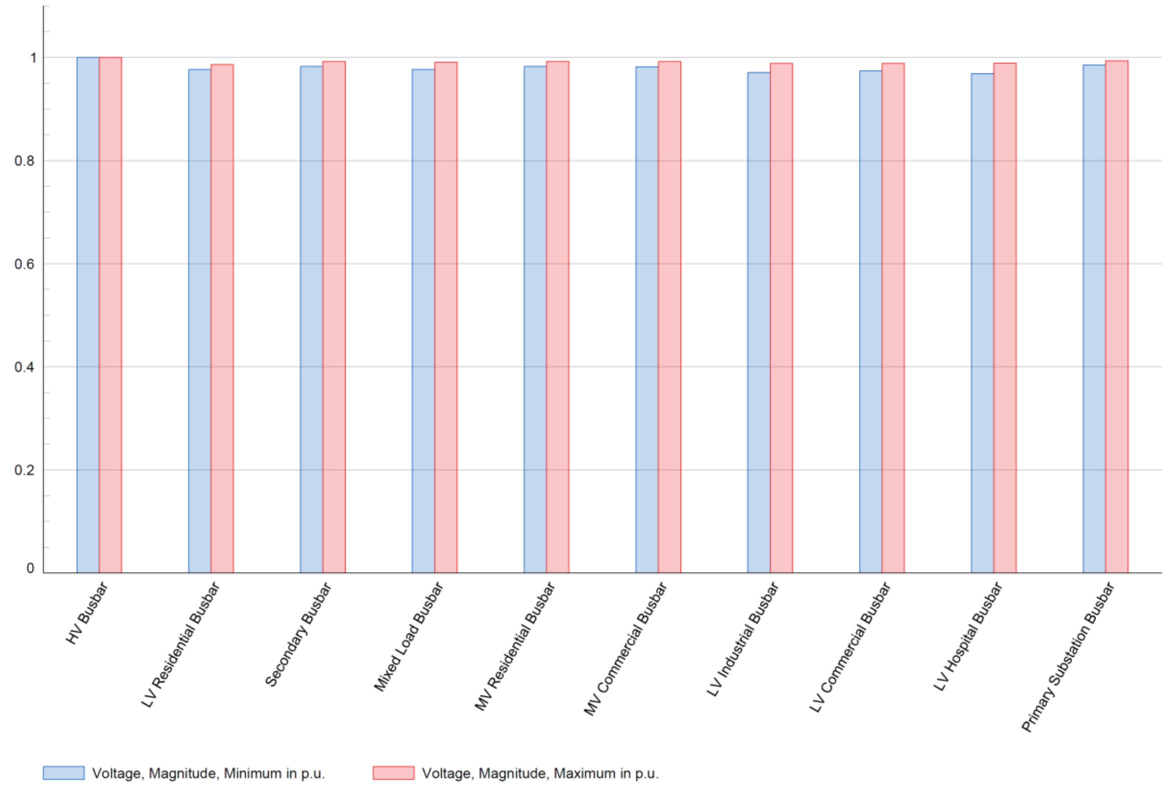

Figure 7-1: Base case busbar voltages

7.2.2 Cable output weekly profile

Figure 7-2 below indicates the base case cable loading in the simulation refers to the amount of current flowing through it. This level of loading is generally considered to be safe and reliable. When cables operate over 60% of their loading capacity, it can cause various issues that affect the safety and reliability of the electrical system. If a cable is carrying current that is over 60% of its rated capacity, it is said to be operating at a high load.

Figure A - 1 in Appendix A indicates the total electrical load on the cable can that fluctuate throughout the week. Typically, the highest load occurs during the day when people are awake and active, and there is a higher demand for electricity to power appliances, lighting, and other devices. The load may also increase during extreme weather conditions, such as heat waves or cold snaps, when people use more electricity for heating and cooling.

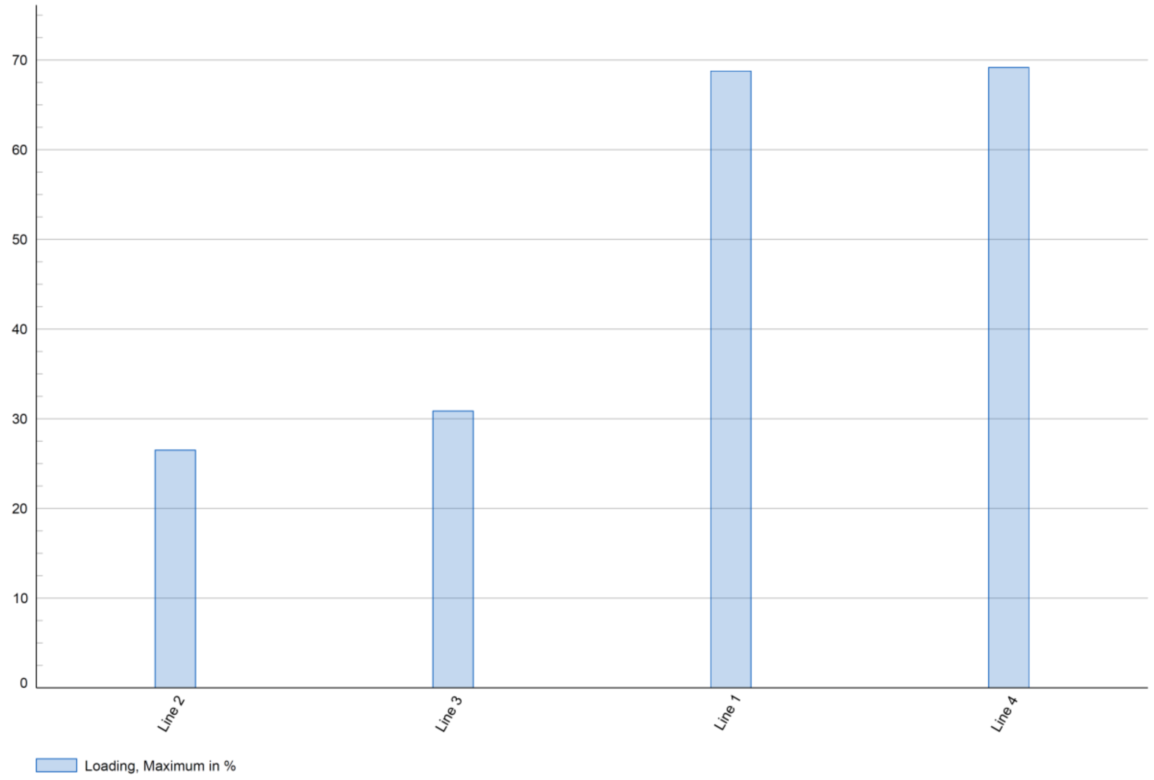

Figure 7-2: Base case cable loading

7.2.3 Transformer loading

Figure 7-3 indicates the base case transformer loadings of the simulation. MV Transformer 4 is the highest peaking transformer and operating at 70% of its loading capacity, it means that it is carrying a significant amount of power but is still operating within its rated capacity. This level of loading is generally considered to be safe and reliable for the transformer.

Figure 7-3 also indicates transformers above 50% loading for extended periods of time can still have some consequences. One of the main issues is increased heat generation. Transformers are designed to dissipate heat generated by the flow of electrical currents, but when operating at higher loads, more heat is generated. This can cause the transformer's insulation to degrade over time, leading to potential faults or failures.

Figure A - 2 shown in appendix A indicates the amount of power that is loaded onto each transformer for the demand from the different consumers that are connected to it. The weekly transformer loading varies depending on the type of consumers that are connected to it.

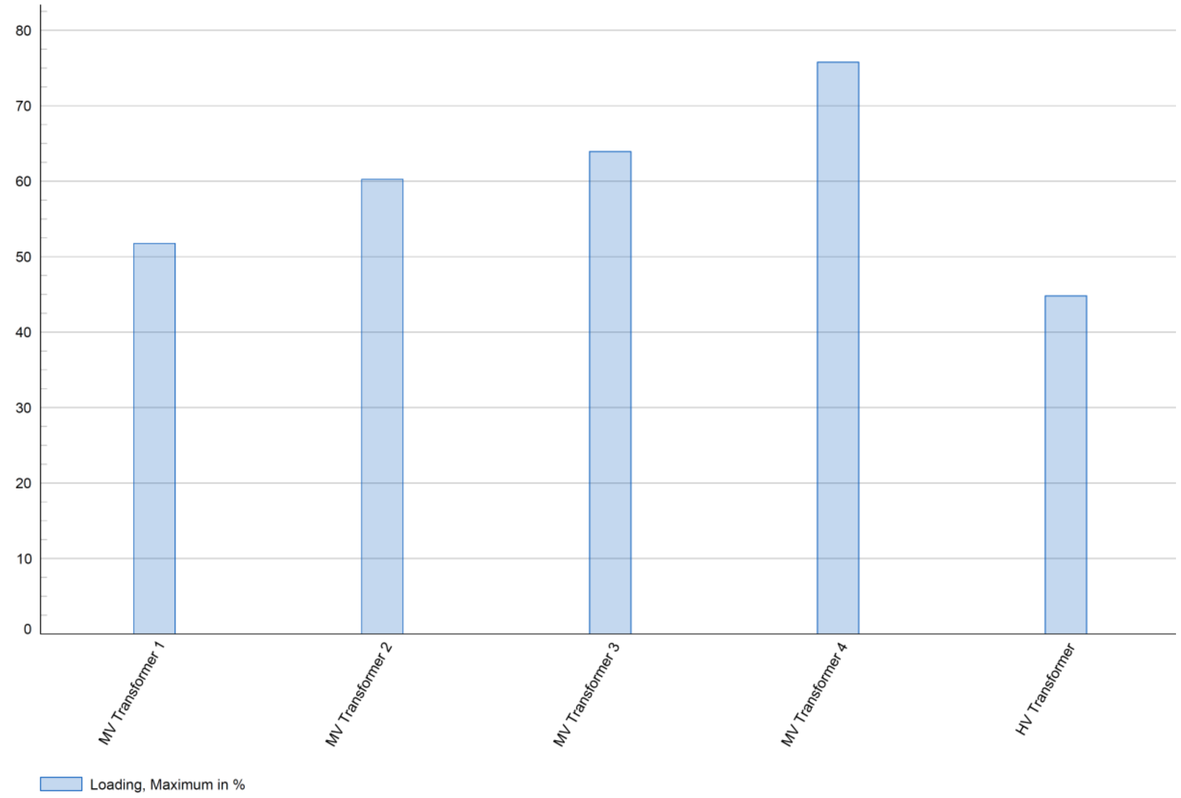

Figure 7-3: Base case transformer loading

7.3 Scenario 1: PV system added

7.3.1 Busbar Voltages

Figure 7-4 indicates a slight increase in minimum and maximum voltage compared to the base case voltage results in Figure 7-1. On the positive side, when a PV system is generating power and injecting it into the electrical grid, it can help increase the voltage in the system if needed. This is because PV systems generate power at the same voltage level as the grid, so they can help to balance the supply and demand of power and reduce voltage fluctuations.

Figure B - 4 shown in appendix B indicates weekly voltage profile of the consumers with the PV system connected to a bus that supplies power to a load, the voltage profile of the bus can be affected by the PV system. The output voltage of the inverter factors such as the amount of sunlight available, the efficiency of the PV cells, and the load connected to the system. The inverter will try to maintain the voltage within a certain range by adjusting its output voltage.

If the PV system is generating more power than the load is consuming, the excess power might be fed back into the grid. This can cause the voltage at the bus to rise, which could affect other loads connected to the same grid. To prevent this from happening, the inverter might reduce its output voltage or limit the amount of power it feeds into the grid.

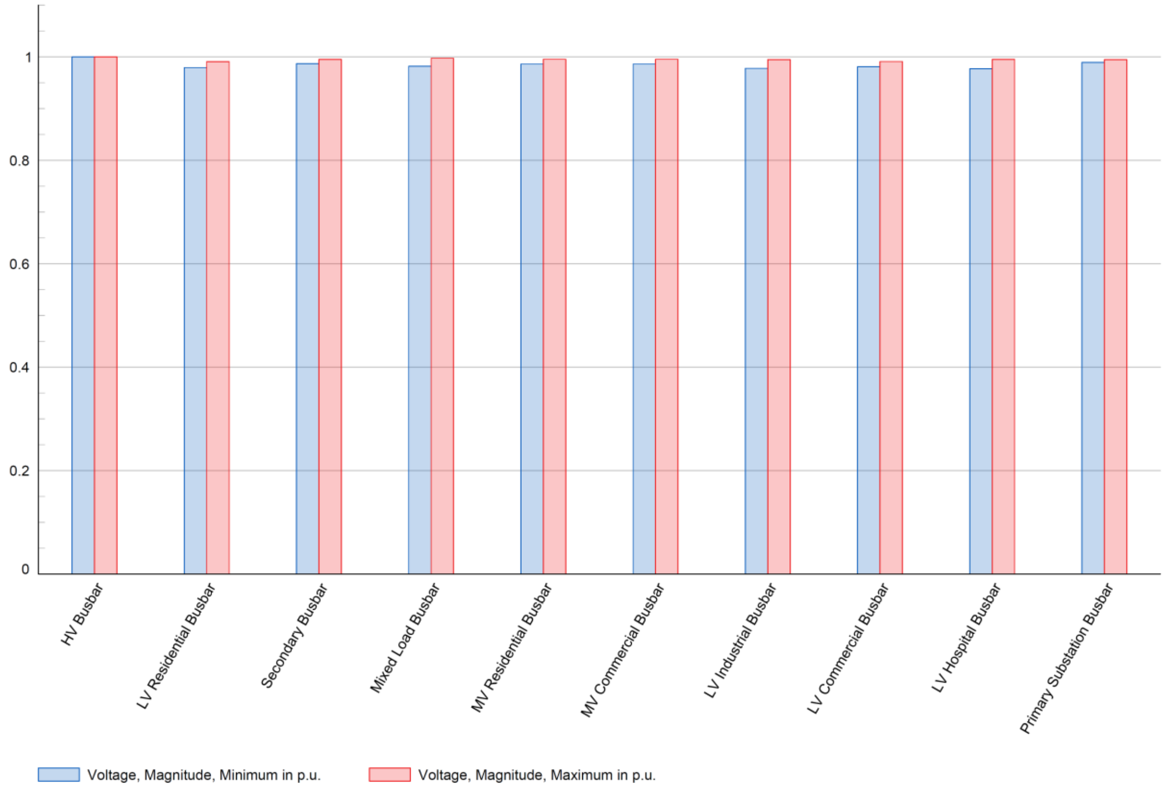

Figure 7-4: Scenario 1 busbar voltage with PV added

7.3.2 Cable loading

Figure 7-5 indicates a decrease in maximum cable loading compared to the base case in Figure 7-2. The reduced demand may lead to a decrease in the current flowing through the cables. When current decreases, the heating effect on the cables may also decrease, reducing the temperature rise in the cables. This may allow cables to operate at higher loading than before, as long as the loading stays below the maximum safe operating limit. The cables may be able to handle more electrical load with a PV system installed, since the overall demand on the system is reduced.

Figure B - 2 shown in Appendix B indicates the cable loading throughout the week with a PV system installed. The PV system can generate electricity during daylight hours, which can reduce the amount of power drawn from the grid and subsequently reduce the loading on the cable. The PV system begins to generate electricity as the sun rises. As the day progresses, demand increases, but the PV system continues to generate power. This means that the cable is under less stress as the PV system is supplying a portion of the electricity needed.

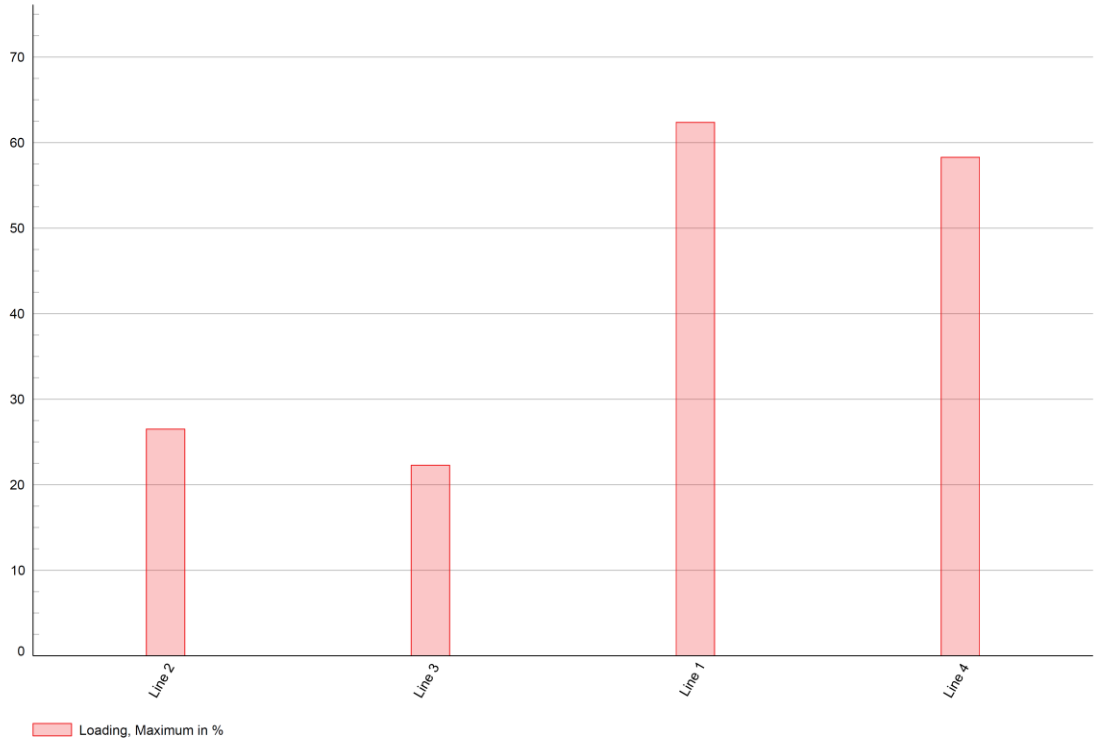

Figure 7-5: Scenario 1 cable loading with PV system added

7.3.3 Transformer loading

Figure 7-6 indicates a reduction of loading on the transformers compared to the base case in Figure 7-3. The PV system have a reducing effect on transformer loading. This can occur when the PV system is generating power during peak demand periods, which reduces the overall demand on the transformer. This can help to reduce the loading on the transformer, potentially increasing its lifespan and improving its efficiency.

Figure B - 3 shown in Appendix B indicates the transformer's weekly loading profile with a PV system installed. The loading is influenced by a variety of factors, including the demand for power, the availability of energy sources, and the capacity of the transformer itself. However, when a PV system is connected to the bus, it can have a significant impact on the transformer's loading profile.

The PV system generates electricity during the day when the sun is shining, and this electricity is typically fed directly into the grid. As a result, the transformer may experience a higher loading during the daytime hours when the PV system is generating power. This may cause the transformer to reach its maximum capacity during these peak periods, which can lead to overloading and potential damage if the transformer is not appropriately sized. On the other hand, during the night-time hours when the PV system is not generating power, the transformer may experience a lower loading profile. This can provide some relief to the transformer and allow it to cool down and recover from the higher loading during the day.

Overall, the exact weekly loading profile of a transformer connected to a PV system will depend on a variety of factors, including the size of the PV system, the demand for power, and the capacity of the transformer. However, it is likely that the transformer will experience a higher loading during the daytime hours and a lower loading during the night-time hours due to the presence of the PV system.

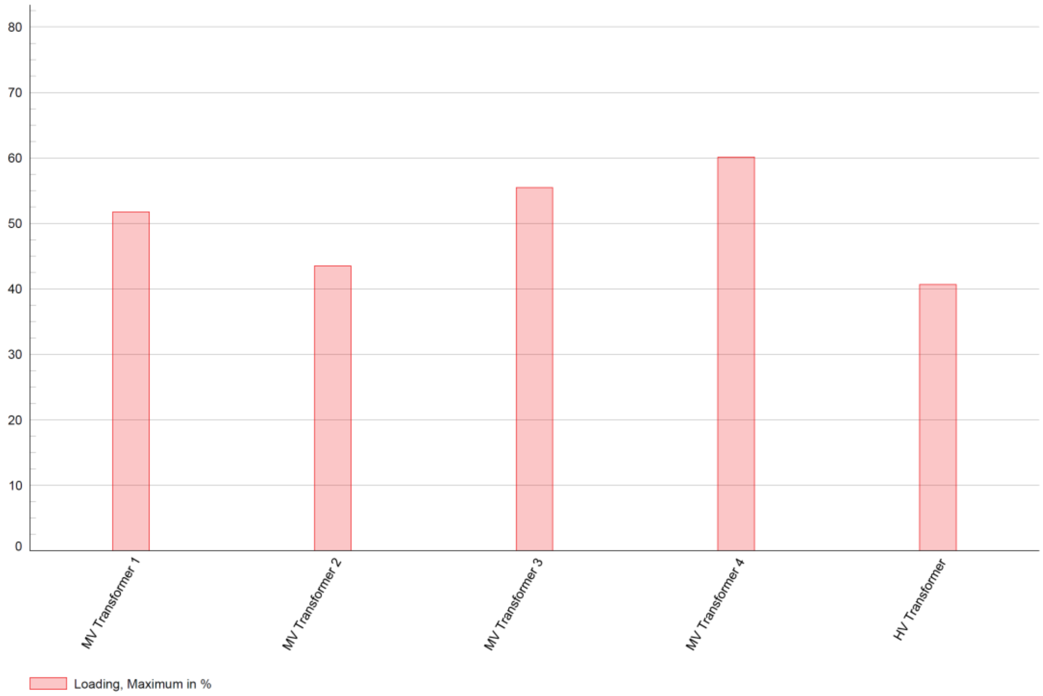

Figure 7-6: Scenario 1 transformer loading

7.3.4 Impact on grid

Figure 7-7 indicates for some days the PV system produces more electricity than is being consumed on the grid, the excess energy can be fed back into the grid. Figure B - 1 in Appendix B indicates the total External grid output that is producing much less than the base case shown in Figure 6-5.

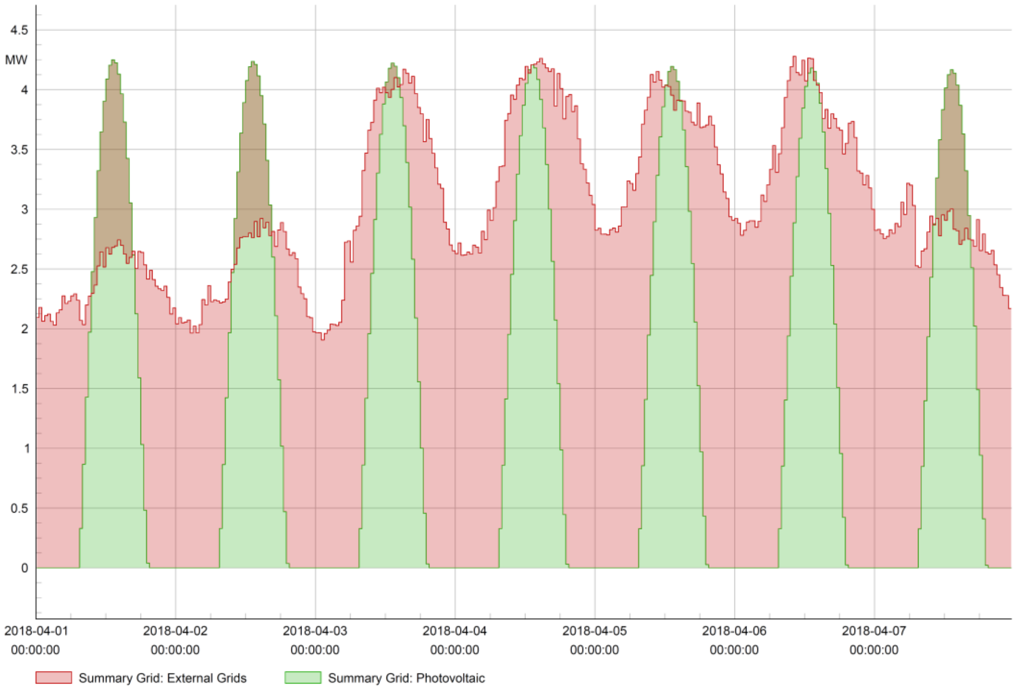

Figure 7-7: Scenario 1- Grid vs PV generation

7.4 Scenario 2: PV with Voltage droop Q added

7.4.1 PV output

Figure 7-8 shows the effect of voltage Q droop on reactive power in a PV system on the operation and stability of the electrical system. The voltage Q droop design control strategy to ensure that it is properly balanced with the need for reactive power in the system.

Figure 7-8 shows the voltage droop is a control mechanism used in some PV systems to regulate the output power in response to changes in the system voltage. Essentially, it involves reducing the system's output power as the voltage increases, which helps to stabilize the system and prevent overvoltage conditions.

Figure 7-8 shows the PV system with voltage droop Q added is operating under constant load demand, then the weekly power profile would likely show a relatively stable output, with variations depending on the available sunlight and other environmental factors. The voltage droop Q would help to regulate the voltage and prevent overvoltage conditions, which could damage the system components.

However, if the load demand is variable, then the power profile would be more complex. During periods of low load demand, the system might generate more power than is needed, causing the voltage to increase. In response, the voltage droop Q would reduce the output power, which could cause the system to operate below its maximum capacity. During periods of high load demand, the system might not be able to generate enough power to meet the demand, which could result in voltage drops or other issues.

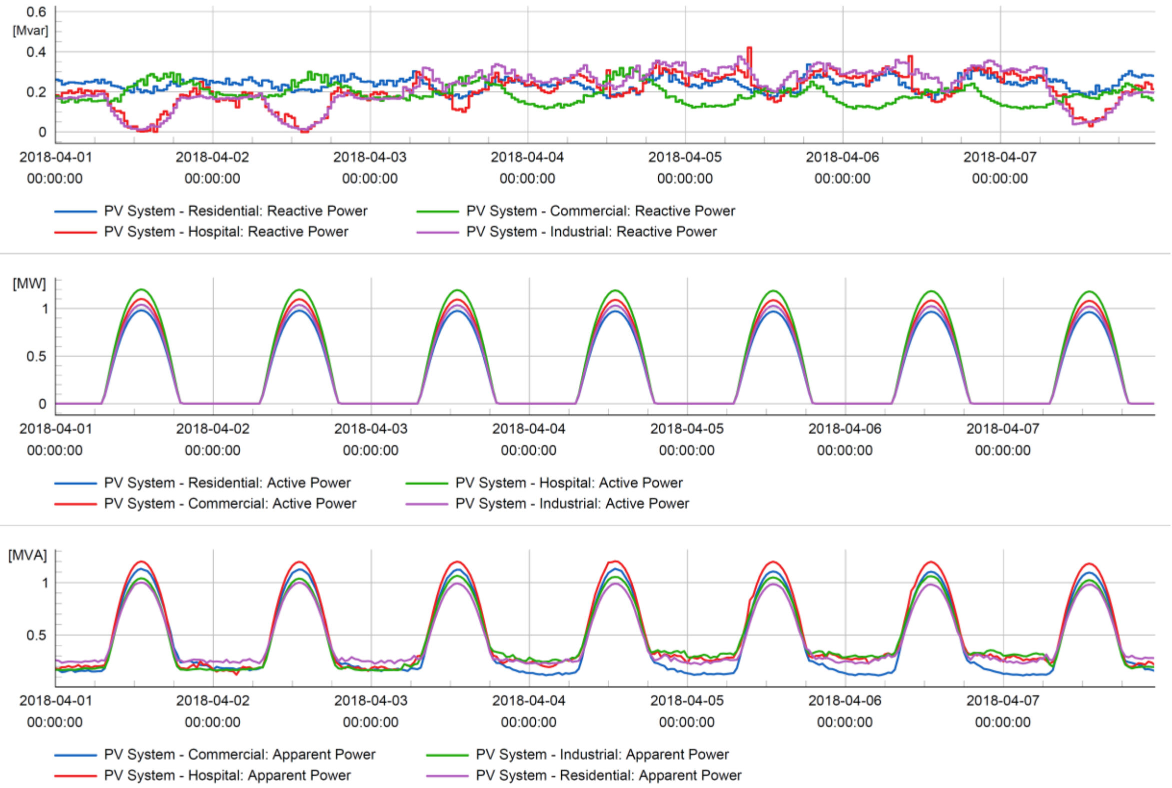

Figure 7-8: Scenario 2 PV system output for voltage Q droop

7.4.2 Busbar voltage

Figure 7-9 indicates the minimum and maximum busbabr voltages all close to 1 pu. The voltage Q droop can be explained by considering the nature of reactive power. Reactive power is the power that is used by inductive and capacitive loads to generate magnetic and electric fields. As the reactive power demand increases, the voltage drops due to the increased current flow through the system's reactance. The Q droop can be compensated for by adjusting the system's voltage control, such as using reactive power compensation devices like capacitors or by changing the system's power factor.

Figure C - 1 shown in Appendix C indicates the consumer busbar voltage profile of a PV system with voltage droop Q added would depend on the system's output power and the nature of the load demand. Generally, the voltage droop Q would help to regulate the busbar voltage and prevent overvoltage conditions, which could damage the system components and lead to safety hazards.

Figure 7-9 shows the PV system with voltage droop Q added, the busbar voltage would be regulated by the droop control mechanism, which reduces the system's output power as the voltage increases. This helps to stabilize the system and prevent overvoltage conditions, which could damage the equipment or cause safety issues.

Figure 7-9 indicates the weekly consumer busbar voltage profile would depend on various factors, including the available sunlight, the system's capacity, and the load demand. During periods of high sunlight and low load demand, the PV system might generate more power than is needed, causing the busbar voltage to increase. In response, the voltage droop Q would reduce the output power, which could cause the system to operate below its maximum capacity. During periods of low sunlight and high load demand, the system might not be able to generate enough power to meet the demand, causing the busbar voltage to drop.

Overall, the consumer busbar voltage profile of a PV system with voltage droop Q added would be a dynamic function of the system's power output and the load demand. The voltage droop Q would help to regulate the busbar voltage and prevent overvoltage conditions, ensuring the safe and reliable operation of the system.

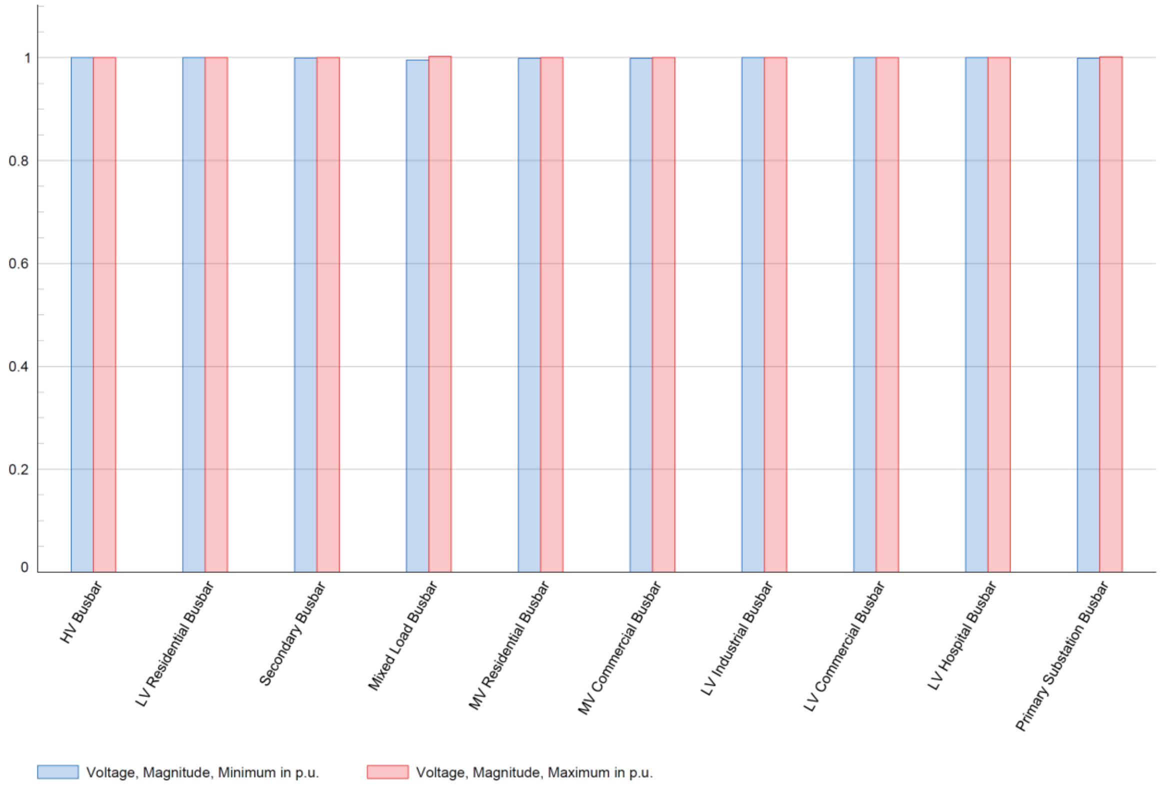

Figure 7-9: Scenario 2 busbar voltage

7.5 Results conclusion

In conclusion, the results indicate the grid-connected renewable energy systems have the potential to provide a range of ancillary services to support the reliable and efficient operation of the power grid. This thesis has explored the capabilities of renewable energy systems, specifically solar to provide a variety of ancillary services, including voltage control and reactive power support.

The integration of renewable energy sources into power grids presents significant challenges but also opportunities for providing ancillary services. By leveraging the inherent capabilities of renewables, such as reactive power the grid operators can enhance the reliability, resilience, and efficiency of power systems.

Various ancillary services, such as frequency regulation, voltage control, and ramping support, can be provided by renewables either individually or in combination with energy storage systems. However, the optimal design and operation of renewable-based ancillary services require careful consideration of technical, economic, and regulatory factors, as well as the coordination among different stakeholders. Future research should focus on addressing these challenges and evaluating the performance and benefits of renewables ancillary services in real-world applications.

CHAPTER 8 **Conclusion and Recommendations**

8.1 Research aims deliverables achieved

1) By examining the systems' ability to respond quickly to changes in grid loads and voltage, as well as their capacity to provide essential grid services like reactive power and voltage control, the assessment determined that the PV system fulfilled these crucial functions.
2) By examining the systems network demand and reducing load with solar energy is the reduction in greenhouse gas emissions. Traditional electricity generation, particularly from fossil fuels like coal and natural gas, releases significant amounts of carbon dioxide and other pollutants into the atmosphere. By generating electricity from solar panels instead, these emissions indicate that there is reduced, contributing to the mitigation of climate change and air pollution.
3) Supplying excess load to the grid offers offsetting electricity costs by supplying excess load to the grid, PV system owners can significantly offset their electricity costs. This is particularly beneficial in areas with high electricity rates or where electricity demand is higher during the day when solar generation is at its peak. The financial savings from reduced electricity bills can contribute to a faster return on investment for the PV system.
4) This models and algorithms can help enhance the predictability and controllability of renewable energy sources. This, in turn, leads to better management of grid stability, reducing the risk of voltage fluctuations. This model will encourage collaboration between energy industry stakeholders, research institutions, and renewable energy developers to conduct comprehensive assessments of the technical feasibility of renewable energy sources for ancillary services. This collaboration will help leverage expertise and resources, leading to more accurate evaluations.

8.2 Research objectives achieved

1) Comprehensive assessment of the existing renewable energy installations and their participation in ancillary services provision. Documentation of case studies highlighting successful integration of renewable sources for ancillary services. Identification of gaps and limitations in the current utilization of renewable energy for grid support.

2) Compilation of a comprehensive list of technical and operational challenges faced by grid operators and renewable energy system owners.
   In-depth analysis of these challenges, offering insights into their causes and potential solutions.
3) Quantitative assessment of renewable energy systems' capabilities to provide specific ancillary services such as voltage control, frequency regulation, and reactive power support.
   Comparative analysis of renewable-based ancillary services against conventional methods in terms of performance and cost-effectiveness.
4) Quantification of environmental benefits, including reductions in greenhouse gas emissions, compared to conventional ancillary service provision.
   Assessment of potential trade-offs, such as increased land use, and exploration of mitigation strategies.
5) Promotion of renewable energy's role as a reliable source of ancillary services, enhancing grid reliability and flexibility. Contribution to the discourse surrounding sustainable energy systems and their potential to transform the electricity landscape.

The culmination of these outcomes would contribute to the advancement of knowledge in the field, inform policy and regulatory decisions, and facilitate the practical deployment of renewable energy systems as valuable contributors to grid stability and ancillary services provision.

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APPENDIX A: Powerfactory Base Case weekly simulation load profiles

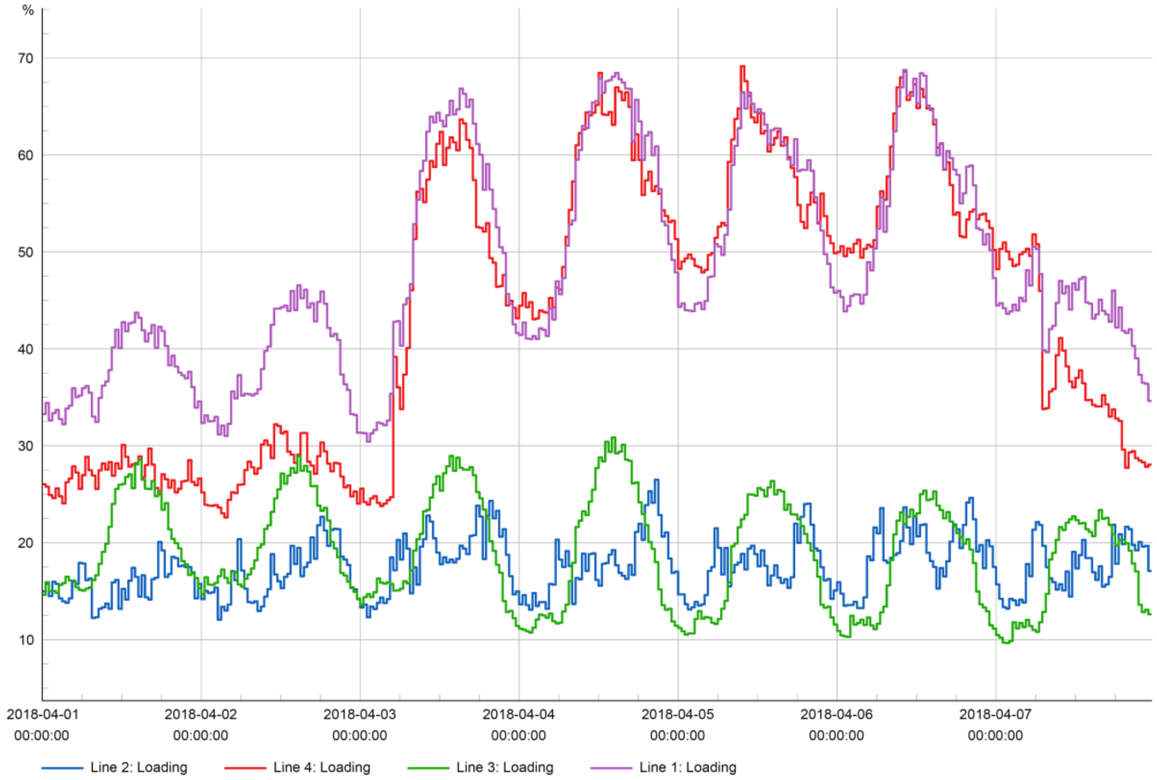


Figure A - 1: Weekly base case cable loadings

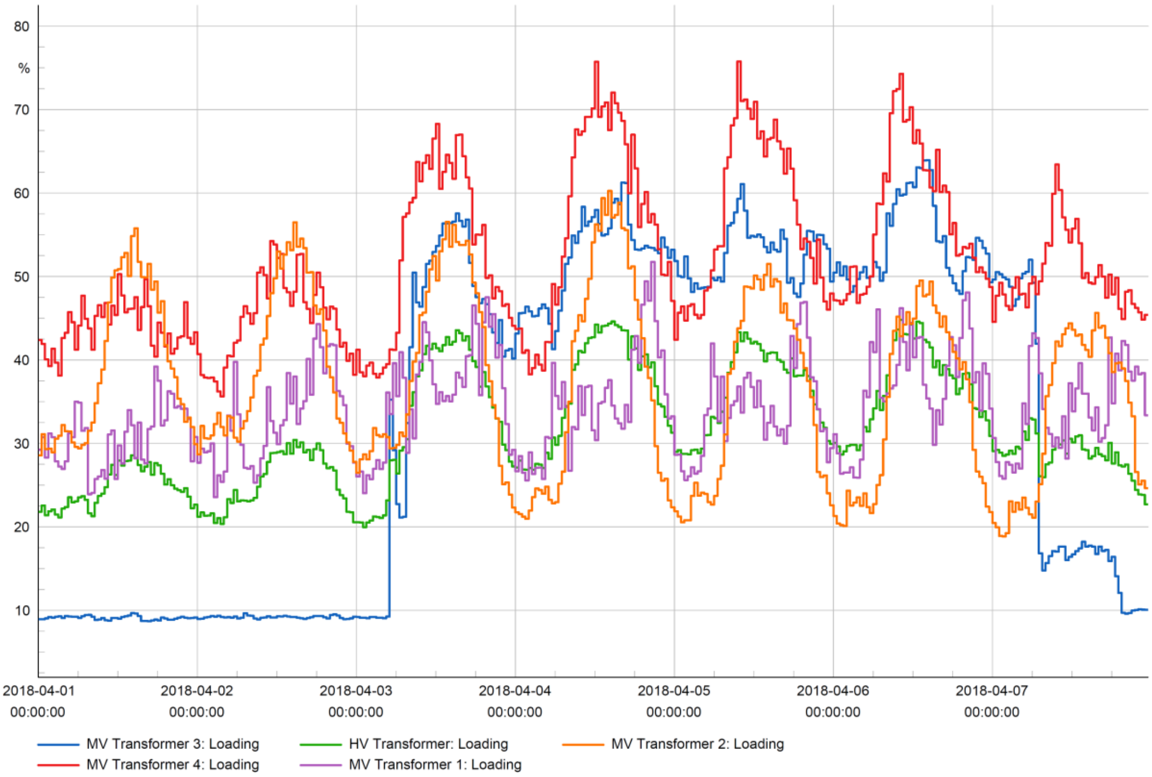


Figure A - 2: Weekly base case transformer loadings

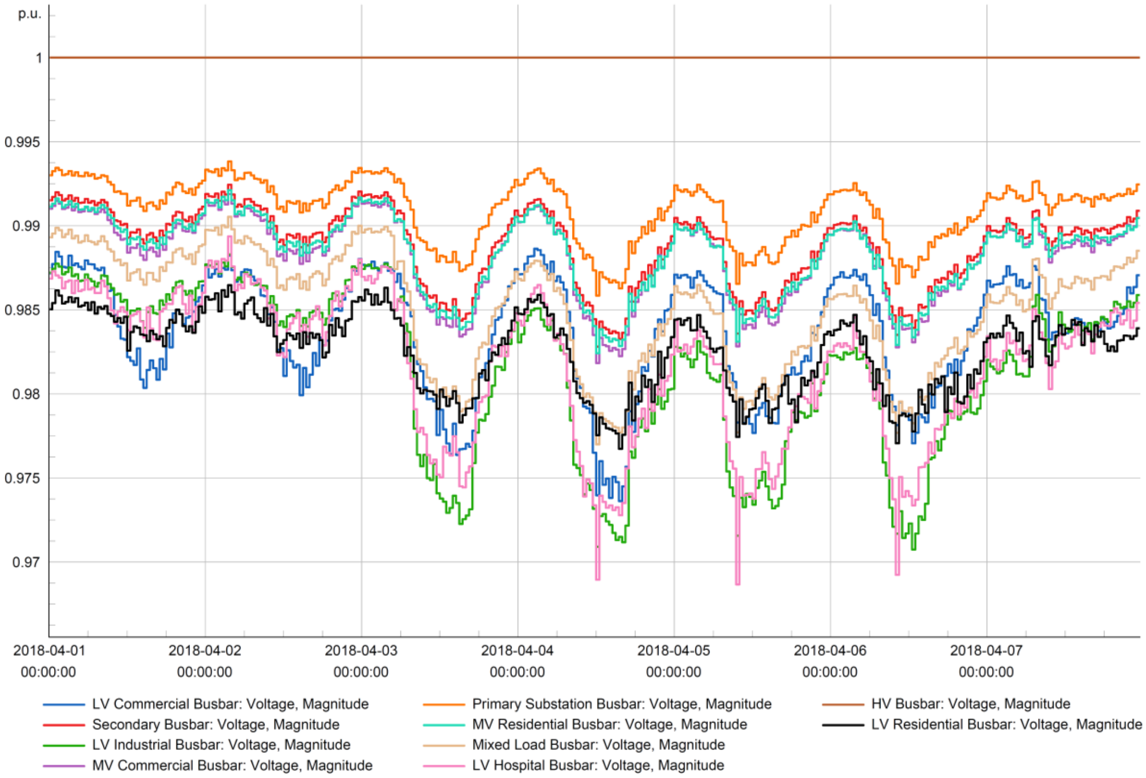


Figure A - 3: Weekly base case busbar voltages

APPENDIX B: Powerfactory Scenario 1 - PV added weekly simulation load profiles

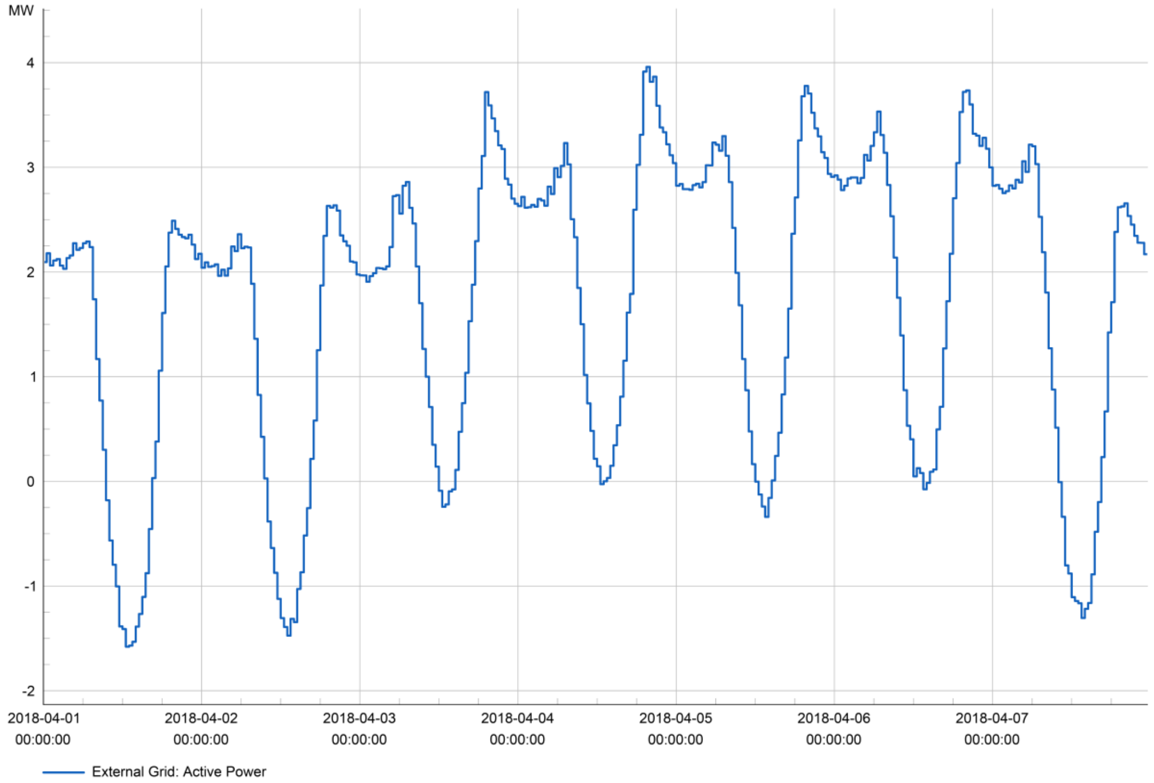


Figure B - 1: Scenario 1 weekly External Grid load profiles

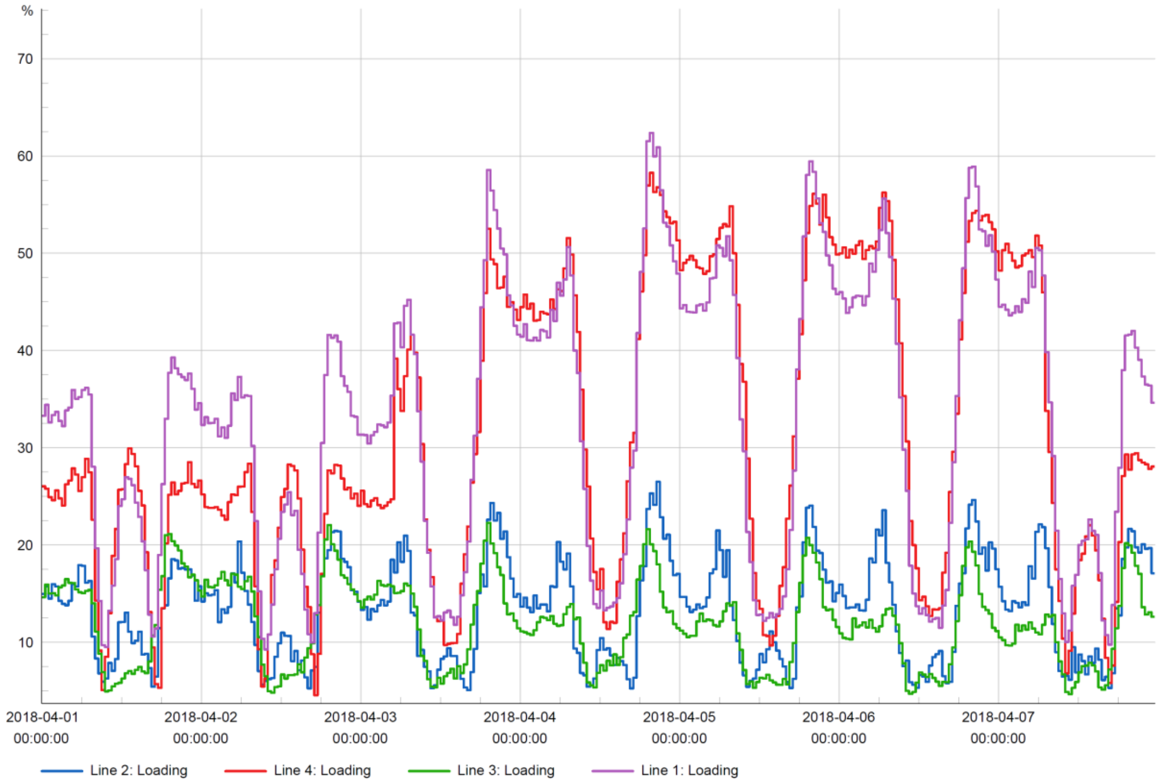


Figure B - 2: Scenario 1 weekly cable loadings

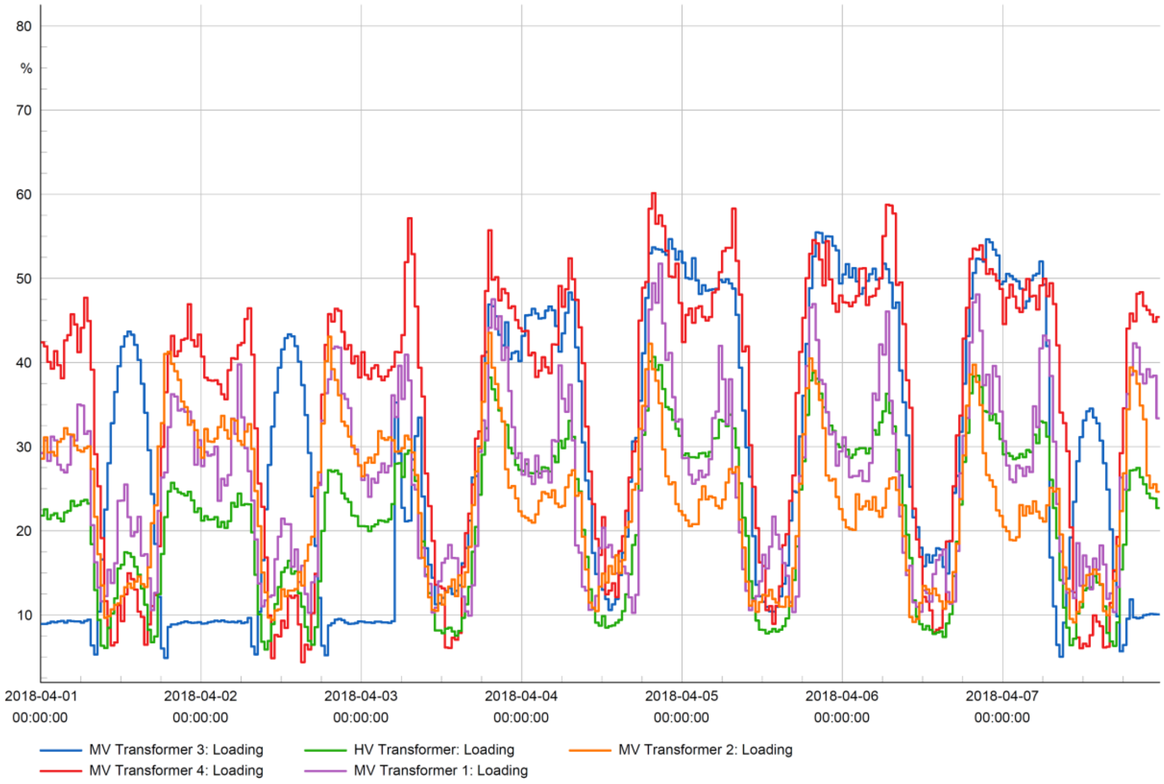


Figure B - 3: Scenario 1 weekly Transformer loadings

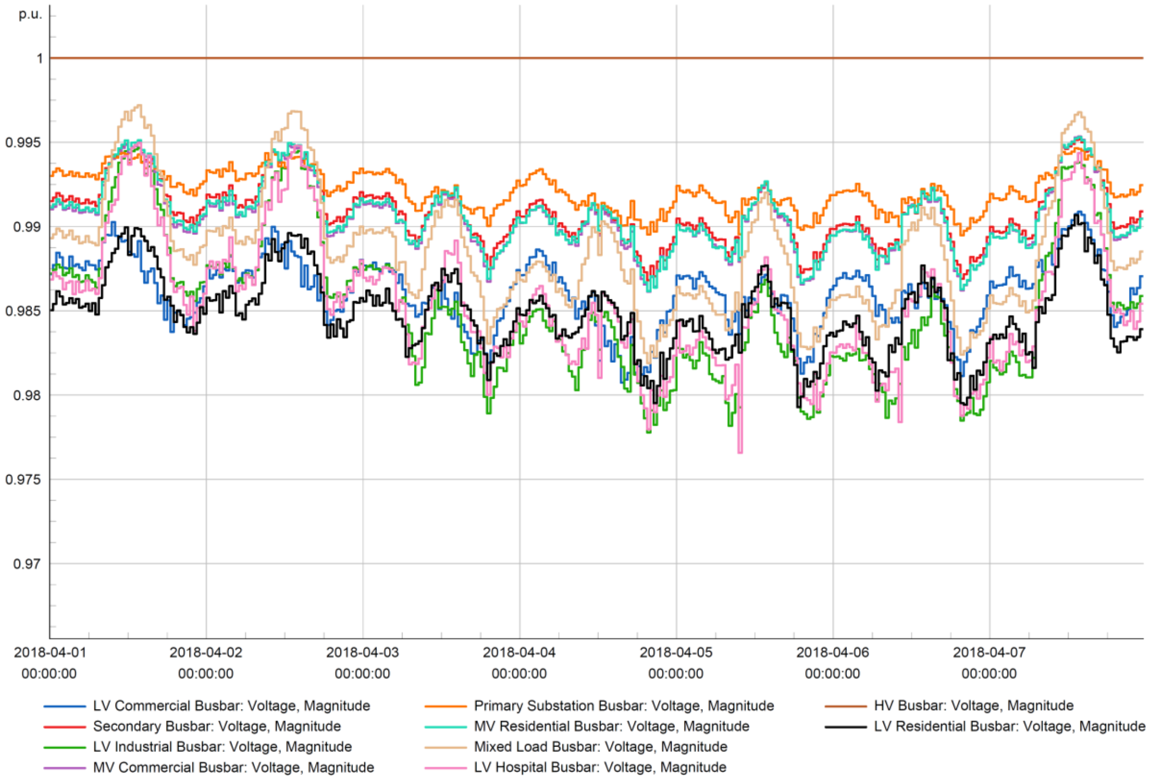
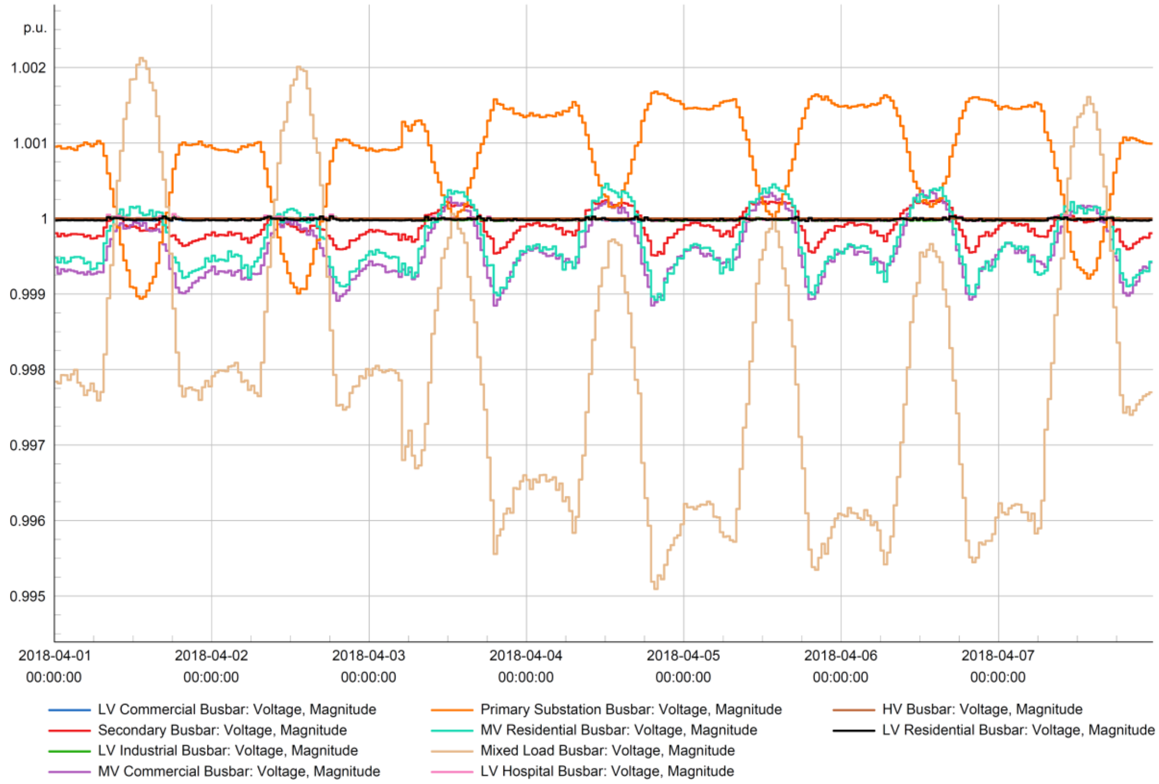


Figure B - 4: Scenario 1 weekly busbar voltage profiles

APPENDIX C: Powerfactory Scenario 2 - Voltage weekly profile



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