Voltage Regulation in Electric Distribution Grid Integrated with Distributed Energy Resources

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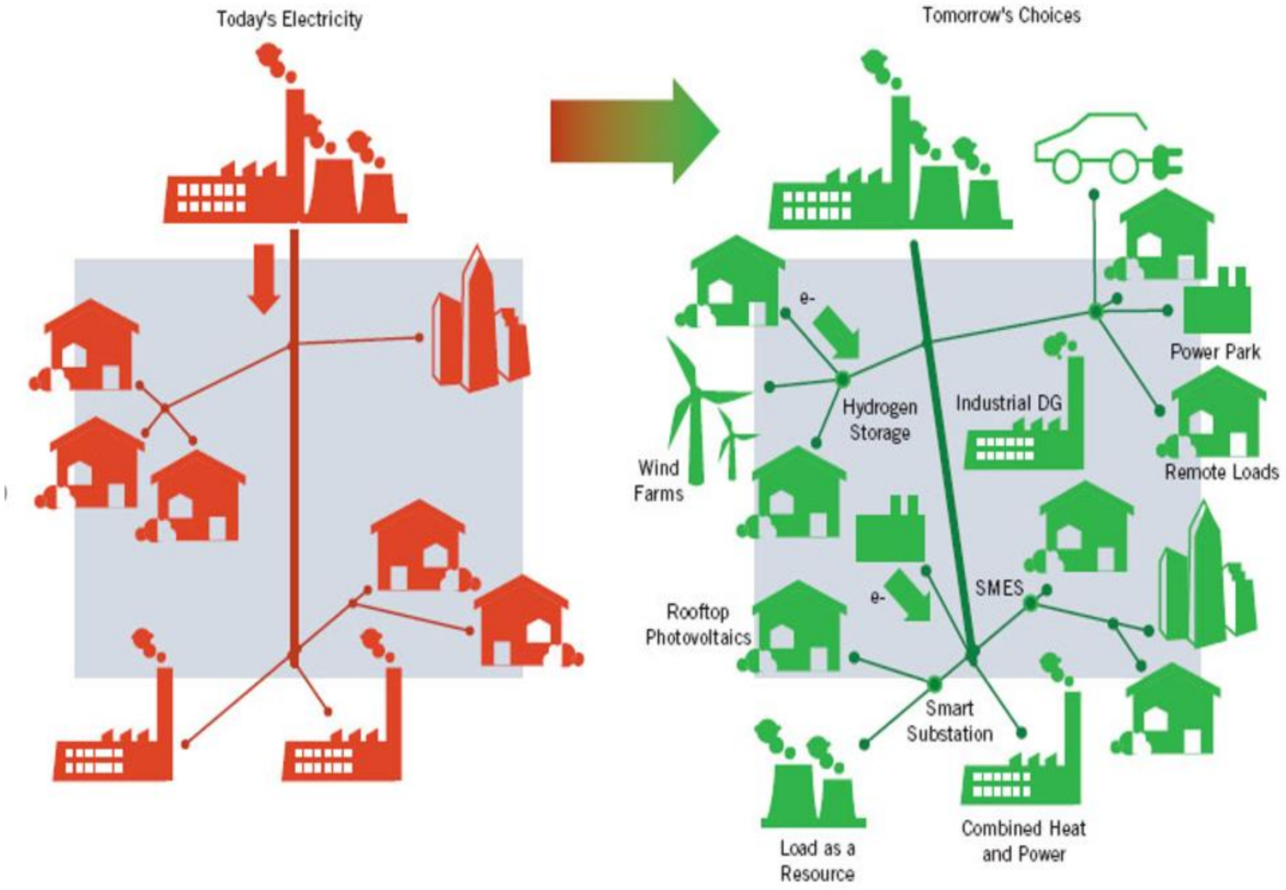

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Synopsis:

According to the recent development in the electricity sectors around the world, an increase in the integration of distributed energy resources (DERs) is expected following the decrease in usage of conventional generators in the systems. In Denmark, the ambition is to become fossil fuel-free by 2050. Renewable energy sources (REs) are expected to introduce voltage challenges for the system operators. DERs such as demand-side flexibility and energy storage systems are to be utilized to solve the voltage issues. High pollution in transport sector has inspired consumers to shift to electric vehicles, since electricity supplied by REs is greener. This increase in EVs has led to an increase in electricity demand, which can cause congestion operational issues for the distribution system operator (DSO). In this MSc thesis, we look at how demand-side flexibility and energy storage systems can be utilized to solve voltage challenges in the medium voltage (MV) grid in relation to EVs. We also investigate transmission system operator-distribution system operator (TSO-DSO) interaction in the future electrical power system network.

Preface

This MSc thesis has been written by Albano Monga in the 3rd and 4th semester at the Department of Energy Technology at Aalborg University. The project takes place from the 2nd of September 2020 to the 28th of May 2021. The purpose of the MSc thesis is to investigate the impact of REs on the voltage in the MV grid, and how DERs such as demand-side flexibility and energy storage system can be utilized for voltage assessment. The project also investigates TSO-DSO interaction in the future electrical power system network.

I would like to thank my supervisors Jayakrishnan Radhakrishna Pillai and Sanjay Chaudhary for their guidance, patience and support during difficult periods of the project. In addition, I would like to express my gratitude to my family for the support, and study Secretary Lisbeth Hold Nørgaard for the guidance.

Reader's Guide: The presented work in this project is based on literature reviews, relevant websites, reports, supervisor guidance, courses etc. The sources are cited through the thesis and can be found in the bibliography. Referencing methods used is IEEE citation style, which refers to sources with a[number]. Figures and tables are appointed sequential numbers and equations are labelled with (numbers).

Abstract

In recent years, there has been a progressive increase in the share of REs in electrical power systems around the world. In Denmark, the ambition is to rely 100% on REs by 2050.

The large increase in REs in the distribution grid leads to operational and security issues for the TSO and DSO. With the increase in REs penetration in the existing MV grid, voltage issues occur in the distribution grid. To enhance future power systems, a combination of conventional voltage regulation of on-load tap changer (OLTC) and DERs such as demand-side flexibility and energy storage system is to be used for voltage assessment in the distribution grid.

In the traditional electrical power system network generation follows consumption. But in future power systems, consumption can follow generation by utilizing demand-side flexibility providing support to the electrical power system.

In recent years, energy storage system (ESS) production has increased. As REs penetration in the electrical power system increases, so do the ESS as they provide a good solution of storing energy during high production hours to be used during low production hours.

This work aims to investigate new ways of providing voltage control in the distribution grid, by utilizing OLTC, demand-side flexibility and energy storage systems. Furthermore, it investigates the TSO-DSO interaction to provide support to the transmission grid.

For this purpose, research and simulation have been carried out to investigate voltage variation in the existing MV grid and the MV grid with an increase in installed capacity of REs. Also, the project investigates the TSO-DSO interaction of the designed model.

The increase in REs installed capacity causes over-voltage issues in the MV grid, which must be solved. Firstly, conventional voltage control (OLTC) is used. Thereafter EV loads are implemented and utilized assuming their consumption increase in the future electric power systems. EV loads are then treated as controllable loads to provide demand-side flexibility and thereby provide voltage support in the MV grid. Furthermore, ESS is implemented for reinforcement of voltage regulation in the MV grid, as its integration in the future power system is also expected to increase.

With enhanced TSO-DSO interaction, the DSO can provide voltage support and frequency support to the TSO with consideration of their power system limitations. The project investigates how TSO-DSO enhancement in future power system networks can be archived.

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Nomenclature

Abbreviation	Description
EVs	Electric Vehicles
TSO	Transmission system operator
DSO	Distribution system operator
OLTC	On load Tap charger
DSF	Demand-side flexibility
DERs	Distributed energy resources
WT	Wind turbine
PV	Photovoltaic
ESS	Energy storage system
QDLFS	Quasi-dynamic load flow simulation
DERMs	Distributed energy resource management
DERs CC	Distribution energy resource control centre
DSM	Demand-side management
REs	Renewable energy sources
DLC	Direct load control
CHP	Combined heat pump
MV grid	Medium voltage grid
BMS	Battery management system
EVSE	Electric vehicle supply equipment
V1G	Controllable electric vehicle
V2G	Vehicle to grid
V2H	Vehicle to home
LFS	Load flow simulation

Chapter 1: INTRODUCTION

The electrical power system networks in the developed countries are undergoing a massive transformation. This transformation has introduced operational and security challenges caused by REs. To support this transformation the interaction between TSOs and DSOs must be enhanced.

1.1 THE BACKGROUND OF DISTRIBUTED ENERGY RESOURCES IN TSO AND DSO

Transmission system operators (TSOs) and distribution system operators (DSOs) are responsible for supplying electrical power in the network [1]. This section covers the current and future power system networks, as well as the reasoning behind the need for transformation.

Centralized power system network and TSO-DSO operation

In the centralized power system networks, electrical power generation is centralized and unidirectional. The electrical power is generated from large power plants, transmitted through transmission lines to the distribution grid, then from the distribution grid to the consumers. Figure 1 shows a centralized power system network, whereby the power is generated from a centralized power generator, sent through a transmission line to distribution stations, and lastly to end-users [2].

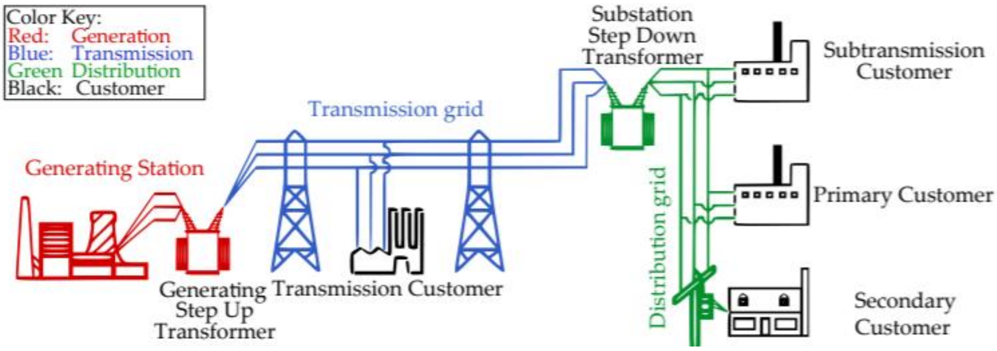


Figure 1 Shows a centralized power system network [3]

Generally, transmission system operators (TSOs) monitor and manage national and international power flow at high and extra-high voltage, while distribution system operators (DSOs) monitor low, medium, and to some degree high voltage levels. It should be noticed that the voltage level of transmission and distribution systems may vary from country to country. In Denmark, the TSO voltage level is typically between 150 kV and 400 kV and for DSO between 0.4 kV and 60 kV [4].

The centralized power network has many conventional power plants capable of providing ancillary services such as frequency control, voltage control, back start, and spinning service, but unidirectional power flow provides a challenge. In this type of power system network, the large installation of DERs in the DSO is limited since they create operational and management challenges for both TSOs and DSOs. This limitation leads to reduced utilization of power produced by REs and inefficient utilization of demand-side flexibility, whereby the DSO's ability to provide services to the system is reduced [4].

Future power system network and TSOs-DSOs operation

When we refer to future power system network we mainly refer to the ideal situation of proper coordination between centralized power generation from TSOs, and decentralized power generation integrated into the DSOs. In the future power system network, the power flow is a bit more complex relative to the centralized power system network. The power generation does not only propagate from TSOs, but rather from different participants in the power system network. The participants such as energy producers, aggregators, and prosumers can interact with the system network at different voltage levels. The interaction can take place in both TSOs and DSOs. It should be noted that conventional generator production in the TSOs will be significantly reduced, due to the increase of production from DERs in the DSOs. This means there will be a drop in TSOs services provided [5] [6].

The transformation of the power system will reform the responsibility for ancillary services for the TSOs and DSOs. The TSOs areas of responsibility are reduced, while the DSOs will increase. Figure 2 shows a simplified overview of future power system generation, where centralized and decentralized generation from TSOs and DSOs are combined [2].

Figure 2 Shows an overview of a decentralized power system network [3]

The driving forces supporting the transformation towards future power system networks are environmental policies, technological advancement, business, etc. Many countries have recognized the severe environmental impact of conventional energy resources such as coal, gas, and oil. To reduce the impact, DERs are considered as an alternative. In Denmark, the government is pursuing the goal of becoming 100% renewable energy resources dependent by the year 2050 [7].

DERs can be categorized into two groups: generation and demand-side. The generation side includes REs such as PVs, WT and ESS. The demand side is related to the power network's ability to utilize flexibility from the demand side, which is control of loads using different technics such as direct load control, where the loads can be connected or disconnected, or efficiency control technic where the consumption of the load is reduced or increased. The demand side flexibility includes combined heat pumps, electric vehicles, etc.

Challenges

A decentralized power system network comes with lots of benefits, but to enhance the future power system networks, different barriers and challenges must be overcome first. For instant, conventional power plants are being replaced with REs. This means there will be an increasing shortage of ancillary services from TSOs, which means the DSOs must depend on the DERs. This also means large units of DERs at different locations must be aggregated well as coordinated to deliver ancillary services for both TSOs and DSOs. Table 1 shows challenges facing future power system networks [8] [9].

Table 1 Challenges in the decentralized power system networks

Challenges	**Description**
Coordination	Proper coordination is needed between TSOs and DSOs in real-time
Market	A new market model is needed to support the transformation
Planning	Proper planning at different levels of the system networks for optimization of power transfer
Data handling	Data must be provided to support forecasts
Operation	DERs creates operational challenges for TSOs and DSOs

Need for interaction

To enhance the future power system networks interaction between the individual participants is necessary. This includes operation, coordination, data exchange, and planning interaction. Data interaction accounts for relevant information exchange between participants. Planning interaction accounts for future planning of power production and power transfer. Operation and coordination interaction accounts for the real-time operation of power systems [8].

TSO-DSO interaction must be improved as it paves the way for the utilization of DERs in the power grid since an increasing penetration of DERs in the network will create challenges for both operators. Proper TSO-DSO interaction allows DSOs to solve their challenges locally. DSOs may be capable of solving congestion challenges and provide voltage and frequency support through demand flexibility and DERs. For instance, to enhance the data interaction the danish TSOs provides a data platform known as DataHub, where all power system participants access data, which can help future planning and coordination of power production [10] [2].

Coordination between TSOs-DSOs is the backbone of a decentralized power system. With the absence of a conventional generator at the transmission level, proper coordination is needed as it opens the door for ancillary services to be provided by DSOs using DERs. Ancillary services are a set of activities in the power grid that increase the reliability of the system, for example, establishing a balance between supply and demand and helping the system recover after an accident[2].

New players and consumer benefit

In the future market model, TSOs and DSOs must provide a platform that supports market competition and grants easy access to all the energy resources connected to the power grid. To keep consumers satisfied, there should be a stable interaction and proper coordination between energy wholesalers and retailers so that energy prices can be accepted by applicants and further allow energy suppliers to offer reasonable contracts to their customers. The future market model must integrate new players such as aggregators and prosumers[11] [12]

1.2 PROBLEM STATEMENT

The increase of distributed energy resources (DER’s) in distribution grids have tremendously raised the need for active grid management. The DERs in distribution grids could introduce operational challenges such as grid congestions, voltage issues, reverse power flow, and power quality issues. Nevertheless, applying the flexibility of demand-side partnership and energy storage could obtain an environment for DERs to provide local services such as voltage support, congestion management, etc. Furthermore, DERs could be actively involved in keeping the entire system reliable and stable by facilitating ancillary services. In general, distributed energy resources (DERs) provide various operational advantages not only at the level of the distribution system but also at the transmission system level.

1.3 OBJECTIVES

The project aims to develop voltage control schemes for enhanced TSO-DSO interaction, utilizing the flexibility of distributed energy resources (DERs). This is realized by various task conducted in this project which are:

- DERs impact on voltage in the distribution grids
- DERs voltage control in the distribution grid and its impact on the electrical power system.
- DERs impact on TSO-DSO interaction in the future power system network
- DSO voltage support to TSO
- DSO frequency support to TSO

1.4 LIMITATIONS

The limitation of this project is as follow:

- The analyses are carried out with consideration of grid topology to be operation in radial mode
- Dynamic of DERs' are not considered
- To activate demand-side flexibility, PV-bus is not defined in the MV grid
- Market modelling is not included
- A simplified transmission line is considered

1.5 METHODOLOGY

The main tool used in this project is the DIgSILENT power factory. The first stage includes a steady-state analysis of the MV grid with the existing installed capacity of REs and loads. Followed by steady-state analyses of the MV grid with an increase in installed capacity of WT, to observe the MV grid behaviour. The design of different profiles has been created including PV, WT, CHP, residential and industrial loads, EVs profile, demand-side flexibility EV loads and ESS, which are mostly created with combination DIgSILENT, excel and obtained data from Energinet.dk. QDLFS have been utilized to observe voltage variation in the MV grid in 1 week.

1.6 OUTLINE OF THE THESIS

Chapter 1 - Introduction: This chapter covers a short review of the topic with related background information and the limitations of the project.

Chapter 2 – The future power system: To clarify the project problem statement, it is necessary to investigate various references to distinguish related material to present a suitable project. This chapter consists of a literature reviews investigation, which analyses the state of the art of future power systems following the transformation from centralized to the decentralised electrical power system network. It investigates challenges that come with it, market framework, and the benefits of integrating DERs in the electrical power system network.

Chapter 3 – Assessment of DERs in integration: This chapter consists of the MV grid model to be investigated. The investigation is conduction for two scenarios, scenario 1 with the existing installed capacity and scenario 2 with an increase of WT installed capacity.

Chapter 4 –Voltage assessment utilizing OLTC and uncontrollable EV loads: This chapter consists of voltage assessment utilizing OLTC and the addition of uncontrollable EV load in the MV grid.

Chapter 5 –Voltage assessment utilizing demand-side flexibility and ESS: This chapter consists of voltage assessment utilizing demand-side flexibility and an energy storage system.

Chapter 6 – TSO-DSO interaction: This chapter presents how DSO can help TSO with voltage and frequency control.

Chapter 7 – Discussion, conclusion and future work: This chapter presents discussion, conclusion and future work.

Chapter 2: DISTRIBUTED ENERGY RESOURCES IN THE FUTURE POWER SYSTEM

The electrical power system networks around the world are continuously transforming from centralized to decentralized, which changes the dynamic of power flow in the power system networks. In future power system networks, the power will be generated at various locations by different power producers. This will lead to bidirectional power flow in the power system networks.

The transformation in power system networks is happening both on the production and consumption side. On the production side, increasing interest in REs leads to conventional fossil-fuelled power generators being replaced by REs. On the consumer side, demand-side flexibility from sizable loads such as EVs and heat pumps are integrated, which means it will be possible for consumption to follow production in the future power system networks [13].

Distributed energy resources in the future power system networks

Distributed energy resources (DERs) refer to a range of technologies used to create the transformation in the future power system networks. DERs can either be power generation plants, controllable loads or storage systems. Table 2 shows categorised examples of DERs [14].

Table 2 DERs

Distribution Generators (DG)	Energy storage systems (ESSs)	Demand response (DR)
Solar panels (PVs)	Batteries	Residential load flexibility
Wind turbines (WT)	Flywheels	Industrial load flexibility
Combined heat pumps (CHP)	Fuel cells	Electric vehicles(EVs) (can be applied)
Small hydropower plants	Thermal energy	Heat pumps
Biogas	Hydro pumps	

2.1 CHALLENGES IN THE FUTURE POWER SYSTEM NETWORK

The increasing integration of DERs in the future power system networks comes with economic and environmental advantages. This section covers the challenges DERs poses to the electrical power system networks.

2.1.1 Operational challenges caused by DERs

One of the main challenges with weather-dependent power generation such as WT and PV is generation uncertainty (forecasting errors). The forecast of power generation happens in advance, but as we approach real-time the forecast is updated continuously. The real-time power generation is always different from the forecast, which leads to a production and consumption mismatch. Figure 3 shows an example of wind production in real-time vs. the day-ahead forecast. The power imbalance is the difference between actual production and forecast production at a particular time [15].

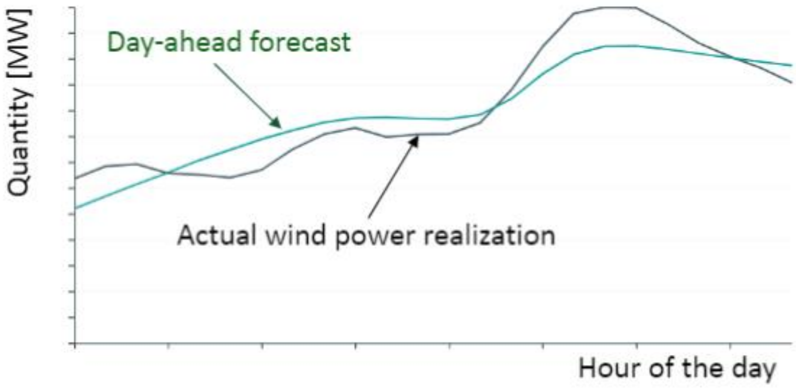


Figure 3 Day-ahead forecast vs. actual power production

Another challenge is under-voltage and over-voltage issues caused by DERs to be handled by TSOs and DSOs. For instance, under-voltage may occur, when instantaneous consumption of big loads such as electric vehicles or heat pump is higher than the instantaneous production in the MV grid, leading to a voltage drop at the node to which they are connected. Over-voltage may occur when instantaneous REs production is higher than overall consumption, leading to reverse power flow [16] [6].

Another issue is related to an increase in installed capacity in the existing grid. If REs installed capacity is increased and their output power is bigger than the rated power of the components in the grid such as cable, circuit breaker, transformers etc. this may lead to congestion issues in the electrical power system networks [17].

Another challenge is related to generation and consumption equilibrium. In an electrical power system, there must always exist a balance between generation and demand. In a time of unbalance, different control responses are used to maintain equilibrium in the system. The inertia response provides an immediate countermeasure between generation and demand. The increase of renewables and the decrease of conventional synchronous generation means lower inertia available in the electrical systems, leading to a higher rate of frequency variation in time of unforeseen events [18].

The increasing share of power generation in the DSOs networks has introduced security challenges for the TSOs and DSOs. Non-synchronous electrical power generation units are replacing conventional power units and TSOs are left with a fewer pool of units available to provide services such as frequency response and voltage control. This transition means DSOs will be partly responsible for the ancillary services previously provided by TSOs [19].

Frequency stability is another challenge in future electrical power system networks. Equilibrium between generation and consumption must be maintained continuously. At the time of loss of power, inertia from synchronous machines provides resistance to changes in frequency using machines kinetic energy. As the number of synchronous generators is reduced, the system inertia and thereby the resistance to changes in frequency is reduced respectively as shown in equation (1). H_{sys} is the system inertia, is the sum of inertia from each machine H_i multiplied by rated apparent power S_i divided by the system apparent power S_{sys} [18].

$$H_{sys} = \sum_{i}^{n} \frac{S_i * H_i}{S_{sys}} \tag{1}$$

2.1.2 Planning and coordination interaction solutions for the future power system challenges

To enhance the future power system networks the TSOs and DSOs must interact with each other during planning and coordination in the electrical power system.

Planning interaction deals with the planning process of generation and consumption in future power system networks. Network planning between TSOs-DSOs must be optimized in a way that supports the consumer-centric market. The integrated planning process must implement the responsibility criteria of both transmission and distribution networks in the future power system. The planning process must incorporate the system services and help with solving the congestion issues. The planning process includes power dispatch planning, with respect to DERs and TSO-DSO constraints [20].

Coordination interaction helps TSOs-DSOs to best utilize the available DERs in the electrical power systems in real-time operation and helps to solve issues such as over-voltage, under-voltage and power loss. For example, during high penetration from REs, the excess of power can cause over-voltage issues. The TSOs-DSOs can coordinate to utilize the power locally by either flexible loads or ESSs and thereby assisting with over-voltage issues and reducing loss in the electrical power system [19].

Also, the existing components in the infrastructures of the electrical power system such as cables, transformers, circuit breakers etc., may not be able to handle an excess of power during high penetration time. TSOs-DSOs can coordinate the power to be used locally, and reduce congestion of the components in the electrical power system [17].

Looking at the consumers’ perspective the newly emerging large loads such as EVs, heat pumps, electric boilers, etc. create planning and coordination challenges. With intelligent coordination and the support of the concept of “loads follows generation” instead of “generation following loads” as it is currently, the large loads can provide demand-side flexibility [12], thereby assisting with challenges mentioned in section 2.1.1.

2.2 MARKET FRAMEWORK

For many years, consumers’ electricity purchase choices have been limited. Development in technologies and global warming awareness for the past few years have been one of the major factors behind the reinvention of how electricity should be bought and sold. Establishing a feasible market framework is the backbone of the future power system networks, in which the market must support consumers' economic interests. Also, the consumers have taken the role of 'prosumers', which has led to increasing competition on the wholesale energy market and at the same time provides arrays of service to the power networks [8]

2.2.1 The existing markets

The flow of power in the electrical power network is ruled by the laws of physics, while the electrical markets are driven by financial interests with buying and selling of energy. The financial market model must, to some degree take electrical laws of physics into account, but at the same time support the financial contracts.

The two existing types of electrical financial markets are Nodal and Zonal. This project focuses on the Zonal type since this is the financial market model used in Europe. The Nodal type is used in the USA. The Zonal financial market model means that the price/MWh is the same for a particular zone. Figure 4 shows an example of the day-ahead price (Euro/MW) for the Zonal financial model from the Nord pool [21].

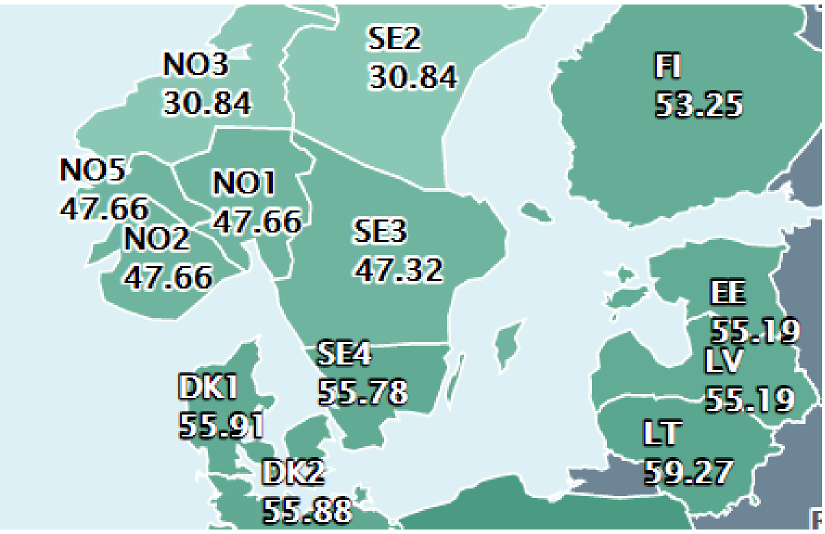


Figure 4 Zonal day-ahead price

European electricity market types

The market operator is an entity that ensures a uniform price in the electricity market by considering the prices from power suppliers as well as the power demand from power consumers. Nord Pool is the market operator for the Nordic countries.

In the Nordic countries, different market participants can trade energy via Nord Pool. When trading on Nord Pool it is necessary to know the activation time for different markets. Nord Pool is owned by TSOs in the Nordic countries [21]. Figure 5 shows the types of markets and who clears them.

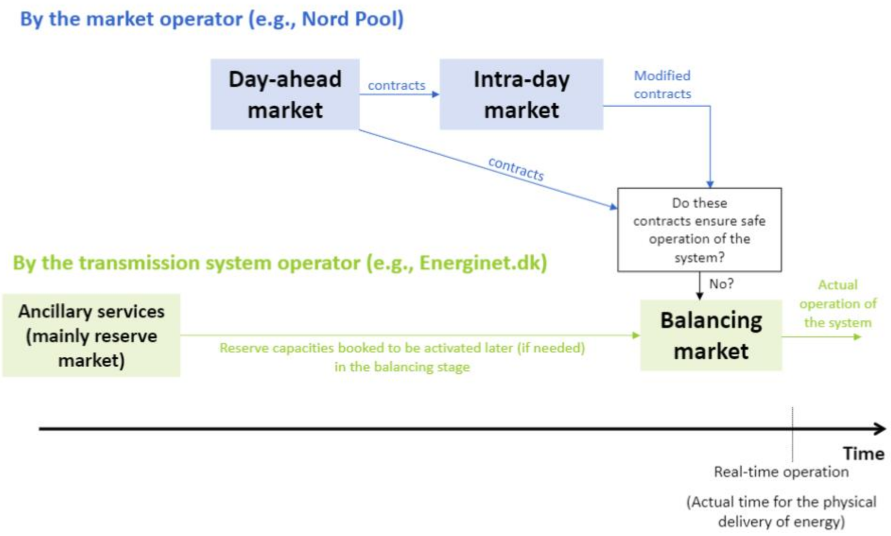


Figure 5 Market types [21]

There are different types of markets as can be seen above. Some are TSOs responsibility, and some are market operator's responsibility. This section describes different market types and the responsible parties [22].

- Capacity market
  In this market, a long-time contract secures needed production for TSOs. The producer is paid for their availability in the market.

- Elspot-market
  Market participants offer to receive or to provide electricity based on their hourly price forecast. This market is cleared 24 hours before, the price is provided as a uniform price for all market participants. This market is also called the Day-ahead market. This market is cleared by the market operator (Nord pool).

- Elbas-market
  This is a continuous hourly market that provides balance adjustments. In this market, energy producers and consumers can agree on different prices which may be higher or lower than the day-ahead market price.

- Balancing market
  This market supports the TSOs and DSOs by increasing or decreasing the generation of energy when needed. In this market, there are two types of agents: balancing service providers (BSPs), which is any generation or demand-side market participant who can change set points in real-time to help balance the electrical system, and balancing responsible parties (BRPs), which is the financial party that gets charged by TSOs for imbalance in the electrical system. This market is cleared by the system operators (TSOs).
- Reserve market
  This market ensures that TSOs has the needed reserves. This market is cleared by TSOs.

- Ancillary services market
  These are services necessary for the electrical system, such as frequency and voltage regulation. This market is cleared by TSOs.

Market clearing optimization for a zonal system

In the European electricity market, the Zonal system is used to clear the electricity market. Each country is considered as one zone, which means a single electricity price is cleared for the entire country. However, a few European countries have more than one zone. For instance, Denmark is divided into two zones DK1 and DK2, whereby the electricity price for the zones can be different as can be seen in Figure 4.

In the following, it is shown how market-clearing optimization for a zonal system in the day-ahead market is done. For simplicity, let's consider the demand is inelastic and the pricing is uniform where one price is provided to electricity suppliers.

$$Max\ SW = \sum_{d} U_d * P_d^D - \sum_{g} C_g * P_g^D \tag{2.1}$$

Subject to:

$$0 \le P_d^D \le \dot{P}_d^D \quad : \ \mu_d$$

$$0 \le P_g^G \le \dot{P}_g^D \quad : \ \mu_g$$

$$\sum P_d^D + \sum f_{a,b} - \sum P_g^G = 0 : \lambda \tag{2.2}$$

$$-ATC_{a,b} \le f_{a,b} \le -ATC_{a,b} : \ \mu_{ACT} \tag{2.3}$$

where:

P_d^D is the maximum load

P_g^D is the maximum load

C_g is the offer price for the generator

U_d is the bid price for demand

$\dot{P}_d^D$, $\dot{P}_g^D$ is demand and generation limits

μ_d, μ_g is the dual variable for the constraint

λ: is the clearing price for the Zonal system

$f_{a,b}$ is trade between zone a and b

$ATC_{a,b}$ is the transfer capacity between them

Equation (2.1) shows, to maximize social welfare (Max SW) of two zones (a and b), generation plus demand must be equal to Max SW. Equation (2.2) shows in a particular zone the sum of demand, generation and the available transfer capacity (ATC) must equal to zero. Equation (2.3) shows the ATC must be within $f_{a,b}$ constraints.

Challenge caused by DERs in the electricity market

A power supplier must decide the amount of power to offer in the day-ahead market, based on the day-ahead forecast. This means unbalance in real-time must be expected. The power unbalance in real-time can be either positive or negative depending on whether the produced power in real-time is lower or higher than the forecasted power quantity. Since REs are weather dependent power unbalance between the forecast power and power in real-time is usually expected to be large. This affects the power suppliers offering strategy, where power suppliers offer less in the day-ahead market to avoid too large discrepancies [22].

2.2.2 The future power system electricity market

The European Network of Transmission System Operators for Electricity (ENTSO-E) aims to develop a single day-ahead coupling for all European countries. This means all European countries will be able to clear the day-ahead market at the same time, providing a single optimization solution. ENTSO-E expects this to increase the overall efficiency of trading. The utilization of all generators across Europe will lead to higher efficiency and promote effective competition at the same time. Intraday market coupling is expected to follow when day-ahead coupling is accomplished. Nominated Electricity Market Operator (NEMO) is the entity created to carry out the task related to market coupling. NEMO is a collection of nominated market operator across Europe. To provide a coupling of electricity market price solutions across Europe, NEMO is working on an algorithm known as Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA) [23].

2.3 BENEFITS OF DERS IN THE FUTURE POWER SYSTEMS

With increasing planning and coordination of TSO-DSO interaction, DERs can be utilized for ancillary services such as [24] [25]:

***Grid network voltage support*:** At the time of high production, over-voltage may occur on a given node, flexible loads and energy storage systems can be used to reduce the increase in over-voltage.

***Grid network frequency support*:** ESSs can be used to maintain frequency balance by regulating injected active power into the system.

***Spinning reserve*:** The power generation that can be provided during an emergency, can be used in a situation to down-regulate during over-frequency.

***Load levelling*:** Power is stored during a high production period to be utilized during a high consumption period.

DERs Management

To fully utilize DERs, proper management is important. One of the current solutions is Distribution Energy Resource Management Systems (DERMS). DERMS is used for monitoring, managing, and maximizing DERs' power output. For DERMS to provide all its functionality, it typically requires an integration of other systems such as a distribution management system and supervisory control and data acquisition system(SCADA) [26].

When DERMS is fully functioning, it can manage DERs and other aggregators in the power system networks. It utilizes all the available active resources in the system network to archive power balance. Table 3 shows some managing areas of DERMs.

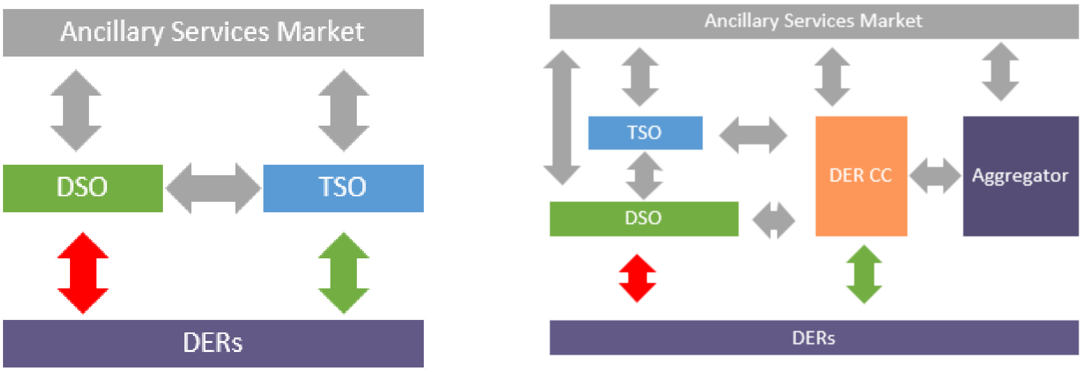
Table 3 shows the control areas of utility DERMs.

Name	Description
Generation management	Due to their intelligent functionality, utility DERMS can manage the output of DERs and then resolve the problems coordinatively.
Flexibility management of the DERs	Can make DERs flexible by adjusting loads and generation to archive system balance.
Managing electric vehicles	Fast charging of electric vehicles can dramatically increase peak load on the power networks; Utility DERMS can avoid overloading the power networks by managing these electric vehicles (EV).
Combination of utilization DERs simultaneously	Utility DERMS can utilize the available resources in the power system network at the same time.

2.3.1 Architecture Framework

Proper coordination of DERs in the electrical power system is one of the keys to unlocking the potential of future power system networks. There are different architecture frameworks used around the world today for coordination schemes of DERs. This section covers the existing coordination schemes for the integration of DERs in the electrical power systems. The schemes show different ways of controlling and monitoring the flow of data between relevant actors [27].

Figure 6 shows different coordination schemes. Grey indicates the flow of information related to dispatch of the DERs, green direct monitoring and control and red activation under emergency scenarios. Scheme A shows the data flow between TSO-DSO and the market. In Scheme A, TSO has direct control of DERs. In scheme B, the DER control Centre (DER CC) and aggregator are present [27]. DERs are directly controlled by DER CC, while data flows between relevant participants. In scheme C, the aggregator has direct control of DERs while data flows between participants. In scheme D, the aggregator controls DERs through DSOs' communication infrastructure, with no data flow between TSO and aggregators [28].



A) In this scheme DERs are controlled by TSOs.

B) In this scheme DERs are controlled by a control centre.

C) In this scheme aggregator controls DERs.

D) In this scheme DERs are controlled by aggregators through DSO communication infrastructure.

Figure 6 Shows different schemes of DERs coordination

2.4 DERs IMPACT ON VOLTAGE IN THE FUTURE POWER SYSTEM NETWORK

With increasing numbers of DERs in the Decentralized power system, voltage fluctuation issues in the system have been one of the highlighted topics; this section covers the voltage challenges related to DERs in the future power system [29].

2.4.1 IMPACT OF REs ON VOLTAGE OF THE FUTURE POWER SYSTEM NETWORKS

In recent years there have been an increase in penetration of DERs distribution grids. They have proven to be economically beneficial, but they come with over and under-voltage challenges.

The Over-voltage occurs when REs generation is much higher than consumption, which generates reverse power flow in the MV grid. Under-voltage happens when the consumption is higher than production, which can lead to damage or degradation of lifetime of the equipment's in the MV grid. [30] [31].

Another challenge is related to speed variation of the WT. The speed variation may cause intolerable levels of voltage flickers on the distribution grid. Voltage flickers severity depends on the depends on the inertia constant associated with blade and rotor mass. Voltage flickers are not an issue for a distribution system with a Large inertial constant [32] [33].

One of the challenges with PVs are related to clouds covering the sunlight, which leads to irregular power output affecting the voltage profile [5] Table 4 shows examples of voltage issues that DERs introduce in the distribution power system.

Table 4 Shows different voltage issues that occur in the distribution power system

Voltage issue name	Voltage issue description
Under-voltage	The voltage at the point of connection is under 95% of the operation voltage, which can be caused by a high load increase
Overvoltage	The voltage at the point of connection is over the operation voltage, can be caused by high penetration of REs
Voltage dips	A brief decrease in voltage, lasting from one cycle to a second, is caused by a brief increase in load.
Voltage swells	A brief increase in voltage, lasting from one cycle to a second

On the demand side under-voltage congestion in the network can occur due to high connected loads. This happens during peak load periods. For instance, certain classes of big loads such as electric vehicles or heat pump consumption may be moved at peak period like in the evening, leading to under-voltage at the time. To solve this issue demand-side flexibility can be utilized by moving bigger loads to a period of low consumption [34].

REs voltage variation

In this section we look at how grid connected PV affects voltage variation in the distribution grid. The voltage output from PVs is U_g, U_N is the nominal grid voltage assumed fixed, Z is the grid impedance with value for R and X, ΔU is the voltage variation, and I is the system current. Figure 7 shows the equivalent circuit of the PV distribution generator connected to the grid [35].

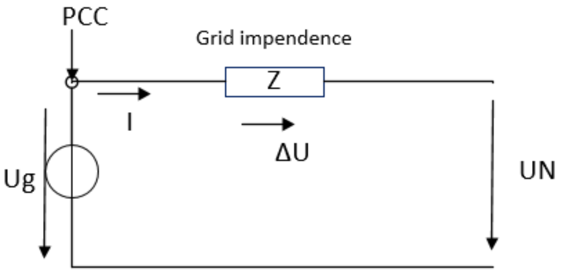


Figure 7 Shows the equivalent circuit of the PV distribution generator connected to the grid

Equation (2.1 shows the relationship between the variation in voltage and the grid voltage

$$\frac{\Delta U}{|U_N|} = \frac{Z * I}{|U_N|} \tag{2.1}$$

Equation (2. shows the current calculation, where S_G is the generated apparate power.

$$I = \frac{S_G}{|U_N|} = \frac{P}{|U_N|} - j\frac{Q}{|U_N|} \tag{2.2}$$

ΔU_d describes the direct-axis components and ΔjU_q the quadrature-axis component of the voltage deviation. Substituting the I and Z can equation (2. be written as:

$$\frac{\Delta U}{|U_N|} = \frac{(P * R) + (\pm X * Q)}{|U_N|^2} + j\frac{(P * X) + (\pm R * Q)}{|U_N|^2} = \Delta U_d + j\Delta U_q \tag{2.3}$$

In most distribution grids is adequate to consider the direct component of the voltage deviation only. Finally calculating the voltage magnitude at the point of common coupling for PV U_{PCC}.

$$|U_{PCC}| = |U_N| + U_d \tag{2.4}$$

Considering only the direct component of the voltage deviation from equation (2., it can be observed that the feed-in of active $(P * R)$ power contributes to the voltage rise problem, well as the reactive power can be used to reduce the voltage by -Q inductive consumption, or by +Q capacitive consumption. Using this for a distribution network, we end up with an equation for voltage variation of $\Delta U = RP + XQ$ and for the receiving voltage, $U_{Resciving} = U_{send} + RP + XQ$, considering $\frac{X}{R}$ ratiol.

Conventional voltage control

In power system operation controlling of voltage is an important task. The terminal voltages of all equipment in an electrical power system must be within their limits. A wide range of variation of voltage is not acceptable given that, both utility and customer equipment are designed to operate at a specific voltage range.

In the power system networks, the system voltage is mainly determined by reactive power generation and consumption. There are different methods used for voltage control in the distribution grid.

Table 5 Shows different conventional voltage control methods mostly used to updateTable 5 shows different conventional voltage control methods mostly used to update [18].

Table 5 Shows different conventional voltage control methods mostly used to update

Conventional voltage control methods	Description
On-line tap changers (OLTC)	A transformer that regulates the busbar voltage at the distribution grid, by changing the transformer winding ratio either by stepping up or down the taps without disconnecting the loads
Step-voltage regulator	This transformer is shunt connected on its high voltage winding side and in series on the low voltage winding side. The voltage winding either aid or oppose their respective voltage. The Step-voltage regulator can boost or buck the system voltage by 10%
Static VAR compensations (SVC)	Electrical device
Static Synchronous compensator (STATCOMs)	Electrical device
Synchronous generator	A generator that compensates reactive power
Capacitor/Reactors	Capacitor and reactors banks, used for compensations of reactive power

2.4.2 VOLTAGE SUPPORT IN THE FUTURE POWER NETWORK

In section 2.1 different challenges related to the transformation of the future power system is described. To solve voltage and frequency challenges, that comes with the absence of TSO support, DSO must acquire other qualified methods to provide the required support. Table 6 shows two examples of how voltage support can be provided in a decentralized distribution grid project [36] [37].

Table 6 Shows DERs voltage support

Methods	Description
REs	Utilizing REs in the distribution grid to provide voltage support, by charging its power factor, to regulate reactive power.
Demand-side flexibility (DSF)	Utilizing load flexibility on the demand side to provide voltage support.
Energy storage system (ESS)	The battery can be utilized at the time of high penetration of power

Demand-side flexibility

Demand-side flexibility basically means increasing flexibility on the demand side to archive more flexibility in the distribution grid. This means adjusting the electricity demand so that it follows the distribution grid generation. To activate this type of ancillary service, DSO must have real-time regional data regarding the production and consumption of electricity. Demand-side management (DSM) is the concept mostly used for this purpose [38].

For demand-side flexibility to be utilized, suitable controllable technologies are necessary. Different technologies are used depending on whether the solution is for residential, or industrial use. For the residential demand-side flexibility can be provided from, electric vehicles, or smart appliances, well as for industries, heat pumps, power-to-hydrogen, batteries, CHP etc. [39].

Demand-side management

Demand-side management (DSM) is essential for the utilization of demand-side flexibility. DSM concept process includes planning, implementing, and monitoring. The planning process normally associates with energy production forecast, load management well as financial aspects [39].

Several technics can be implemented in DSM for load profiling; it all depends on the interaction level between consumers and power suppliers. For this project, only the direct load control (DLC) technic will be properly explored for further usage in the voltage support.

In DLC, customer’s consumptions are directly controlled by the electricity supplier, for this to be feasible direct communication is required. The supplier has the freedom of disconnecting or moving the load during low electricity production. Table 7 shows examples of a few technics that may be used in DSM [40].

Table 7 shows technics for use in demand-side management

DSM Technics	
Name	**Description**
Energy-saving and load efficiency	Deals with the improvement of electrical equipment’s efficiency to reduce energy loss
Direct load control	Direct access to the loads, with the option of connecting or disconnect when required
Frequency control	Use of frequency to measure power imbalance, to provide require a response
Pricing	This is technic is based on electricity price incentives

DERs can cause voltage challenges in the distribution grid, but with planning and coordination, the issues can be solved. Economical it is beneficial to promote DERs in the future power system since their come low operation cost, which leads to a reduction in electricity price.

Chapter 3: ASSESSMENT OF DERS INTEGRATION

This chapter investigates the behaviour of a European benchmark model of a 20 kV MV grid, whose detailed design is described in section 3.1. The followed section 3.2 investigates the grid's behaviour with two defined cases, Base-case and Future-case. The Base-case investigates the behaviours of the MV grid with the existing installed capacity of the DERs. Assuming the installed capacity of DERs in the MV grid will increase, the Future-case investigates how it will affect the MV grids' behaviour.

3.1 THE MV GRID MODEL

The proposed grid model is based on a European benchmark model of a 20 kV MV grid connected to an external grid. As it can be seen in Figure 8, the MV grid consists of two feeders, interconnected to a 110kV transmission system. Feeder 1 consists of 11 nodes (1-11) linked with underground cables. Feeder 2 consists of 3 nodes (12-14) linked with overhead lines. The 20 kV MV grid also consists of three switches, making radial or ring operation possible for reliability. The power production comes from 3 DERs: CHP, WT and an aggregated PV. There are two types of aggregated LV loads, residential and industrial loads, distributed on the14 nodes in the grid.

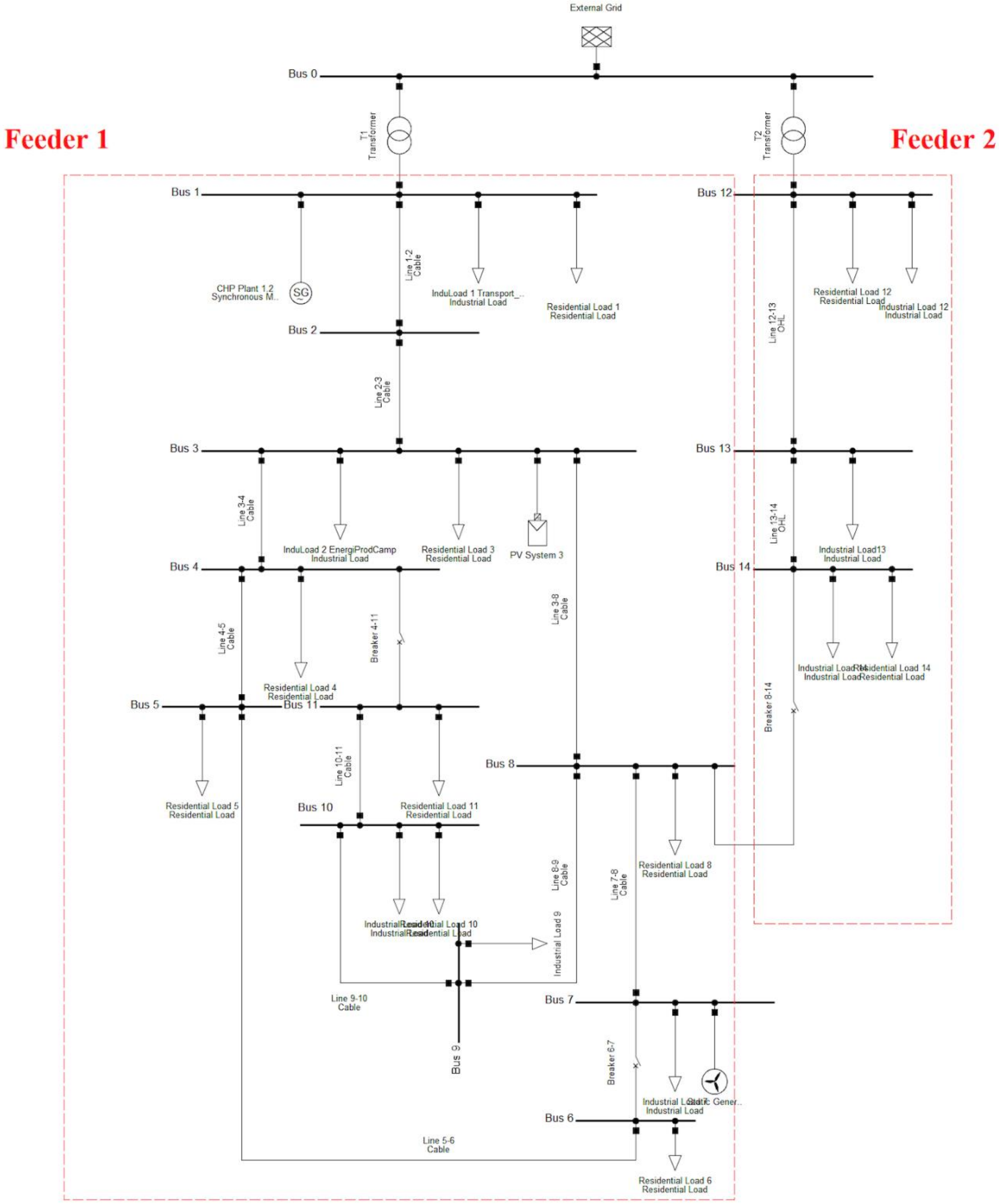


Figure 8 The European benchmark model of a 20 kV MV grid

The MV grid power generation and consumption model

The 3 DERs in the grid, WT, PV and CHP are located at different nodes, The CHP is connected to node 1, PV is connected to node 3 and WT is connected to node 7. The external grid is connected to node 0, which is stepped down by transformer 1 for feeder 1 and transformer 2 for feeder 2. Table 8 Data for generation and consumption in the MV grid shows the installed capacity for the DERs.

There are two types of aggregated loads, residential and industrial, distributed on the 14 nodes. Table 8 shows their corresponding power factor and the installed capacity.

Table 8 Data for generation and consumption in the MV grid

Node	**Loads Apparent power [MVA]**				**Generation Installed capacity**		
	Residential	**Industrial**	**Power factor**		**WT [MVA]**	**CHP [MVA]**	**PV [MW]**
			Residential	**Industrial**			
1	15.3	5.1	0.98	0.98	6	6	1
2	-	-	-	-			
3	0.285	0.265	0.97	0.85			
4	0.445	-	0.97	-			
5	0.750	-	0.97	-			
6	0.565	-	0.97	-			
7	-	0.090	-	0.85			
8	0.605	-	0.97	-			
9	-	0.675	-	0.97			
10	0.490	0.080	0.97	0.85			
11	0.340	-	0.97	-			
12	15.3	5.280	0.98	0.95			
13	-	0.040	-	0.85			
14	9.215	0.390	0.97	0.85			
Total	42.615	11.920	-	0.85			
Total Sum	54,535						

Lines and Transformer

The MV grid consists of two types of lines, underground cables and overhead lines. The underground cables are connected to feeder 1, and the overhead lines are connected to feeder 2. Table 9 shows the rated voltage, current, and impedance of the lines.

Table 9 Parameters for the lines in the MV grid

Underground cables					Overhead cables			
Nodes Connection	**R [Ω/km]**	**X [Ω/km]**	**I [kV]**	**V [kV]**	**R [Ω/km]**	**X [Ω/km]**	**I [kV]**	**V [kV]**
	0.51	0.715	0.5	20	0.508	0.365	0.5	20

The MV grid consists of two transformers on each feeder. Transformer 1 is connected to bus 0 and 1, while transformer 2 is connected to bus 0-12. Both transformers have a capacity of 25 MWA as presented in Table 10.

Table 10 Parameters for the transformer

S [MVA]	U1[kV]	U2[kV]	Short circuit U%	Z[ohm]
25	110	20	10.3	0.016+i1.92

3.2 ASSESSMENT OF DISTRIBUTED GENERATION INTEGRATION IN THE EXISTING MV GRID MODEL

This section investigates two cases, Base-case and Future-case. The Base-case investigates the behaviour of the MV grid with its existing installed capacity and a steady-state load flow simulation is conducted. In the future case, the installed capacity of DERs is increased and quasi-dynamic load flow simulation is conducted, to observe the MV grid behaviour over a longer period. The section also consists of a discussion of the base case and the future case.

3.2.1 Base-case

The Base-case investigates the behaviour of the MV grid under the worst expected conditions, regarding production and consumption capacity. The first scenario occurs when there is high production with low consumption, and the second scenario occurs when there is low production with high consumption. The report only includes the result for the first scenario, high production and low consumption, as the results for the second scenario is the same.

High production low consumption scenario

This scenario investigates the behaviour of the MV grid model when the production is high, and the consumption is low. PV production is assumed to be 1 MW, WT and CHP production is assumed to be at 100% of their installed capacity of (6MVA). The consumption is assumed to be only 10% of the installed capacity.

The steady-state load flow simulation of the MV grid behaviour under this scenario is shown in Figure 9. The voltages on all nodes are within permissible limits of $\pm 10\%$, which is properly showed in Figure 10. All the lines loading in the MV grid are below 40% of their rated value. Transformer 1 is the most loaded, with 43,8% of the rated value.

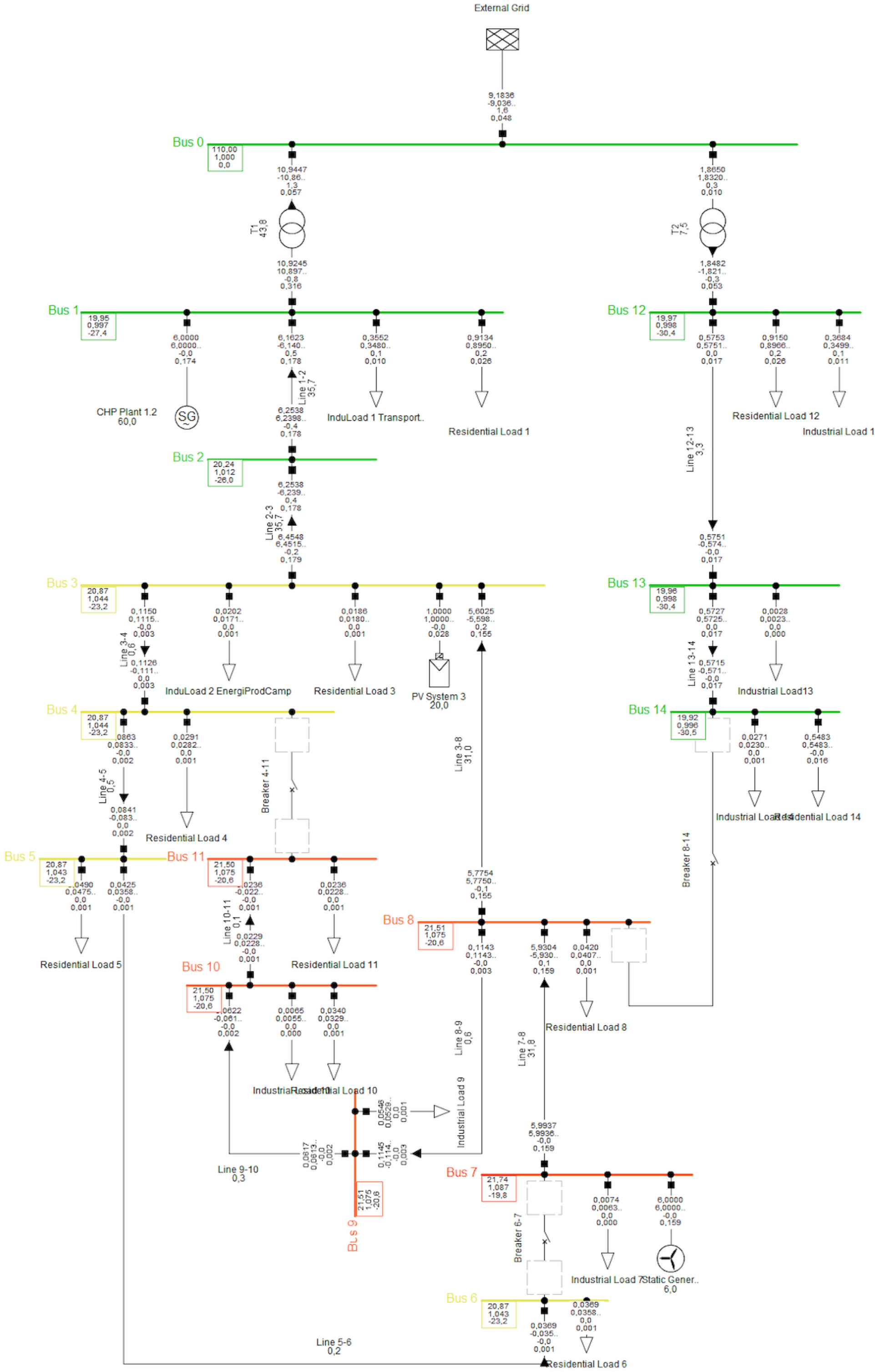


Figure 9 MV grid under high-production with low-consumption

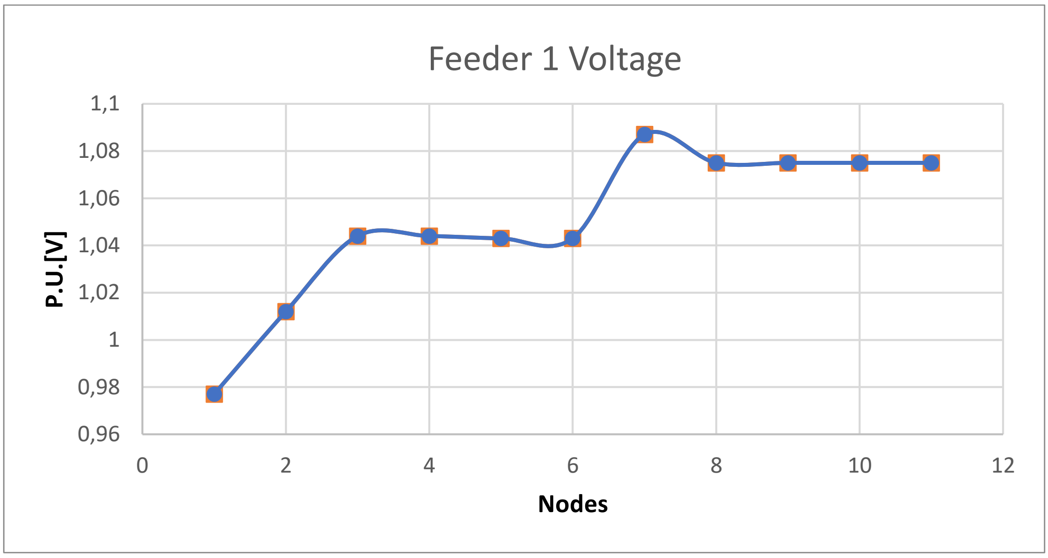


Figure 10 Voltage on each node

3.2.2 Future-case

In the future power system networks DERs will increase and TSOs and DSOs power production will depend on more REs. In this case model, only the installed capacity of WT in the proposed European MV grid model has increased. The installed capacity for WT increases to 15MWA, while the rest of the components such as transformers and lines are the same.

In the future-case, we wish to observe the MV grids behaviour over a longer period of time. For this reason, a Quasi-dynamic load flow simulation (QDLFS) is selected for the simulation. QDLFS can be done for different time scopes. In this case, the simulation is done for a week, which corresponds to 168 hours. The project simulates a typical winter week, in this case, 16/12/2019 to 22/12/2019. To perform QDLFS load flow simulations, it is necessary to design a production and consumption profile, which is covered in the section below.

Quasi dynamic load flow simulation production profile design

To obtain realistic production profiles, real-life data is used for the time period of 16/12/2019 to 22/12/2019. The WT production profile is based on wind speed data from the DBeaver database [41]. Figure 11 shows the production profile for WT. The PV production profile is based on data obtained from the irradiation registered in the simulation program (DIgSILENT). The PV production profile is shown in Figure 12. The CHP production profile is based on data from a CHP in Skagen, Northern Denmark and is shown in Figure 13.

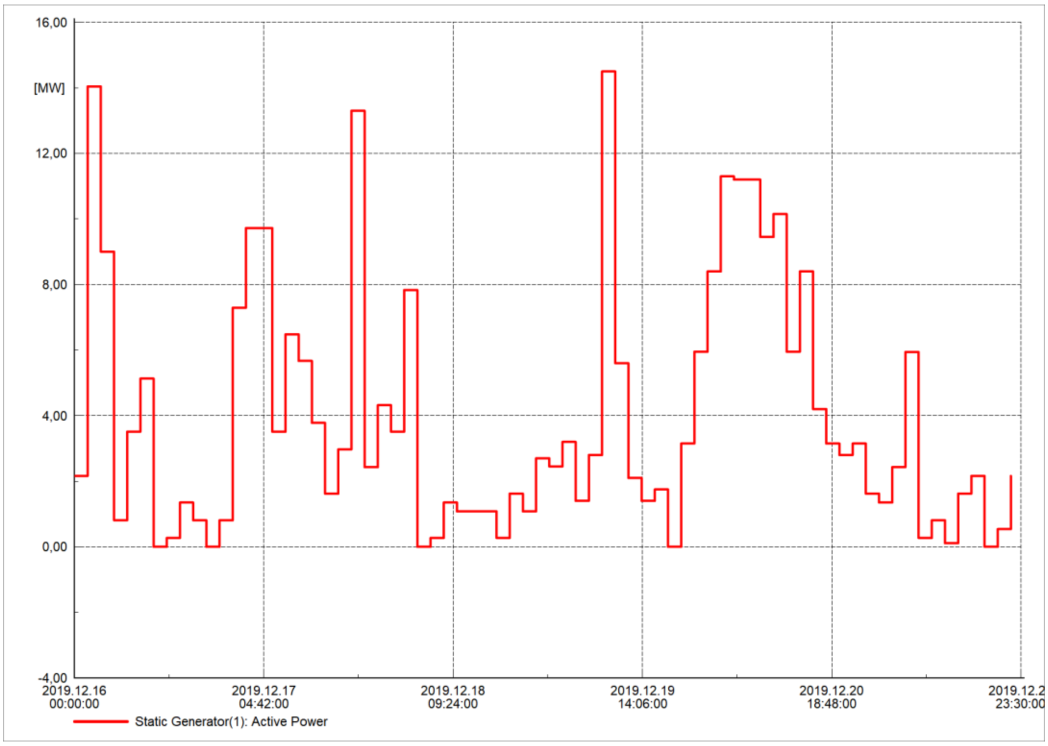


Figure 11 WT production profile

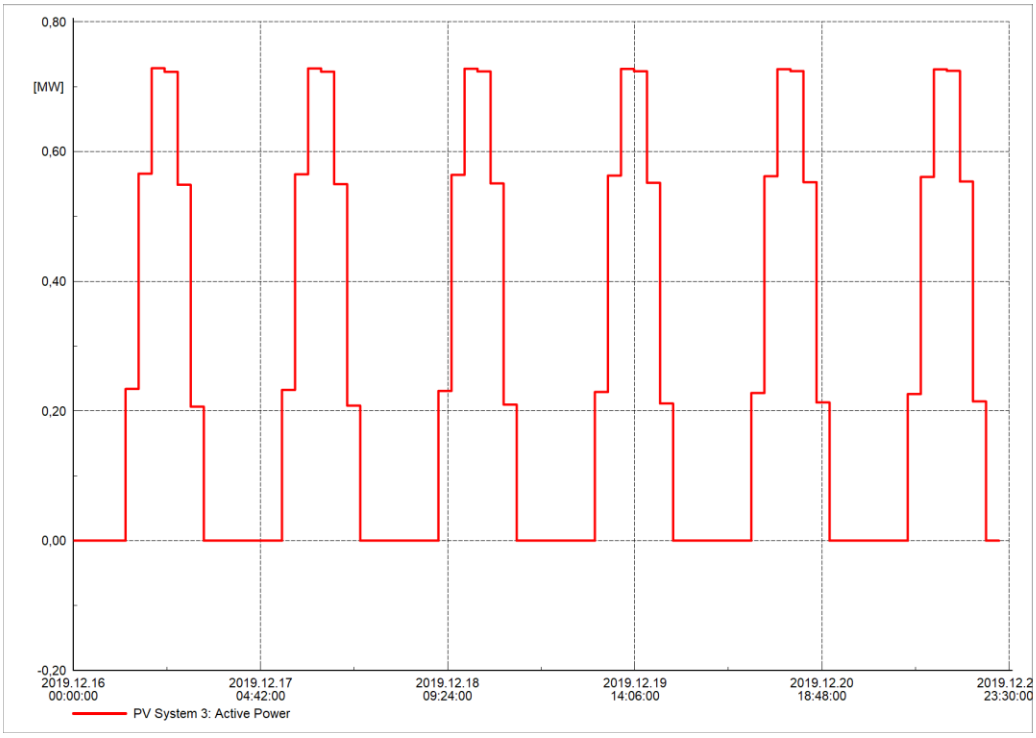


Figure 12 PV production profile

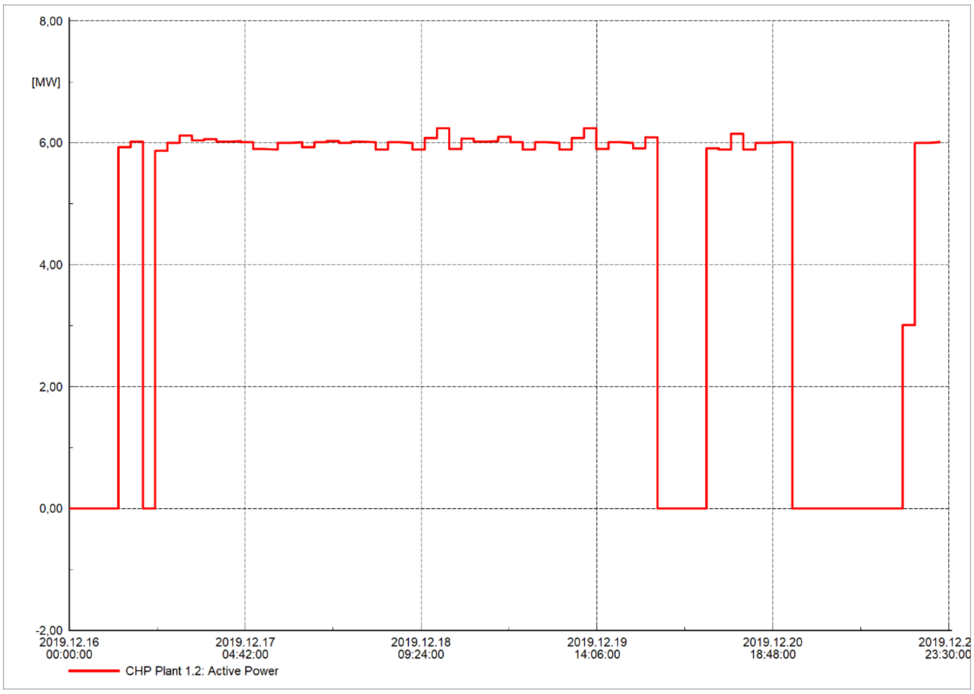


Figure 13 CHP production profile

Quasi-dynamic load flow simulation consumption profile

The design of all 18 load profiles in the MV grid is divided into two types, residential and industrial, and the installed capacity corresponds to the European benchmark MV grid model seen in Table 8.

The load profiles are designed from consumption data of 16/12/2019 to 22/12/2019 from Energinet.dk, which is scaled down to fit the MV grid model capability. Every load profile consists of a weekday(Mon-Fri) and weekend(Sat-Sun) profile. Figure 14 shows an example of a weekday residential load profile.

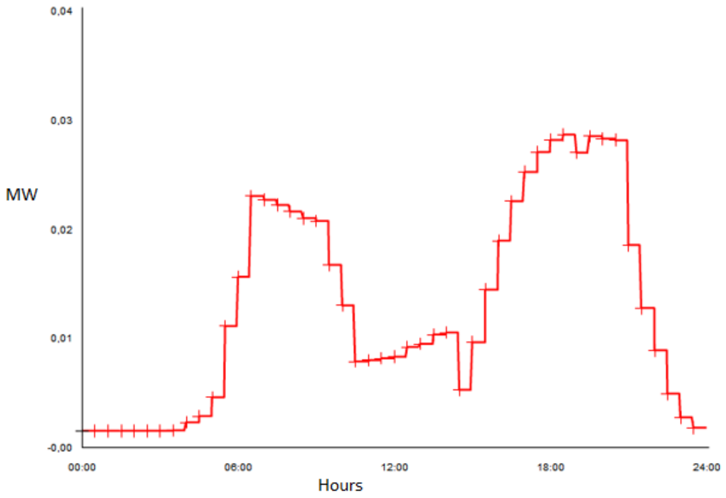


Figure 14 Weekday Residential Load Profile

Future-case results

In the future-case, QDLFS shows two challenges in the MV grid, over-voltage and reverse power flow.

Over-voltage problems are happening several times during the simulation surpassing the limit of ±10%. Table 11 shows that during 168 hours of simulation (1 week), over-voltage occurs for 28 hours, which corresponds to 16% of the time. This issue must be dealt with to fulfil the voltage regulation limits.

Table 11 Over-voltage hours

QDLFS for 16/12/2019-22/12/2019			
Names	Total over-voltage hours	Total QDLFS hours	Total overvoltage in percentage
Node 7	28	168	16%
Node 8,9,10 and 11	18	168	10%

The over-voltage issue is caused by the increase in the installed capacity of WT. Over-voltage is happening on node 7,8,9,10 and 11 which can be seen (Appendix B). Since the WT is located at node 7, this node has the highest over-voltage, which occur at 02:00 on 16/12/2019. Figure 15 and Figure 16 show node 7 and 8 voltage profiles under QDLFS from 16/12/2019 to 22/12/2019. Nodes 9,10 and 11 are like node 8, because of the short distance between them.

Reverse power flow is also a concern for both TSOs-DSOs. Figure 17 shows the reverse power profile during QDLFS, where reverse power flow occurs at values below zero. The highest reverse power flow of 10,9MW is on 17/12/2019 at 02:00.

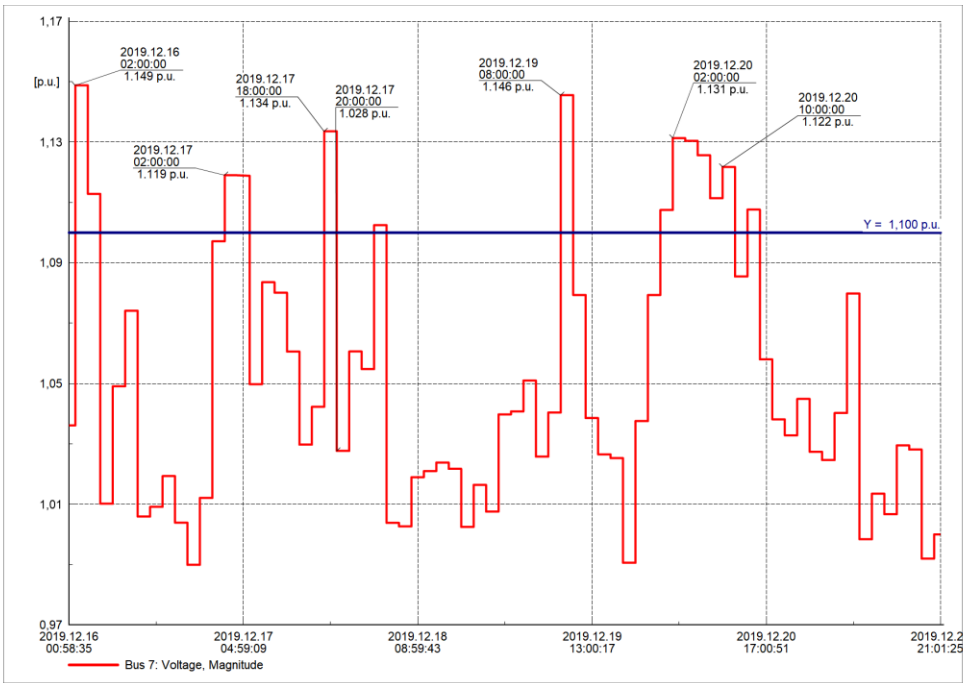


Figure 15 Node 7 voltage profile

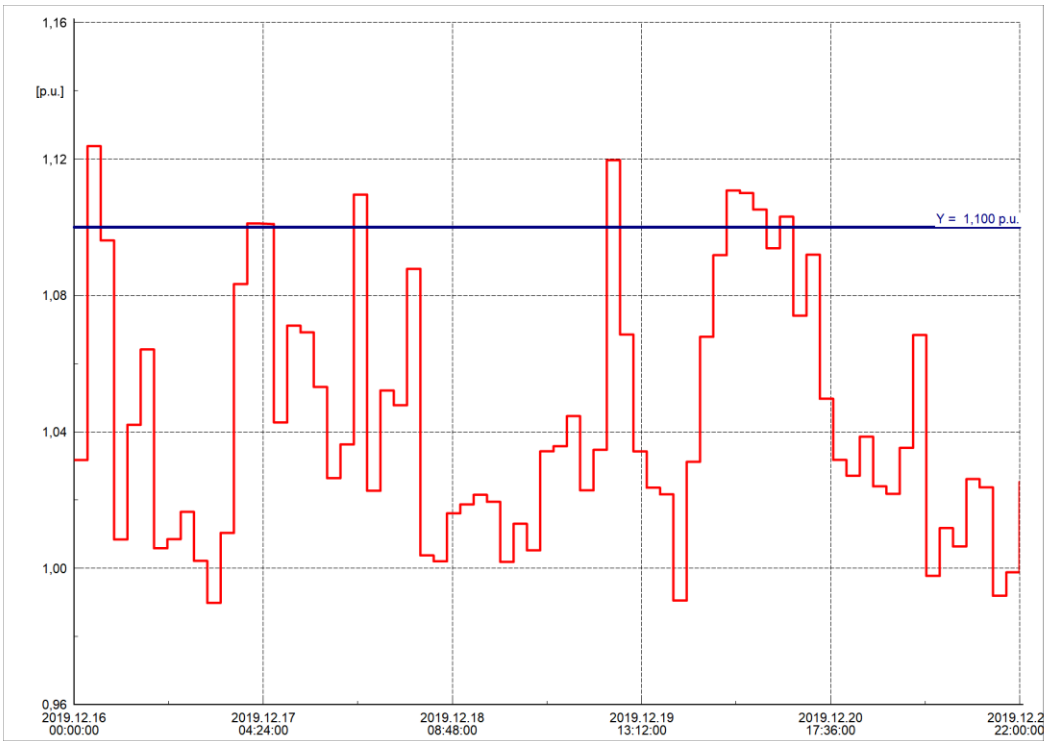


Figure 16 Node 8 voltage profile

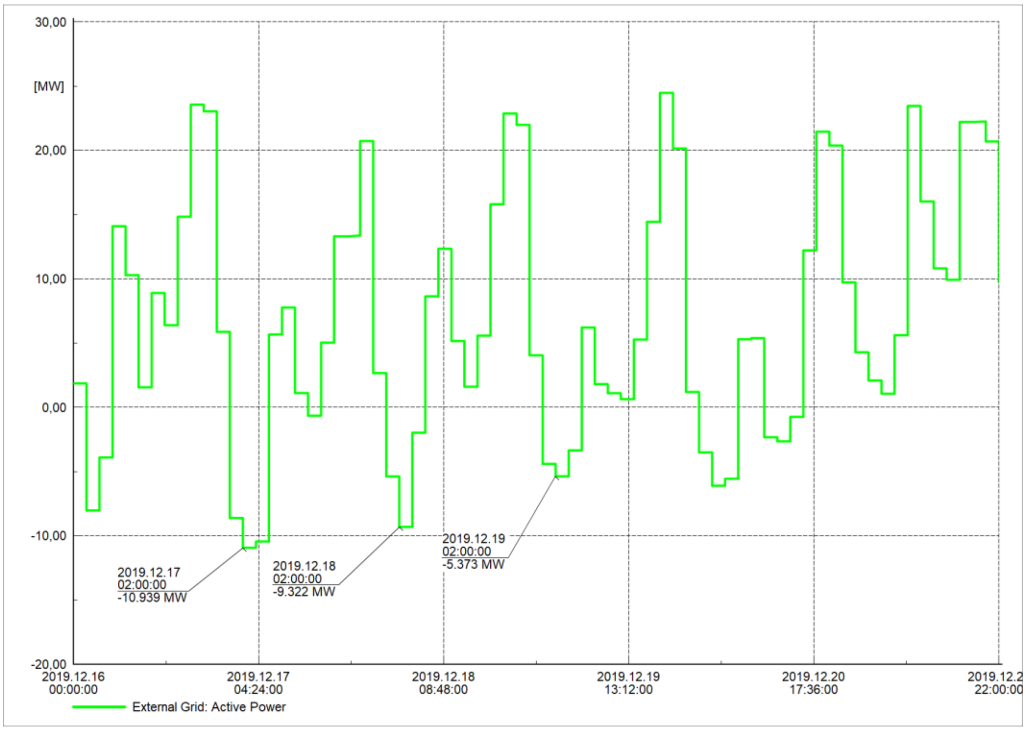


Figure 17 Reverse power profile

The excess of power produced by the WT on node 7 is not consumed locally, leading to power flow back to the transmission grid. The power travels through lines, which leads to an increase in power loss in the MV grid. The largest loss is happening on line 3-8 followed by line 2-3, mainly because of the reverse power flow and the line length (impedance), which is over 4 km for both lines. Line 7-8 is nearest to the excess power generated from the WT, but the power loss is not equal to, or larger than line 2-3 and 3-8 because it is shorter. The power loss is large at the time of high WT penetration, and origins at the lines affected by the reverse power flow, line 1-2, 2-3, 3-8 and 7-8. Increasing the installed capacity of WT has led to an increase in line loadings. Table 12 shows line loading for the future-case for the lines affected by reverse power flow.

Table 12 Line Loadings

Line name	Loading [%]
Line 1-2	73.17%
Line 2-3	73.26%
Line 3-8	72.66%
Line 7-8	73.07%

When investigating power loss related to lines in Figure 18, reactive power loss is higher than active power loss, mainly because the lines are consuming the reactive power in the MV grid. However, the amount of active power loss for the lines affected by reverse power flow is still high. Figure 18 shows the active and reactive power loss for line 3-8 during the QDLFS.

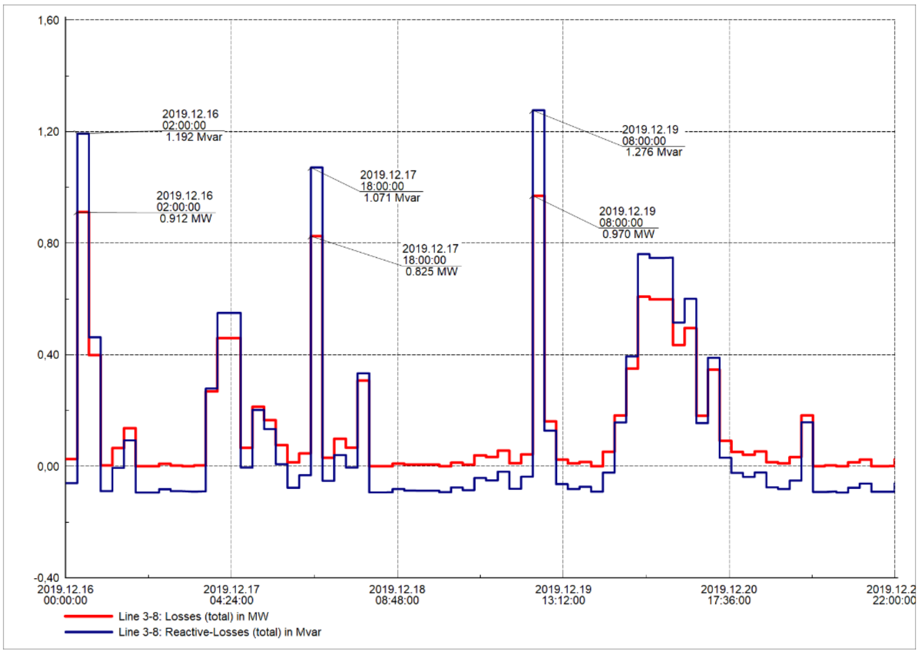


Figure 18 Line 3-8 Active and reactive power loss

3.2.3 Base case and future case discussion

The Base-case results show that the voltage profile for all nodes is within ±10%. This means the MV grid voltage limits are fulfilled. However, the results show reverse power flow, which must be coordinated by TSO-DSO to optimize the usage of electricity in the system.

The future-case results show over-voltage and reverse power challenges, which leads to a higher power loss in the MV grid. Power loss in the electrical system is mostly related to lines affected by the reverse power flow. Even though the lines are not fully loaded, the resulting power loss has an economic impact on the DSO in the long run, since transmission power loss, leads to less generated profit.

The over-voltage is happening during high production and low consumption hours, peak over-voltage is happening consequently at 02:00 every day, which is the period with the highest power unbalance between generation and consumption, mainly due to low consumption. Solutions to the over-voltage issues are explored further in the following chapters.

Another challenge is the reverse power flow. As with the Base-case, TSO-DSO must coordinate the reverse power flow to optimize the overall electrical power system and thereby provide operation security and economic benefits for both parties. Coordinating the reverse power in such a way, that the power is consumed close to the MV grid, will yield a reduction in transmission loss thereby optimising the electrical grid. In a case where the reverse power can not utilize locally, TSO and DSO must coordinate for the best usage of power in the electrical power system.

To summarize, the described simulations show that increasing the installed capacity from REs, as intended in the future power systems to decrease pollution and operational cost, will entail challenges that must be solved. This will be discussed further in the following chapters.

Chapter 4: VOLTAGE ASSESSMENT UTILIZING OLTC AND UNCONTROLLABLE EV LOADS

The QDLFS in 3.2.2 shows two important concerns for the MV grid when increasing WT installed capacity: reverse power flow and over-voltage on several nodes. Over-voltage issues have to be solved locally in the MV grid, whereas the reverse power flow must be coordinated between TSO-DSO to enhance the future power system networks.

This chapter aims to solve over-voltage issues using conventional and futuristic voltage control methods. The voltage control methods to be utilized are OLTC and a futuristic voltage control such as demand-side flexibility. These methods will be assessed in relation to the described model in the Future-case in chapter 3. For this purpose, modelling of a realistic transformer tap changer and aggregated loads(EVs) are necessary.

The first assessment used for voltage control is OLTC, as shown in Figure 19. The OLTC is one of the reliable and most used voltage regulation mechanism in electrical power systems. It can regulate its voltage while carrying the load by utilizing its turn ratios.

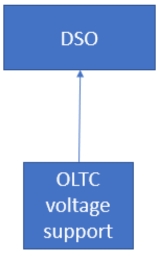


Figure 19 OLTC voltage support

OLTC taps can either be added or subtracted to control the voltage on the primary or secondary side of the transformer. Most of the variable taps of the transformer are located on the HV side, due to low current, making voltage regulation more precise. Figure 20 shows the equivalent circuit of the LTC, where I, U, n and y respectively indicates the current, voltage, normalization of the turn ratio and the transformers admittance. P indicates the primary side while S indicates the secondary side of the transformer.

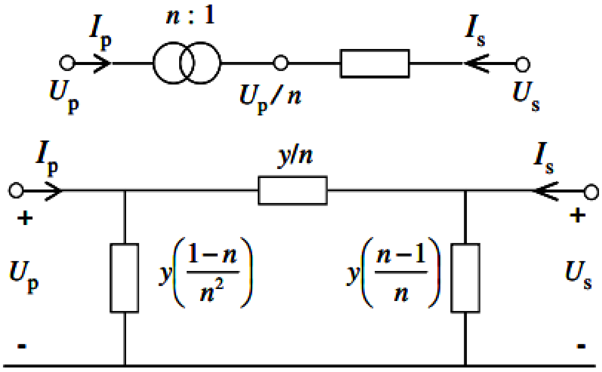


Figure 20 LTC equivalent circuit

Figure 21 shows the basic arrangement of the OLTC. Its job is to keep the secondary voltage bus at U_0 within its defined boundary.

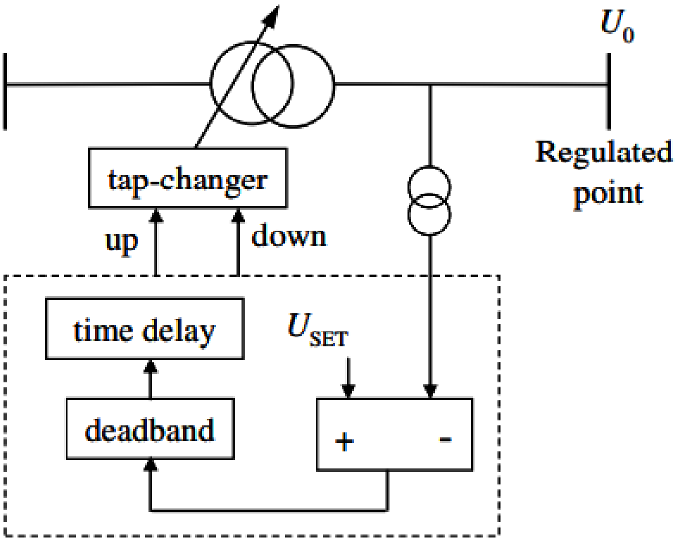


Figure 21 OLTC set-up

As equation 3.2 and 3.3 shows, the upper boundary and lower boundary of the voltage can be regulated to reach U_0 by changing the step size of T.

$$U_{LB} \leq U_0 \leq U_{UB} \tag{3.1}$$

$$U_{Lb} = U_{set} - T * U_{DB} \tag{3.2}$$

$$U_{UB} = U_{set} + T * U_{DB} \tag{3.3}$$

where:

U_0 is the voltage target point

U_{Lb} is the lower boundary of the voltage

U_{UB} is the upper boundary of the voltage

U_{set} is the voltage set-point

U_{DB} is the dead band.

T is the step size of the percentage of the OLTC

OLTC voltage assessment results

For this project, the selected transformer consists of ± 9 taps, each tap increases or decreases the voltage by 0,356 kV, which corresponds to 1.78% per. step.

The QDLFS with the implementation of OLTC has not shown any improvement of the over-voltage in the MV grid, as Figure 22 and Figure 23 shows. The over-voltage profile for node 7 and 8 are still the same as in the Future-case, section 2.2.2.

The voltage profile for node 9,10 and 11 looks like that of node 8. This is mainly because the lines linking nodes 9,10, and 11 are relatively close to each other, their total line length is 1.42km. The voltage profile highly depends on the line length between nodes.

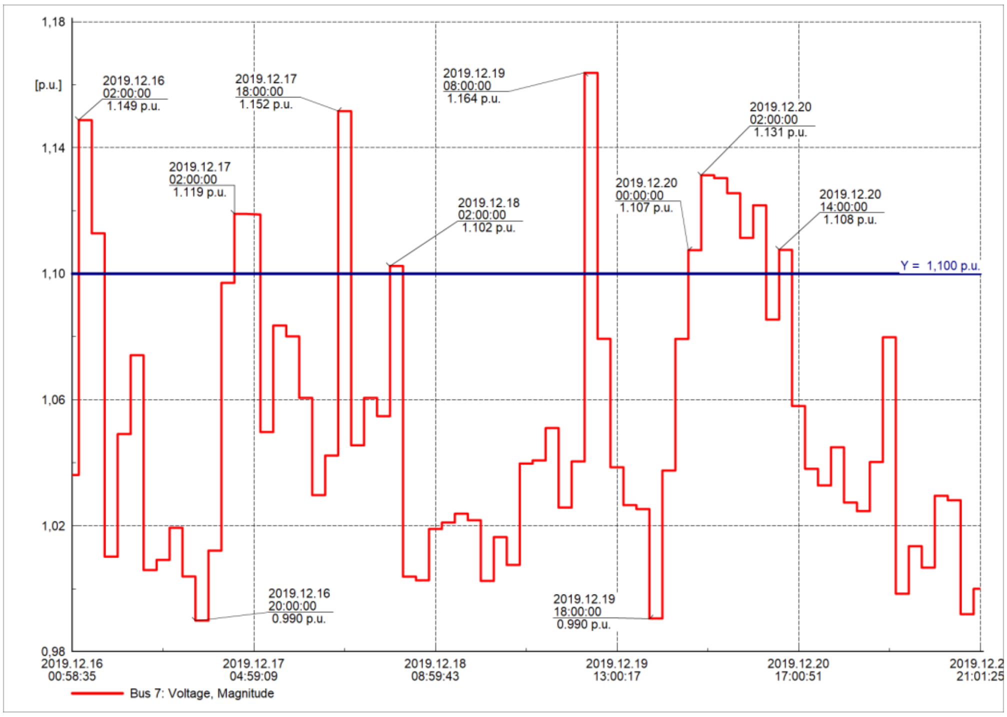


Figure 22 Node 7 voltage profile OLTC

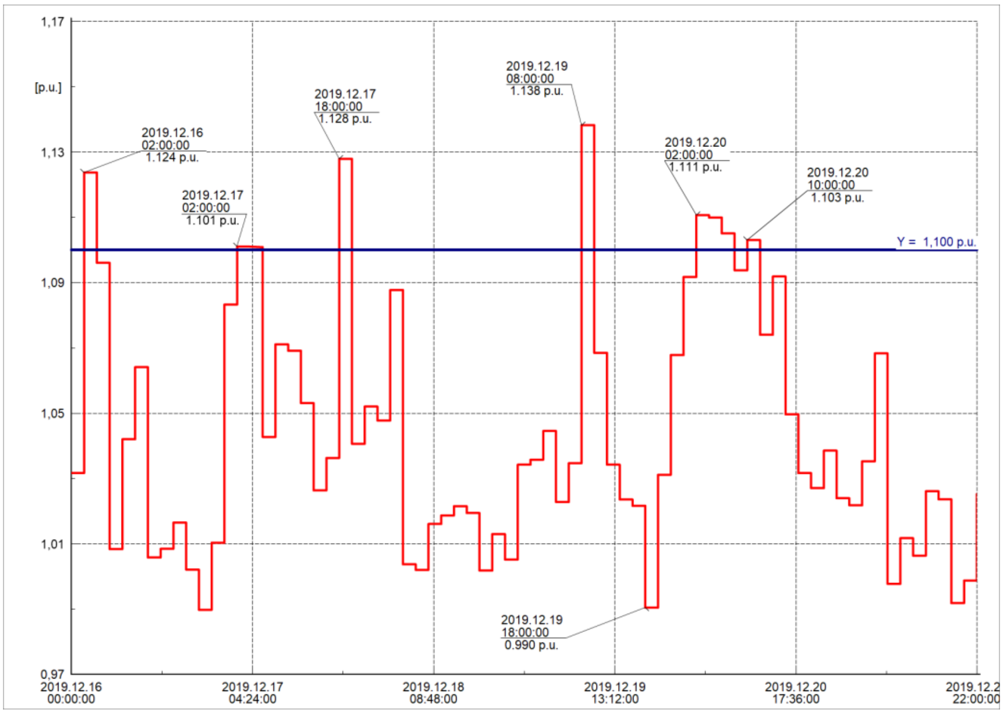


Figure 23 Node 8 voltage profile OLTC

To improve the voltage issue for feeder 1, transformer 1 OLTC is activated twice during the QDLFS. As shown in Figure 24 the activation occurs on 17/12/2019 at 18:00-22:00 and 19/12/2019 at 08:00-10:00. The activation does not create new voltage issues. OLTC only intervene twice, irrespective of over-voltage happening multiple times, because a continuous attempt to reduce the voltage on node 7, will result in a voltage drop in other nodes. It can be concluded, that the OLTC has not improved the over-voltage issue for the MV grid in the Future-case.

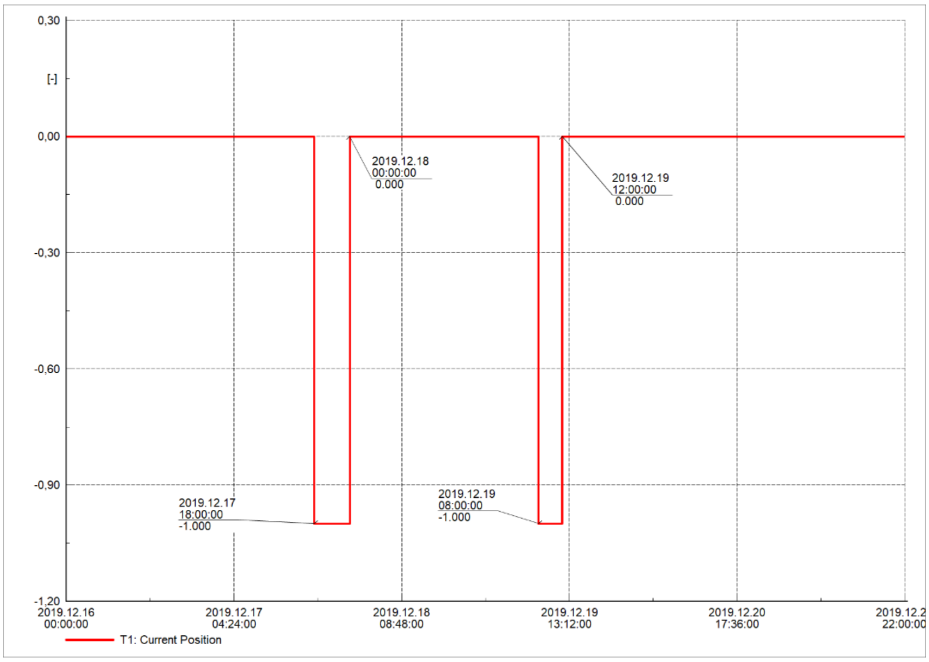


Figure 24 Transformer 1 OLTC

Implementing OLTC has slightly improved the line loading in the MV grid. Table 13 shows line loading compared with and without the implementation of OLTC.

Table 13 Line loading with OLTC

Line names	**Loading [%]**	
	Without OLTC	With OLTC
Line 1-2	73.17%	72.03%
Line 2-3	73.26%	72.11%
Line 2-8	72.66%	71.52%
Line 7-8	73.07%	71.93%

The reverse power flow is not improved with the implementation of the OLTC as shown in Figure 25.

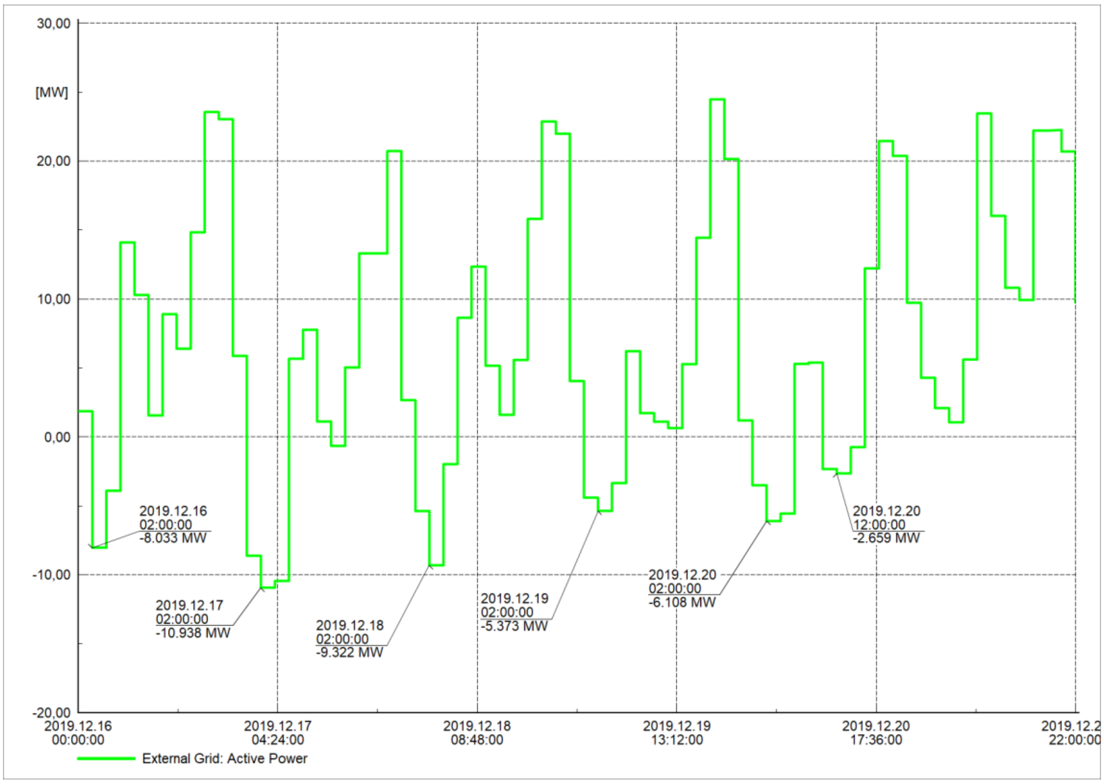


Figure 25 Reverse power flow with OLTC

4.1.1 Voltage assessment utilizing uncontrollable Electric vehicles

Many countries around the world consider EVs to be the future of transportation due to crucial factors such as CO2 footprint, tax reduction and technological development. EV deployment has been growing rapidly over the past years. According to the European Electric Vehicle factbook for 2019/2020, the average EV sales share in Europe has increased by 3.6% and is expected to double by 2020/2021 [42].

EVs component infrastructure can be divided into three categories: control, hardware and communication, as can be seen in Figure 26.

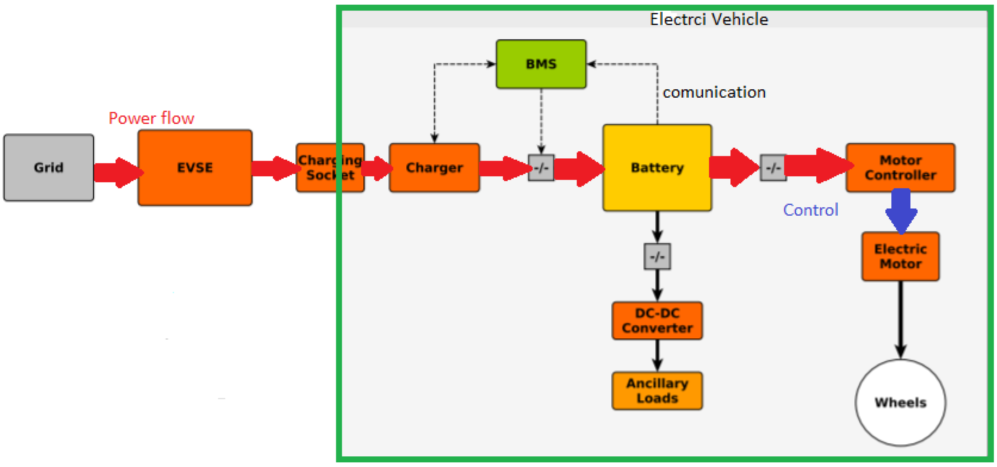


Figure 26 Simplified EVs architecture

The continuous interest in EVs has pushed the technological development of EVs and many of their components. EV charging time plays a significant role for consumers in terms of EV purchase. The EV charging types are categorised by their capacity. Currently, in the market, the charging types found are slow charging, fast charging, rapid charging and ultra-rapid charging. Table 14 shows their capability, connection types and where they are usually located.

Table 14 EV Charging Types

Charging Type	**Connection**	**Power[kW]**	**Location**
Slow charging	1-phase AC	3-7	Residential
Fast charging	1 or 3-phase AC	7-22	Residential/Public
Rapid charging	3-phase AC or DC	>22	Public
Ultra-rapid charging	DC	>22	Public

Batteries

In today's market, the most used battery for EVs is lithium-ion, due to better performance compared to other batteries such as lead-acid or nickel-based batteries. EVs battery pack are composed of multiple battery cells connected in series and parallel configuration, depending on the desired voltage and current level. Figure 27 shows the energy density for different types of batteries in today's market.

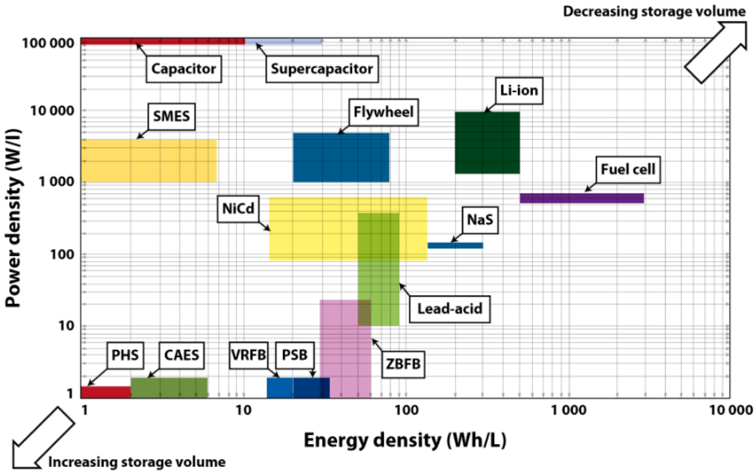


Figure 27 Batteries' power and energy densities [43]

EVs typically charge at a constant current, which is usually equal to or less than the nominal battery current. As the charging process continues, the voltage of the EV battery increases until it reaches maximum voltage usually around 80% of the state of charge (SOC). At this point, the current start decreasing slowly until the battery reaches SOC of 100%, also known as the CC charging region. Figure 28 shows a typical charging of an EV lithium-ion battery.

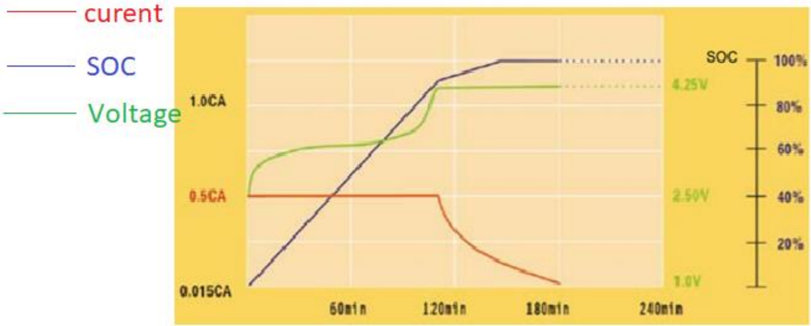


Figure 28 EV charging process [44]

Battery management system (BMS)

The battery management system manages the charging and recharging of a battery. It consists of an algorithm that protects the battery from operating outside its safe operating region. It monitors the battery state, balances individual cells, and controls its temperature. Figure 29 shows a battery management system structure.

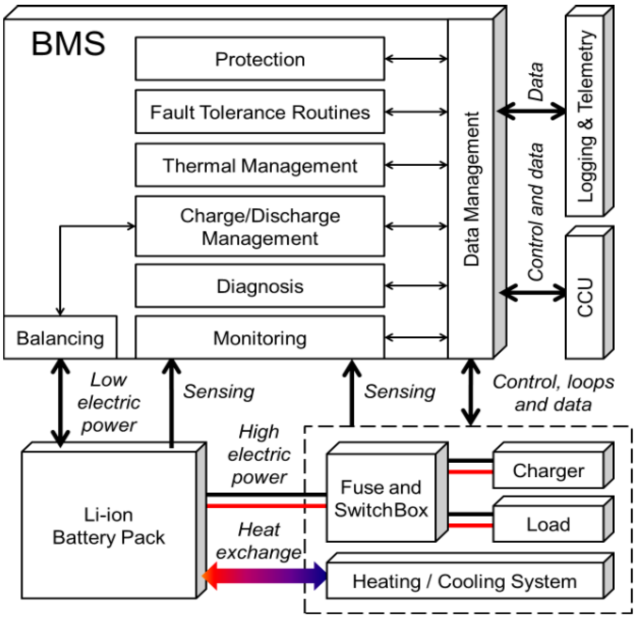


Figure 29 [43]

EV profile design

While an EV is our biggest load in a household, a single EV load has a very little impact load in the power grid, but when EVs are aggregated in large numbers, its impact on distribution and transmission is on a large scale.

In this section, we look at how aggregated EVs affects the voltage in the MV grid with OLTC, without consideration of demand-side flexibility, as shown in Figure 30.

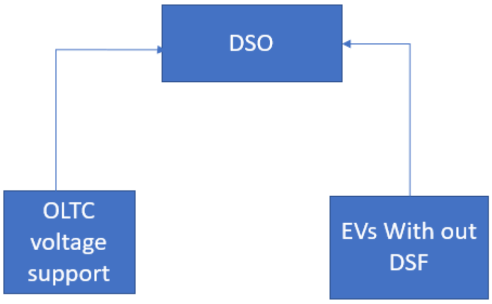


Figure 30 OLTC and EVs without demand-side flexibility

The EV design of this project consists of three EV charging types. Table 15 shows the EV types, their charging capacity and the available aggregated charging units in the MV grid. Table 15 also shows their assumed location in the MV grid.

Table 15 Charging types

Types of charging station	Capacity	Available Unit	Expected full charging duration	Installed capacity	MV grid location
Slow charging (residential) AC	6kW	100	6-8 Hours	0.6 MW	Node 11
Fast charging (commercial/residential) DC	22kW	100	3-4 Hours	2.2 MW	Node 9
Rapid charging (commercial) DC	50kW	100	1 Hours	5 MW	Node 8

To perform QDLFS with the EV loads, it is necessary to design their load profile. For this, human factors such as day to day routines related to work and family have to be considered. The design is based on EVs users probable behaviour based on a research paper and own observation, which shows different charging pattern for slow, fast and rapid chargers [45].

Slow chargers are in a residential area, which means they are typically charging when people are home. Slow charging is estimated to be from 2:00 pm to 7:00 am the next day, depending on the consumers' occupation. It should be noted that the EV charging for weekdays are different since most consumers are not working at the weekend, which can lead to a shift in consumption. Figure 31 shows the estimated slow charging EV load profile.

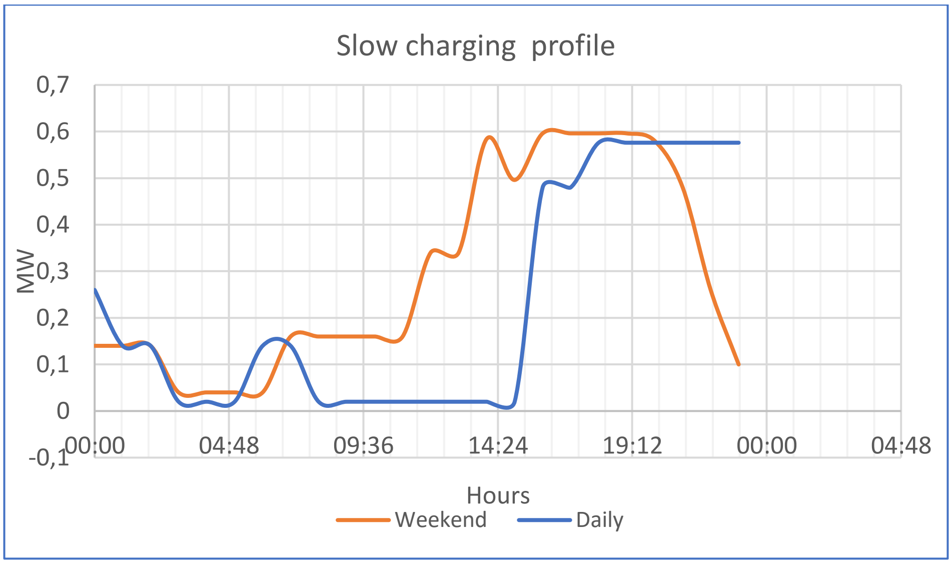


Figure 31 Slow charging profile

Fast charging are in public areas. Considering their location, their loads are expected to start increasing early in the morning, peak during working hours and decrease when people leave work. Weekends have similar profiles due to the location in public areas. Figure 32 shows the estimated fast-charging EV profile.

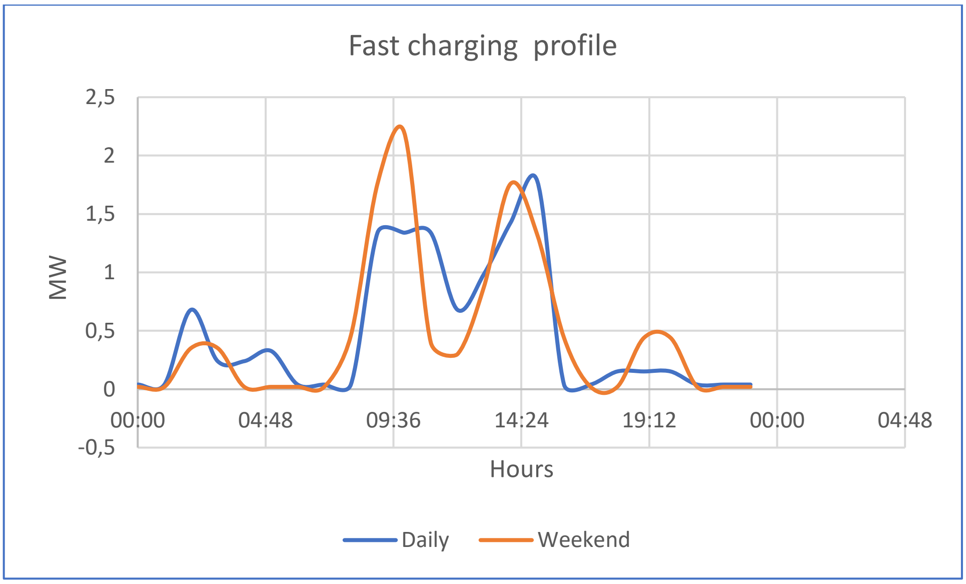


Figure 32 EV fast-charging profile

Rapid charging are located at public places, such as big shopping centres or petrol stations on the motorway. Its peak load is estimated to take place during working hours on both weekdays and weekends as can be seen in Figure 33.

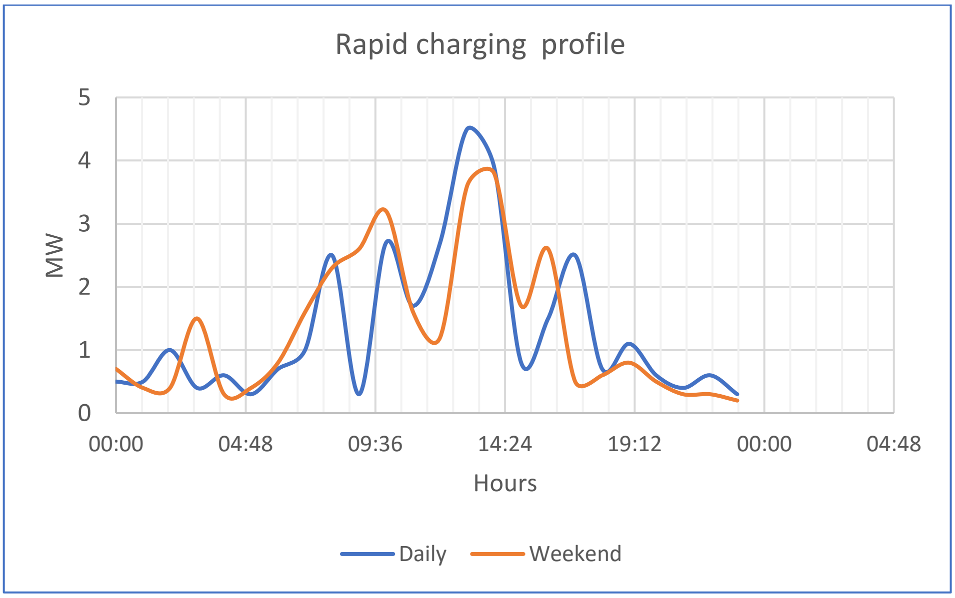


Figure 33EV rapid charging profile

EV voltage assessment results

These designs and estimations of EV loads are implemented in the QDLFS, to observe how it affects the voltage behaviour of the MV grid. Figure 34 and Figure 35 shows the voltage profile results of QDLFS for node 7 and 8. The results show EV loads have improved the over-voltage issue in the MV grid. This is mainly because of the local increase in consumption. However, an EV loads implementation has led to a significant voltage drop on 16/12/2019 but still within ±10%, which is because the MV grid is heavily loaded during this period.

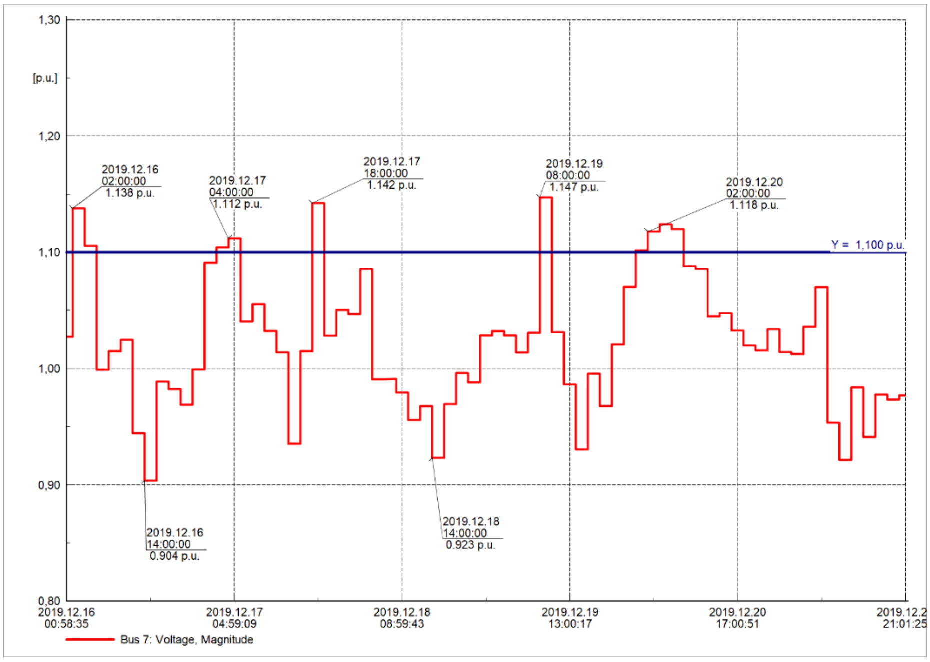


Figure 34Voltage profile node 7 with OLTC and aggregated EV loads

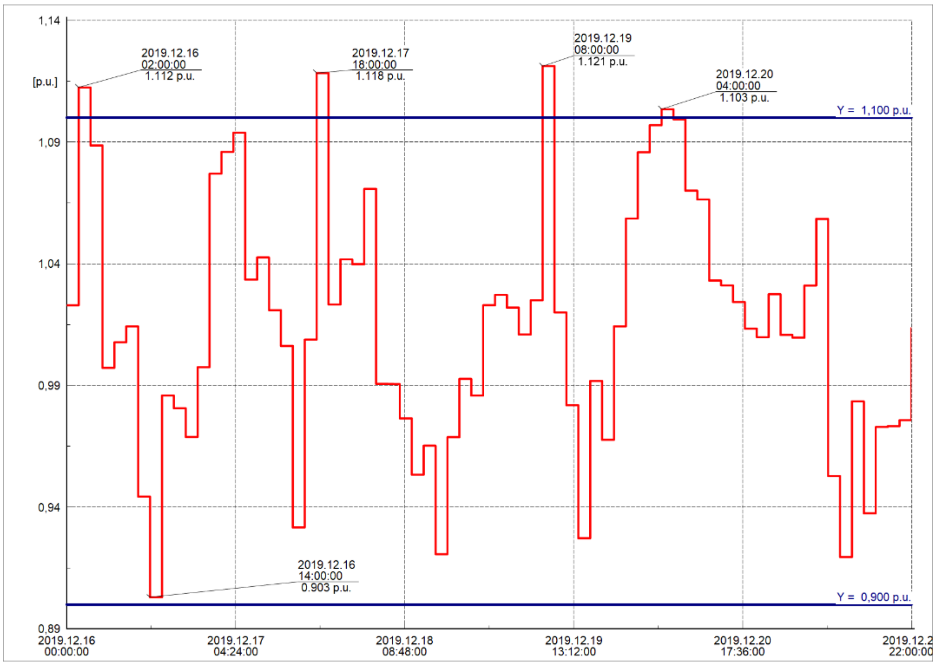


Figure 35 Voltage profile node 8 with OLTC and aggregated EV loads

Implementing EV loads has led to a decrease in reverse power flow, mainly because some of the power produced by REs are consumed locally. This is shown in Figure 36.

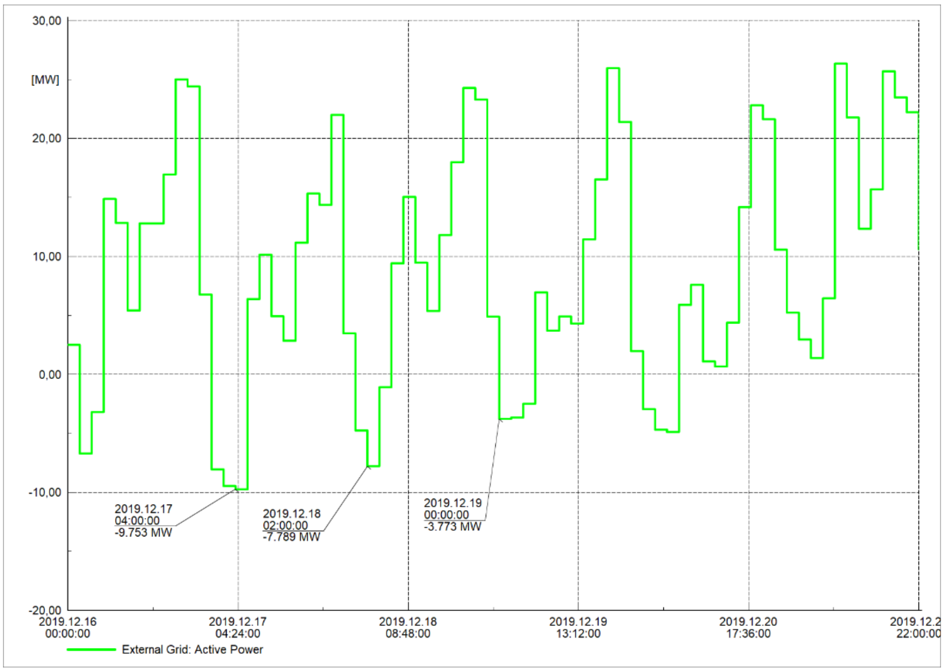


Figure 36 Reverse power flow with OLTC and aggregated EV loads

Table 16 compares the highest reverse power flow of the QDLFS with and without EV loads, it shows a decrease of 10%.

Table 16 Reverse power flow comparison for with and without EV loads

Peak reverse power flow Without EV loads [MW]	Peak power With EV loads [MW]	The difference in [%]
10,94	9,75	10,8%

Implementing EV loads has also further improved line loading in the MV grid, Table 17 Line Loadings comparison of without and with EV loads shows line loading without and with EV loads implementation.

Table 17 Line Loadings comparison of without and with EV loads

Line names	**Loading [%]**	
	Without EV loads	With EV loads
Line 1-2	72.03%	61,50%
Line 2-3	72.11%	61,58%
Line 2-8	71.52%	61.70%
Line 7-8	71.93%	72.97%

4.1.2 Discussion for OLTC and uncontrollable EV loads

The implementation of OLTC voltage control does not make any significant difference to the over-voltage, reverse power flow and power loss challenges in the MV grid. The OLTC voltage control is located at node 1, while the over-voltage issue is happening on node 7,8,9,10 and 11. Considering distance dependency, OLTC cannot provide an over-voltage solution. If the remote control is implemented in OLTC to solve the over-voltage issue on node 7, the closest node to OLTC will be subjected to severe under-voltage issues, which increases complexity in solving voltage issues.

The increasing consumption followed by the integration of EV loads in the MV grid has improved the over-voltage issues. Peak reverse power flow is reduced by 10% with the increase of EV loads, leading to a higher instantaneous local consumption of electricity. As it can be seen in Figure 37 EV loads account for a large amount of consumption in the MV grid relieving the grid during high-production hours. However, the high consumption can also cause a risk of under-voltage, which will be explored further in the following chapter.

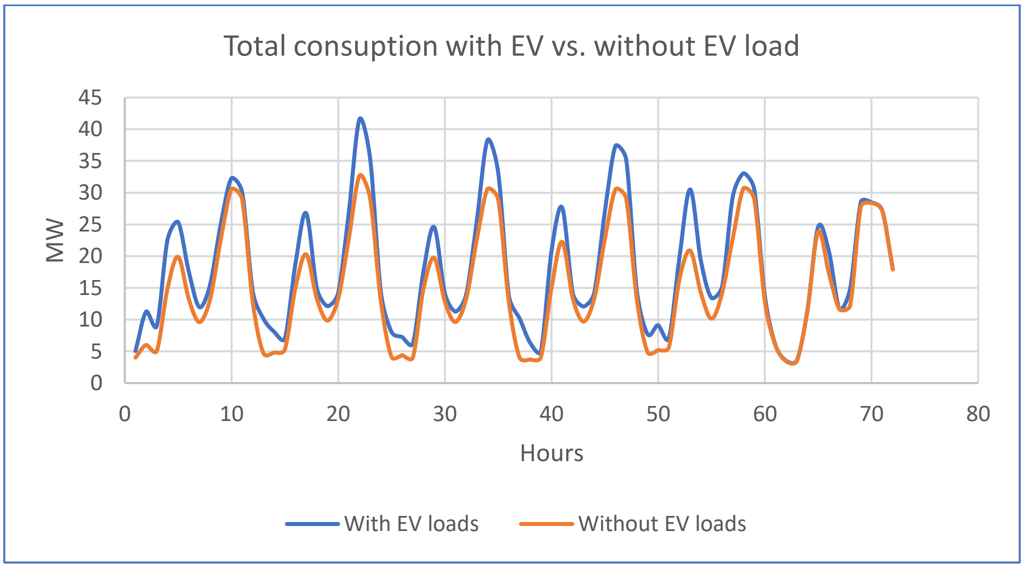


Figure 37 grid consumption with vs. without EV loads

Chapter 5: VOLTAGEASSESSMENT UTILIZING DEMAND-SIDE FLEXIBILITY AND ENERGY STORAGE SYSTEMS

In the previous chapter, we tried to solve the issues of over-voltage, reverse power flow and power loss described in the Future-case, by implementing OLTC and uncontrollable EV loads. However, several issues remained although there was a reduction on over-voltage as well as reverse power flow.

In this chapter, we will try to assess the voltage issues utilizing demand-side flexibility in the form of direct load control(EVs) and energy storage systems.

EV demand-side flexibility in the future power system

The low cost of electricity production by REs is one of the driving forces pushing consumers to shift from fuel-based vehicles to electric vehicles. This charge contributes to a reduction in carbon footprint, and EVs can be utilized to provide services to the distribution grid, due to their capability of storing vast amounts of electricity. EVs can either act as flexible loads or decentralized storage resources, with the capability of providing additional power operational support, by utilizing smart charging.

Smart charging or intelligent charging refers to an intelligent system where EVs' charging device and charging device operator share data. Smart charging can implement EVs and power system constraints to fulfil both parties need. It can optimize the charging process according to the DSO constraints and the availability of power generation from the local REs. Smart charging comes with a certain level of control such as different pricing and charging options that encourage consumers to move their demands from peak to off-peak hours. Figure 38 shows the different mechanism that can be obtained from smart charging.V1G allows increases and decrease of charging rate with respect to DSO technical challenges (flexible load), V2G allows EVs to provide services to the DSO, V2H allows EVs to provide power to a home, and V2B allows EVs to provide back-up power supply during a power outage [38].

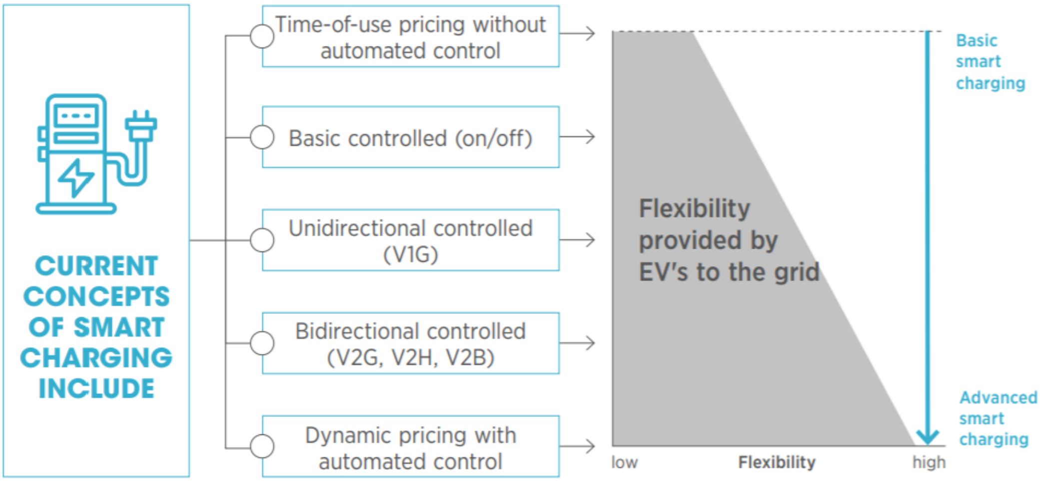


Figure 38 EVs smart charging for demand-side flexibility [38]

5.1.1 Voltage assessment EV demand-side flexibility

This chapter investigates how OLTC and aggregated EVs can be utilized for demand-side flexibility, to provide voltage support service to the MV grid as shown in Figure 39. In this strategy, direct load control (Figure 38, V1G) is considered.

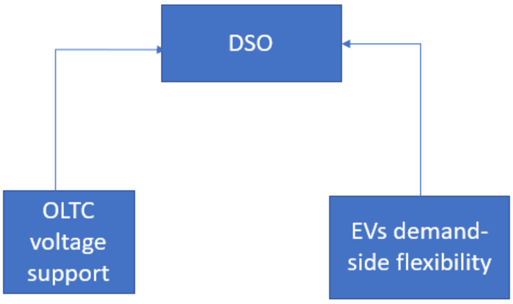


Figure 39 OLTC and EVs demand-side flexibility

Over-voltage in the MV grid is happening at specific hours of the day. EV demand-side flexibility is utilized during these hours to reduce over-voltage. For this simulation, it is necessary to design a demand-side EV load profile, shifting the demands to the hours of the largest unbalance between generation and consumption. Figure 40, Figure 41 and Figure 42 show comparisons of EV load profiles, with and without demand-side flexibility for the three types of EV charging respectively. Figure 40, Figure 41 and Figure 42 show EV demand-side flexibility for one day (16/12/2019), however a profile for each day in the simulation period (16-22/12/2019) have been created

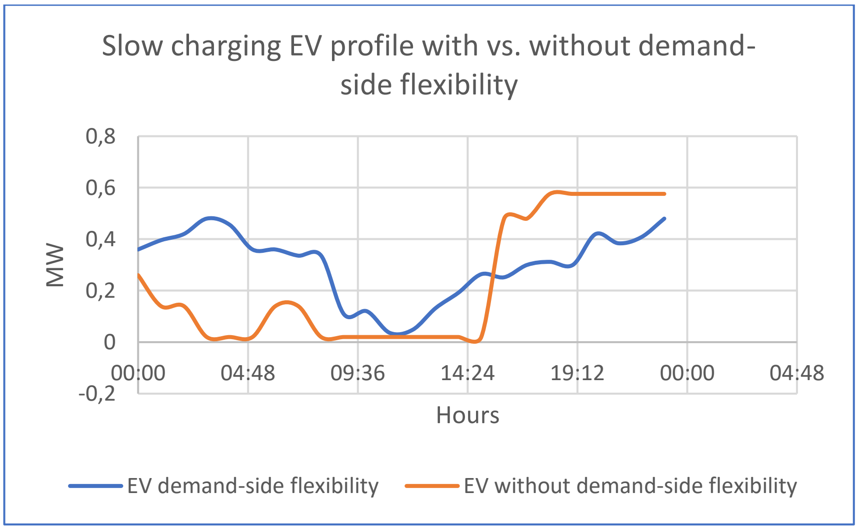


Figure 40 Slow charging with demand-side flexibility for EV

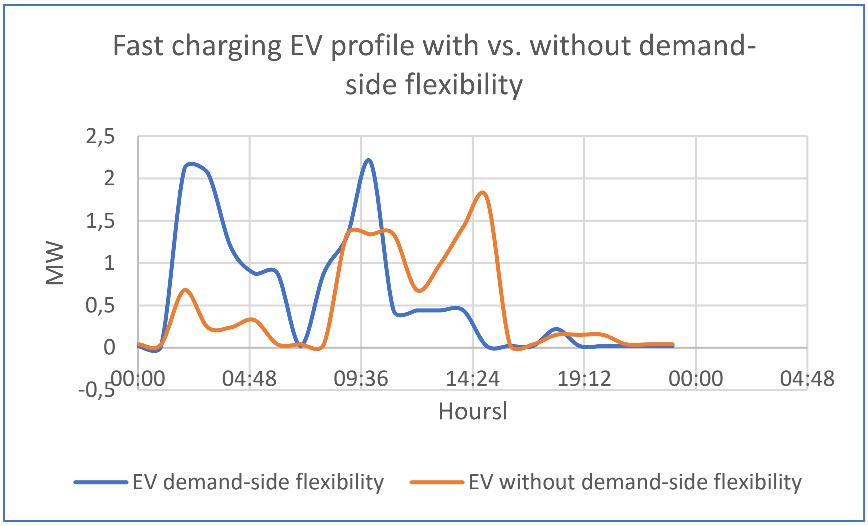


Figure 41 Fast charging with demand-side flexibility for EV

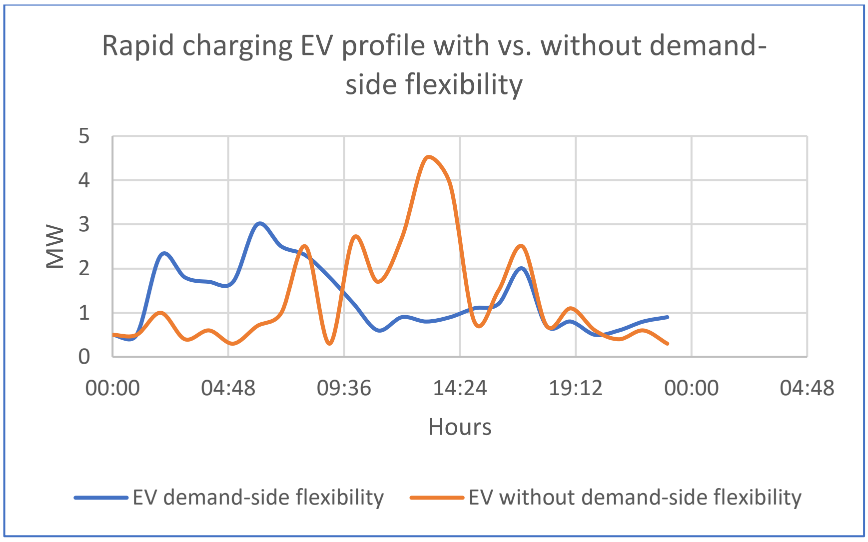


Figure 42 Rapid charging with demand-side flexibility for EV

Voltage assessment EV demand-side flexibility results

Demand-side flexibility from EVs has further improved the over-voltage issue in the MV grid, as shown in Figure 43 and Figure 44, when compared to the over-voltage profile in section 0. The main reason for this is that the excess produced power from the WT is coordinated to be consumed at the time of high penetration of WT and overall low consumption in the grid.

EV loads have solved most of the over-voltage issue in the MV grid, however, a new issue related to under-voltage has emerged, as Figure 43 and Figure 44 shows. This is happening due to high consumption in the MV grid, primarily from EVs, during the low power generation period.

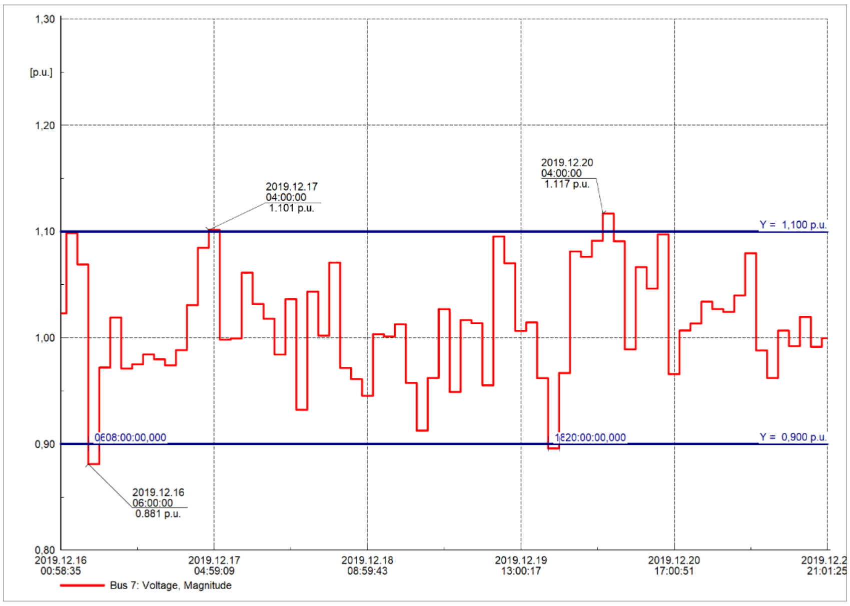


Figure 43 Node 7 voltage profile with demand-side flexibility

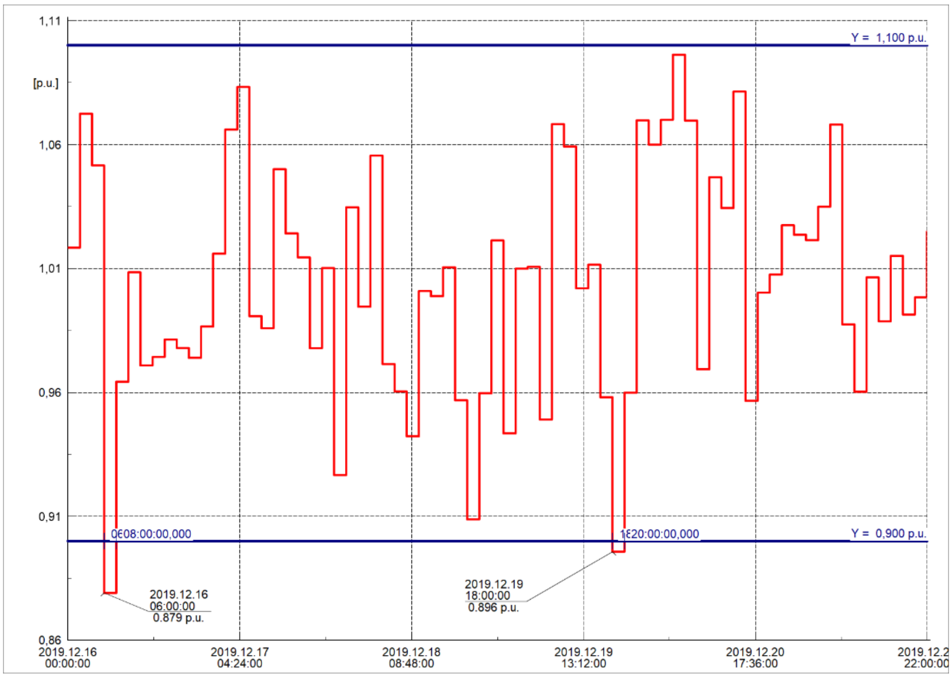


Figure 44 Node 8 voltage profile with demand-side flexibility

Implementing demand-side flexibility also improved the reverse power flow, primarily because WT power generation is consumed locally. Figure 45 shows the reverse power flow profile with demand-side flexibility.

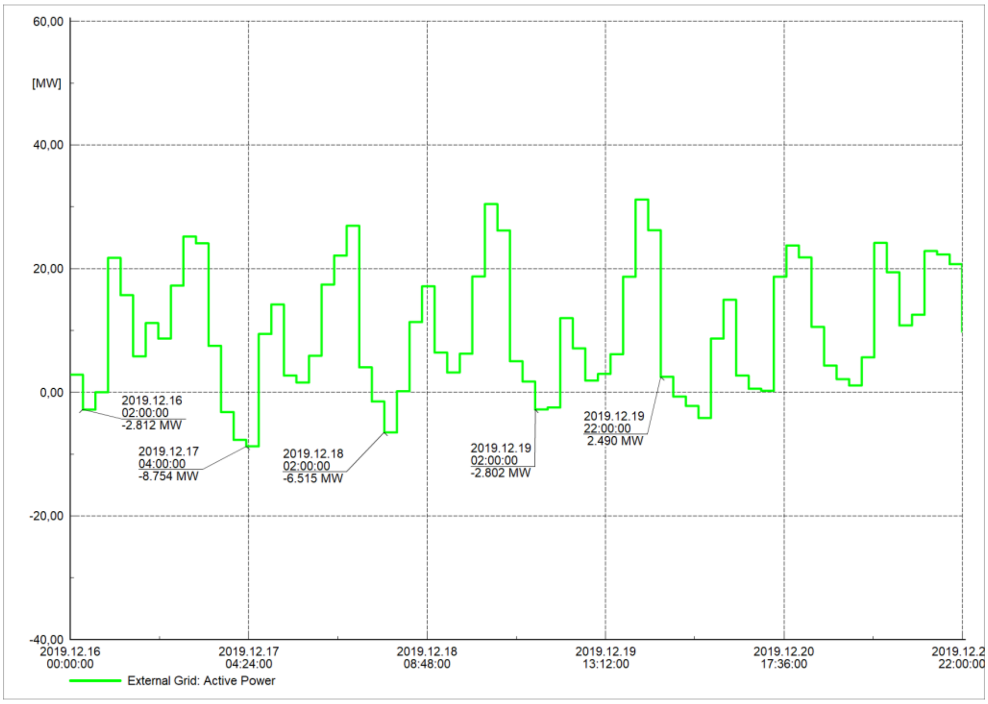


Figure 45 Reverse power flow with demand-side flexibility

Demand-side flexibility has further reduced line loading. As mentioned before, most of the loss in the MV grid comes from lines. As reverse power flow is decreased, line loading decreases as well, reducing power loss in the MV grid. Figure 46 [46]shows the power loss in the grid with and without EVs demand-side flexibility. Losses for line 3-8 is lower with EV implemented. The same conclusion implies for all lines apart from line 7-8.

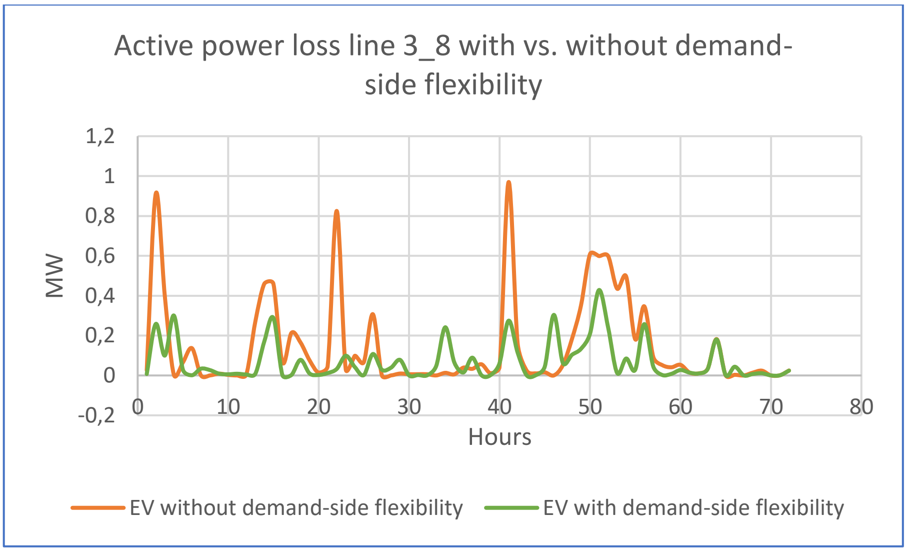


Figure 46 Line 3-8 active power loss for with vs. without demand-side flexibility

Line loading for 7-8, is not improved, mainly because the excess production from WT is still happening at node 7, then transmitted through line 7-8. Table 18 shows peak line loading comparison with and without EV demand-side flexibility in the MV grid.

Table 18 Line loading with demand-side flexibility

Line names	Loading [%]	
	EV loads without demand-side flexibility	EV loads with demand-side flexibility
Line 1-2	61,50%	48,13%
Line 2-3	61,58%	48,18%
Line 2-8	61.70%	48,3%
Line 7-8	72.97%	76,43%

5.1.2 Voltage assessment utilizing energy storage systems

Energy storage systems in the future power system

Projection of changes in the electrical system around the world has raised interest in energy storage systems. REs such as WT and PV has limited capacity for balancing and regulation, therefore we should expect an increase in system balancing technologies, especially ESS due to their low operational cost. ESSs can be used to store energy during high production hours to be used when production is low. Figure 47 shows the existing types of ESSs.

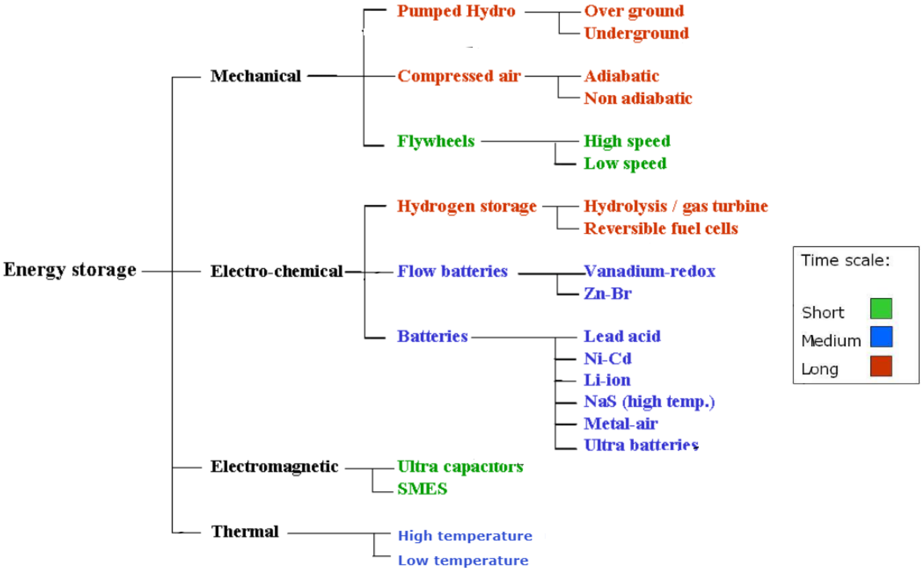


Figure 47 Types of ESS [43]

Voltage assessment energy storage systems

OLTC and EVs demand-side flexibility has not fully solved the voltage issue in the MV grid as described previously. To enhance the future power system, DSOs must rely on other voltage support techniques. In this chapter, the energy storage system (ESS) together with demand-side flexibility provide voltage support to the MV grid, as shown in Figure 48.

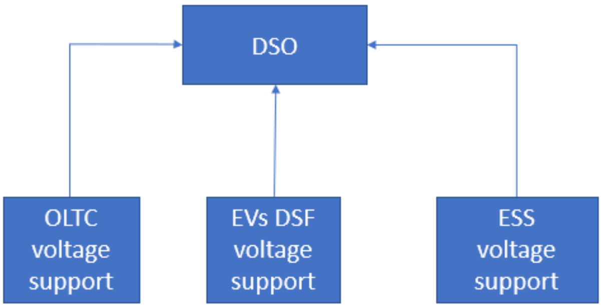


Figure 48 ESS voltage support enhancement

It is assumed, TSO-DSO has coordinated to allow activation of grid-connected energy storage. The energy storage system is connected to node 7 in the MV grid, as shown in Figure 49.

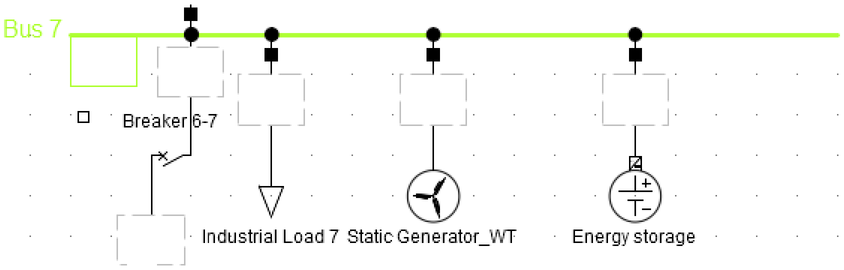


Figure 49 ESS point connection

For simplicity, dynamic modelling of the ESS is not considered. A simplified model is designed based on the MV grid consumption vs. REs production as shown in Figure 50. The energy storage system charges when the production is higher than consumption, and the stored energy is to be used during low production hours. In Figure 51 the charging (-) and discharging period (+) of the ESSs is shown.

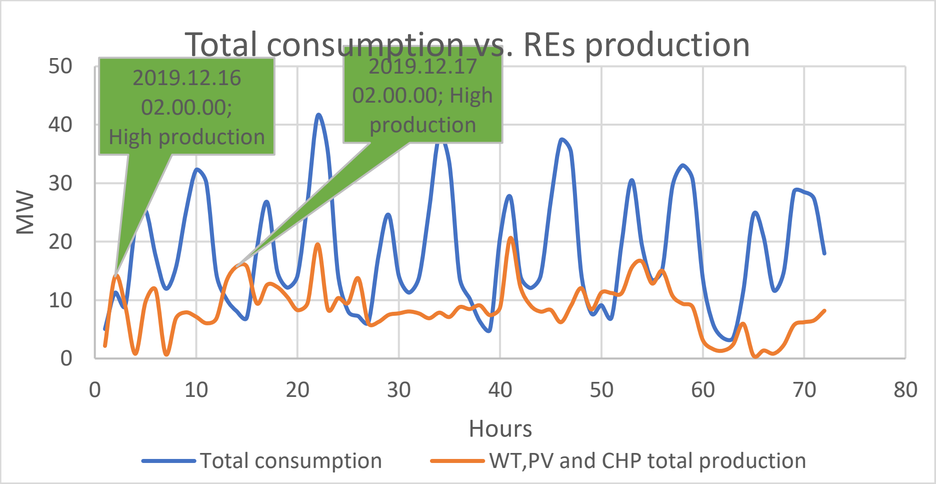


Figure 50 MV grid Total consumption VS. REs total production

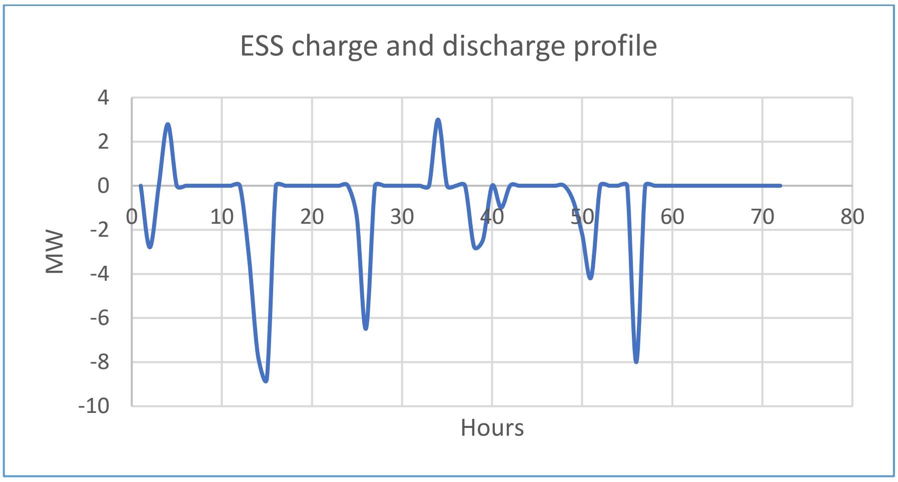


Figure 51 ESS charging and discharging period

Voltage assessment energy storage systems results

Implementing an ESS has further improved the MV grid voltage. In Figure 52 and Figure 53 the voltage profile for node 7 and 8 is shown. The voltage profile for all the nodes in the MV grid is within the limits of ±10%. Implementation of an ESS has introduced bi-directional power flow in the MV grid at node 7, which acts as power demand during high production and low consumption periods and act as power producer during low production and high consumption periods, thereby assisting in maintaining equilibrium in the MV grid.

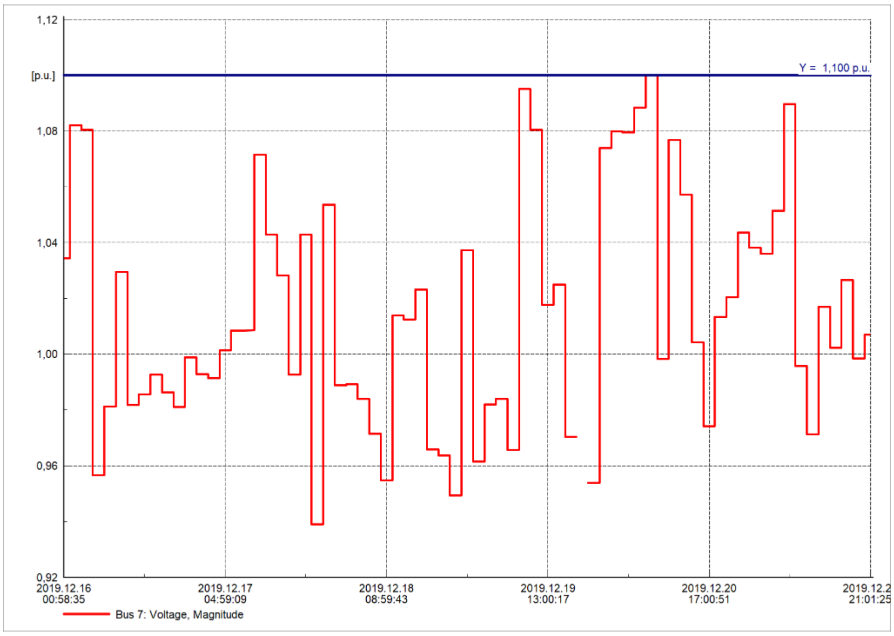


Figure 52 ESS node 7 voltage profile

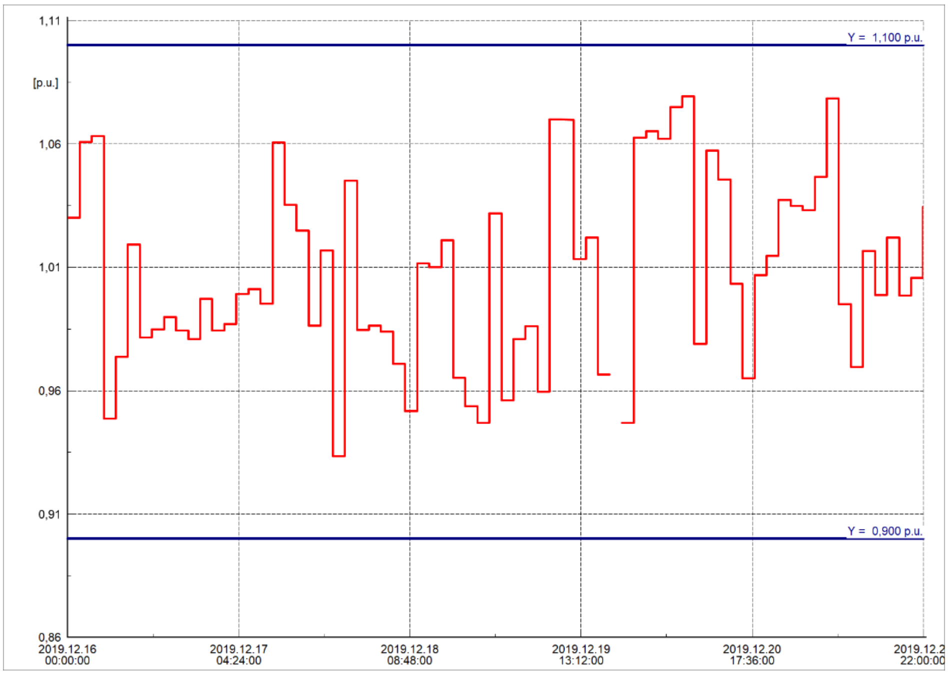


Figure 53 ESS node 8 voltage profile

As the ESS storage all excess power available, reserve power flow is almost eliminated. This leads to a reduction in power loss in the electrical system, because of the decrease of power travelling through the lines. Figure 54 shows the power loss comparison of line 3-8, with the integration of an ESS and without an ESS. As it can be observed the power loss is significantly reduced with the ESS. This is observed for all lines in the MV grid including line 7-8, where the loss was not reduced by EVs demand-side flexibility alone.

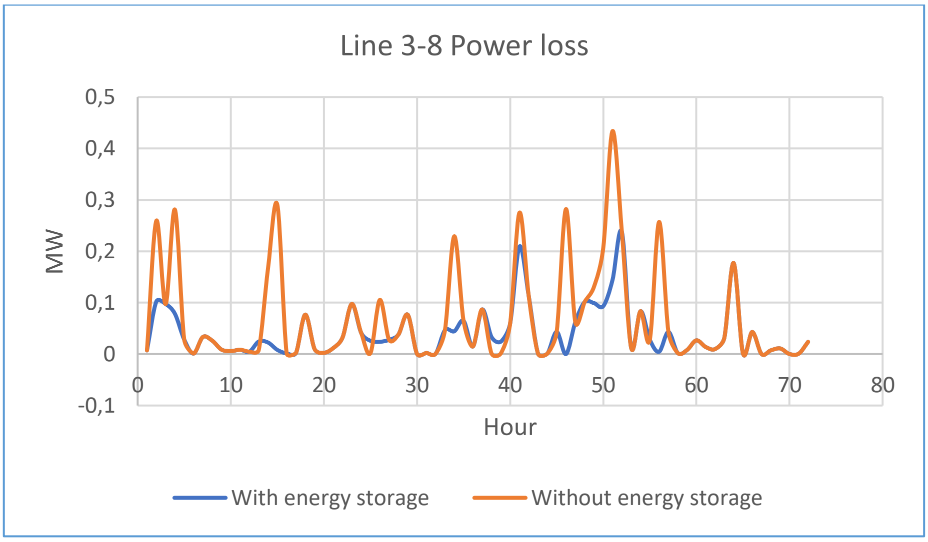


Figure 54 Line 3-8 Power loss

5.1.3 Discussion EV demand-side flexibility and energy storage system

When comparing the over-voltage profile for EV with and without demand-side flexibility it can be observed that demand-side flexibility provide a better solution for the voltage issue in the MV grid. By shifting the EVs loads at a needed period, EVs can provide voltage support to the MV grid. Figure 55 shows a comparison of node 7 over-voltage profiles obtained in different voltage assessments.

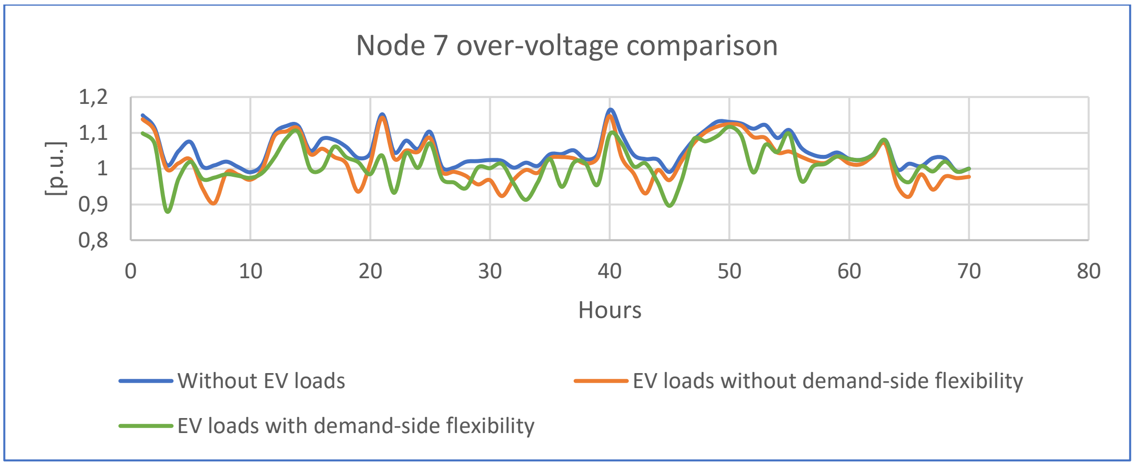


Figure 55 Node 7 over-voltage comparison for different voltage assessment

Its should be noted, demand-side flexibility from EVs has been primarily utilized for over-voltage support in the MV grid. The same principle can be utilized for under-voltage support. In the future power system, under-voltage occurs, when instantaneous consumption exceeds production at a given time. For such a scenario EV demand-side flexibility can be utilized by shifting EVs loads to reduce instantaneous consumption and obtain power equilibrium in the electrical power system.

In the assessment of EV demand-side flexibility, the issue of under-voltage is encountered. This calls for a new array of voltage support. In the assessment of the ESS, we see that this can provide a possible solution to under-voltage as well as over-voltage problems. The ESS also reduces reverse power flow and power loss. However, in this assessment, we use a simplified model of the battery and do not account for different aspects such as battery discharge, efficiency and potential power loss related to energy storage.

When considering EVs demand-side flexibility as a solution to power system issues, it is important to remember the EV users. The solutions need to be feasible for the EV users as well as TSO-DSO. The EV user will be dependent on a charged EV at specific times to specific SOC in order to maintain daily life. This can create limitations for the flexibility available.

In this project, TSO-DSO interaction is manually controlled for simplicity. TSO-DSO interaction opens the way for the utilization of DERs in the electrical power system. TSO-DSO data interaction should provide information about the accessibility of DERs in the grid for the optimization of TSO-DSO power flow coordination. In this investigation it is assumed, TSO-DSO utilizes an aggregator for activation of EV demand-side flexibility. Figure 55 shows the interaction utilized without consideration of the market. The grey arrows illustrate data interaction, TSO, DSO and aggregator can interact with the market and exchange data between themselves. Under normal operation, only the aggregator can activate DERs, but in emergencies, DSOs can activate DERs.

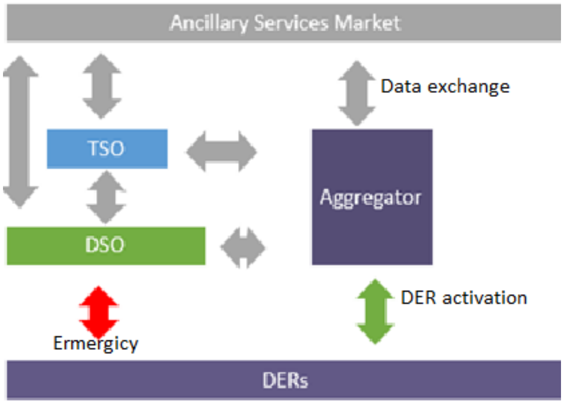


Figure 56 TSO-DSO interaction for activation of DERs in the MV grid

EV loads in the MV grid have led to a reduction in reverse power flow, which has further led to a decrease in power loss. Figure 57 shows a reverse power comparison of the provided voltage assessments.

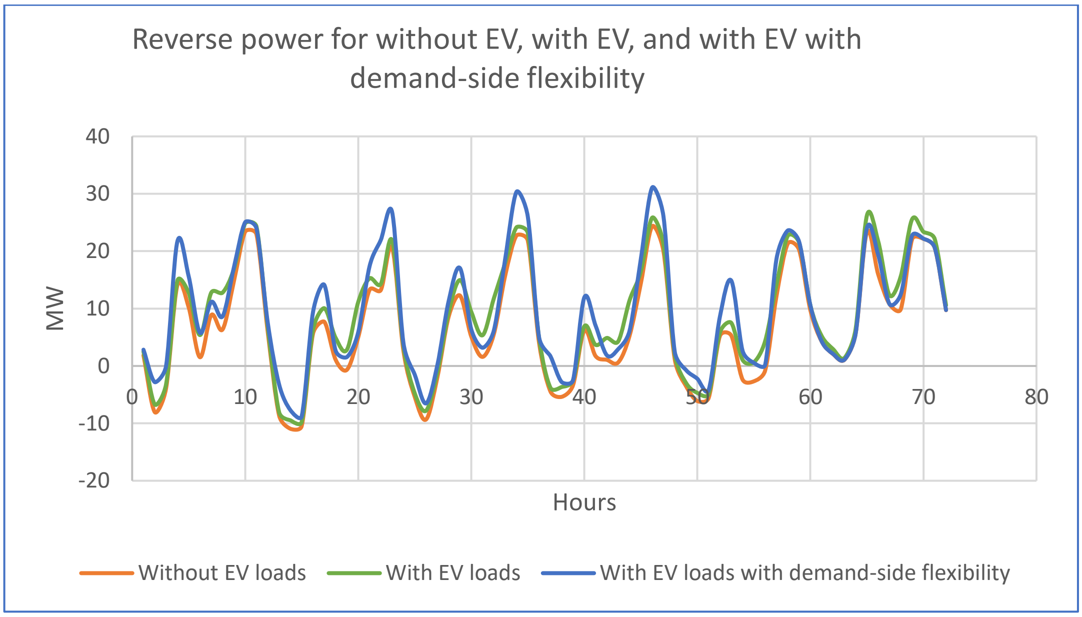


Figure 57 Reverse power flow comparison

The reverse power flow in the DSO can either create a challenge or provide a solution for the TSO depending on the TSO-DSO coordination. The TSO is connected to multiple DSOs, in the scenario where DSOs produce an excess of power, TSO-DSO must coordinate to ensure the security of the grid. In such a scenario TSO-DSO can coordinate to reduce TSO production or redirect its power flow, to optimize the social welfare of the grid, whereby the consumption of the cheapest power is prioritized first.

Chapter 6: TSO-DSO INTERACTION

This chapter covers TSO-DSO frequency and voltage interaction of the future power system network.

6.1.1 TSO-DSO voltage interaction

In the future electrical power system, in some cases DSO can provide voltage support to TSO, this chapter investigates how it can be archived, using sending, receiving voltage and reactive power relationship shown in the equations below. An increase in Q leads to an increase in voltage well as a decrease leads to voltage drop.

$$Q_R = \frac{V_S * V_R}{X_L} * \cos(\delta_1 - \delta_2) - \frac{V_R^2}{X_L} \tag{5.1}$$

$$\delta_1 - \delta_2 \approx 0 \tag{5.2}$$

$$Q_R = (\frac{V_S * V_R}{X_L}) - (\frac{V_R^2}{X_L}) \tag{5.3}$$

$$V_R^2 - V_s * V_R + X_L * Q_R = 0 \tag{5.4}$$

$$Q_R > 0; V_R < V_S \tag{5.5}$$

$$Q_R < 0; V_R > V_S \tag{5.6}$$

where:

V_S ; Sending voltage

V_R; Receiving voltage

δ_1, δ_2; Sending and receiving voltage angle

Q_2, Q_1; Demand and supplied reactive power

Q_R; Receiving reactive power

DSO can support TSO voltage regulation through reactive power transfer. In this project, it is assumed that DSO does not produce any reactive power, but ideally, DSO can provide voltage support by reducing or increasing its reactive power consumption or production. Table 19 shows the power factor of node 0 connected to the transmission line and node 1 connected to the distribution grid. For node 1, an increase in the reactive power leads to voltage increase and a decrease in reactive power leads to voltage drop.

Table 19 Power and reactive power

	Node 0, sending	**Node 1, receiving**	**Reactive power** node 1
Time in s	Cos (Phi)	Cos (Phi)	
2019.12.16 00.00.00	$Q \downarrow$ 0,971388	0,98	$Q \uparrow$
2019.12.16 02.00.00	$Q \downarrow$ 0,957609	0,988183	$Q \uparrow$
2019.12.16 04.00.00	$Q \downarrow$ 0,966574	0,998793	$Q \uparrow$
2019.12.16 06.00.00	$Q \uparrow$ 0,98008	0,98829	$Q \downarrow$
2019.12.16 08.00.00	$Q \uparrow$,970486	0,989239	$Q \downarrow$
2019.12.16 10.00.00	$Q \uparrow$ 0,982006	0,999551	$Q \downarrow$
""	""	""	""

By adjusting the reactive power on node 1, DSO can provide voltage support to the TSO. One DSO voltage support to TSO is insignificant since TSO operates at a much higher voltage potential, but if multiple DSOs are utilized, DSO voltage support can be higher.

For proper TSO-DSO voltage support investigation to enhance TSO-DSO interaction, a proper transmission grid needs to be designed, well as a PV bus in the DSO, that regulates the distribution grids voltage by increasing and decreasing its reactive power.

6.1.2 TSO-DSO frequency interaction

Frequency control is an important parameter in the electrical power system. The electrical power system frequency changes when active power and varies with time. By controlling the balance between generation and consumption frequency balance is archived. In times of unbalance in the electrical power system, different type of response is utilized to maintain a stable electrical power system. The inertial response is the first to act reducing frequency drop. In the future power system this type of response will be significantly reduced, which will be replaced by virtual inertial control.

Primary control follows, which is also known as governor response, mostly done by controlling the speed of the synchronous machines. Figure 58 shows frequency responses in the electrical power system.

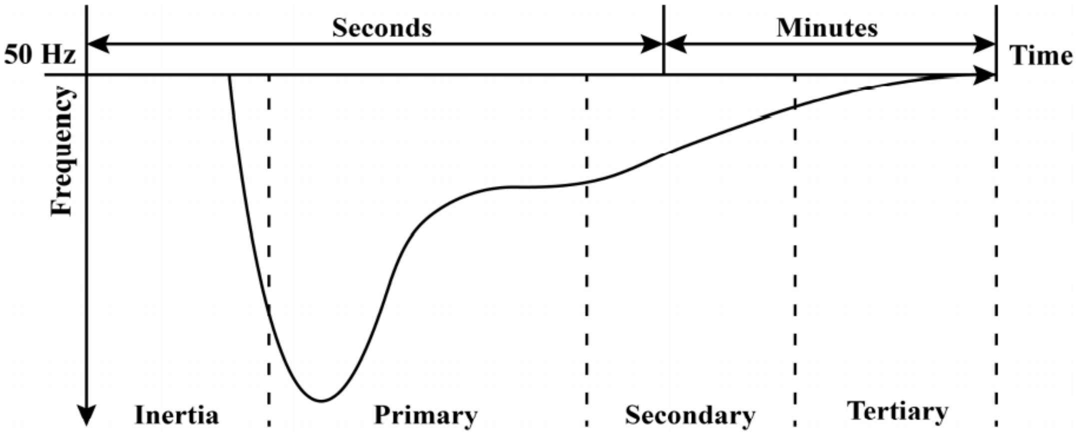


Figure 58 Frequency response

Primary control is a proportional gain, also known as droop control, which relates to a change in frequency to the output of the active power. Eequation 6 shows the relationship between change in frequency, change in power and droop control.

$$R = \frac{-\Delta f}{\Delta P} \tag{6}$$

Where:

R – controller droop

Δf – frequency deviation

ΔP – change in power

Primary control can alter active power output until there is a balance between load and generated active power. This establishes a steady state between frequency and the generator's active power. The behaviorur of the primary control can be observed in Figure 59, which shows how changes when there is variation in active power, control droop R, is the slope between frequency and active power.

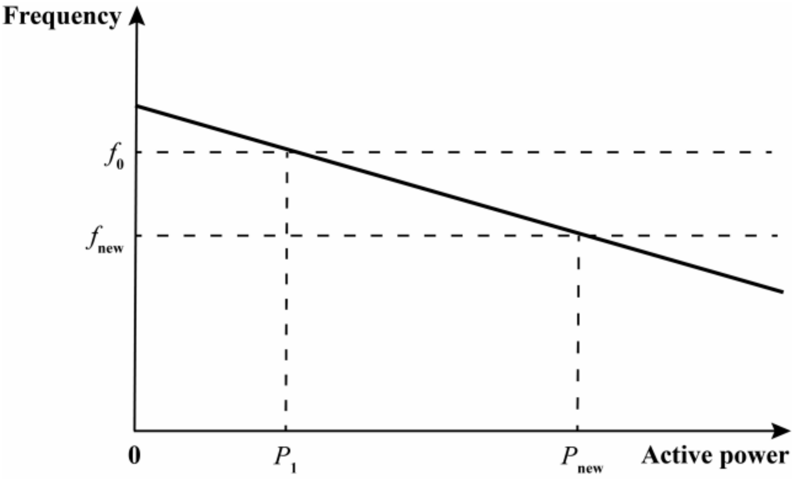


Figure 59 Droop control

In the future electrical power system, TSO-DSO interaction paves the way for interconnected DERs in the distribution grid to provide primary control to the TSO. This chapter investigates how the DSOs reverses power flow provides primary control to the TSO.

This project does not consist of time-domain simulation, which can be used to investigate frequency behaviorur in the electrical power system, therefore a partial solution is demonstrated numerically.

Let us consider a scenario where TSO frequency f_0 is 49.962002, and at the time of reverse power of 10,939 MW, Figure 60 shows the reverse power considered at this given time. The frequency characteristic of the primary control is 15000MW/Hz.

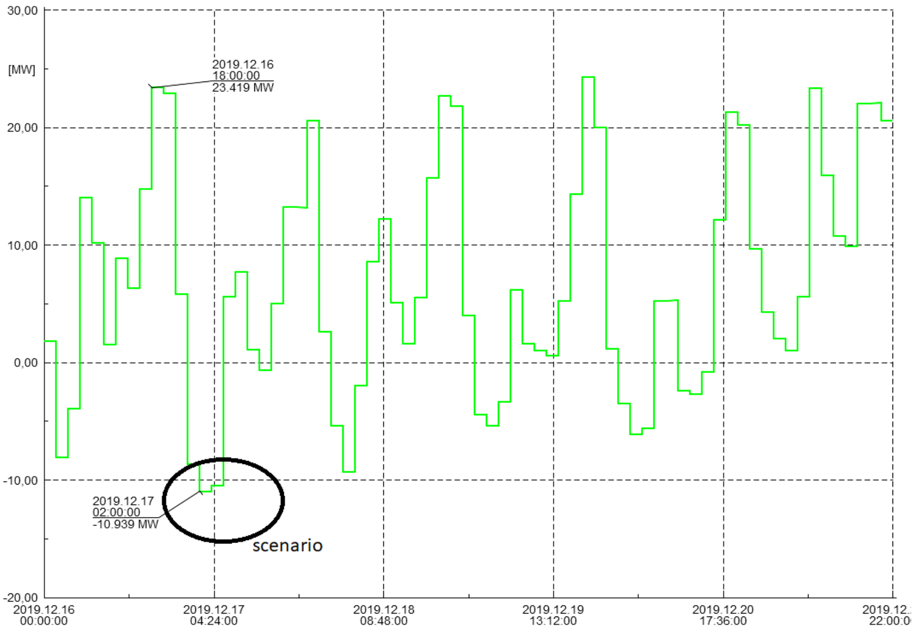


Figure 60 Reverse power impact on the frequency

$$\Delta f_{TSO-DSO} = \frac{10{,}939MW}{15000\mathrm{MW/Hz}} = 0{,}000666Hz \tag{7.1}$$

$$TSO_{new\;Hz} = f_0 + \Delta f_{TSO-DSO} = 49.962002Hz + 0{,}000666Hz = 49{,}962662Hz \tag{7.2}$$

where:

$\Delta f_{TSO-DSO}$ – effect of DSO active power on TSO frequency

$TSO_{new\;frequancy}$ – TSO new frequency

f_0 – The frequency at the time

As $TSO_{new\ Hz}$ shows, DSO reverse power flow has helped with bringing the frequency to its nominal value of 50Hz in this scenario. It should be noted, if the same scenario occurs but f_0 is above 50Hz, DSOs reverse power would worsen rather than improving it. This is one of the reasons why TSO-DSO interaction enhancement is important.

Numerically this chapter shows, DSO can provide voltage and frequency support to the TSO in the future power system network. For this to happen TSO-DSO interaction must be enhanced.

Chapter 7: DISCUSSION, CONCLUSION AND FUTURE WORK

The main objective of this project was to investigate how DERs can be utilized for voltage regulation in the future electrical power system network, and interaction of TSO-DSO for enhancement of the future power system network.

An Increase in installed capacity from WT in the distribution has introduced voltage and a higher power loss in the MV grid. In order to solve voltage issues, OLTC, and two type of DERs (EVs and ESS) is utilized.

OLTC ability to provide voltage support highly depends on the location of the voltage issue in the distribution grid. OLTC can provide voltage control if the voltage issue is close to the transformer, but if voltage issue location is far away, OLTC does provide any significant voltage relation. If the OLTC is force into remote mode, to solve voltage issue that is located far, new issue related to undervoltage is introduced in the MV grid. In the case of this project the highest over-voltage occurs on node 7, if OLTC tries to solve the over-voltage issue on node 7 by remote control, it will cause under-voltage issues on the nodes closest to the transformer.

Since OLTC has not solve the issue, uncontrollable EVs are implemented in the MV grid to assist with the over-voltage issue. Increase in demand in the MV grid, has ensure that more power is consumed locally, leading to reduce in over-voltage issue and losses in the MV grid.

Uncontrollable EVs has also not sufficient to solve over-voltage issue in the MV grid. Therefore, EVs are further utilized, by assuming they can be controlled and utilized for demand-side flexibility.

As the results in section 0 shows, by utilizing demand-side flexibility over-voltage issues has been further solved. In Demand-side flexibility voltage assessment, EVs loads are moved at the period of high production and low consumption hours, leading to a significant change in over-voltage profile. The implemented EVs have the capability of drawing a large amount of current, leading to voltage drop on the EVs connected nodes in the MV grid.

Demand-side flexibility has not also been sufficient to solve over-voltage issue in the MV grid, and furthermore, it has introduced under-voltage issue in the MV grid. To solve these issues ESS is utilized, for its bi-direction power flow capability. ESS can store energy during high production period to be utilized during low consumption period, ensures even larger amount of power to be consumed locally, thereby decreasing the losses related to reverse power flow.

It should be noticed in this project, EVs has been utilized to solve over-voltage issue, which is happening during high production and low consumption periods. In a case when REs productions are low and consumption is high, EVs can contribute to under-voltage issues in the distribution grid. Demand-side flexibility can also be utilized to solve this issue too. By either controlling load's demands or utilizing local ESS to provide voltage support by injecting current in the distribution grid to reduce voltage drop.

The main challenge with EVs demand-side flexibility is their coordination. Let us consider a situation where demand-side EVs is activated to solve the over-voltage issue during working hours. Since most people are not at home, slow charger contribution will be limited. This means the demand-side flexibility ability to provide voltage support in the MV grid is limited.

To fully utilize EV demand-side flexibility for enhancement of the future power systems, it will be necessary to integrate more smart charging EVs in both residential and commercial areas rather than uncontrollable EV charging. It comes with a variety of solution for EV charging, at the same time it can follow the distribution grid constraints, which contributes to demand-side response.

In general demand-side flexibility form big loads such as EVs, can be utilized for voltage assessment and frequency control in the MV grid. And furthermore, with addition support from DERs such as energy storage system, voltage support in the future MV grid can be even stronger.

Increasing the installed capacity of REs in the MV grid, without increasing the resizing of components such as cables, transformers etc. can result in other issues such as congestion and a higher power loss in the grid. Therefore, a stepwise increase of components with consideration of generation and demand is recommended. Since losses in the distribution grid are highly dependent on the line, increasing the conductor size of the lines, connected to the REs with high installed capacity should be considered, as it leads to a reduction in power loss in the electrical power system.

In TSO-DSO interaction, DSO can provide voltage support to TSO through reactive power. For voltage support TSO can coordinate with DSO, to increase or decrease the DSOs reactive power for TSO voltage support. But it should note that DSOs reactive power production is significantly lower than TSO. Therefore, one DSOs reactive power impact on the TSO is little.

In TSO-DSO interaction, DSO can provide frequency support to the TSO. Increasing the installed capacity of the REs leads to an increase in the reverse power flow, which can either assists or disturb the frequency depending on the frequency at the concerned time scope. Therefore, the reverse power flow must be coordinated to ensure steady-state frequency, since it is directly proportional to active power. TSO-DSO coordination help TSO to maintain stable frequency as it is more aware of when, and the amount of active power to be expected in the scheduled time, from different DSO. As shown in chapter 6.1.2 reverse power flow impact on the frequency is small, but if a large amount comes from multiple DSOs, the frequency variation can be significant.

7.1 FUTURE WORK

Over-voltage has been the main concern for the distribution in this project. Another scenario can be created, where there is an increase in consumption rather than the installed capacity from REs, which leads to under-voltage issues. This scenario could investigate how under-voltage issues can be solved utilizing DERs. Furthermore, aggregated EVs can be used to provide support to the grid, utilizing V2G (vehicle to grid) or V2H (vehicle to home)

In this project QDLFS is conducted which is a series of load flows. By implementing dynamic modelling of DERs, RMS simulation can be used to observe how DERs affect the frequency, or how DERs can be used to provide frequency support. RMS simulation can also be used to the observe frequency response of the MV grid with additional implementation of virtual inertial and other frequency response.

In this project a simplified transmission grid is used as a model. To properly analyse TSO-DSO interaction, it is necessary to model a transmission line system network. Furthermore, PV-bus can be added to the distribution grid for reactive power regulation and to investigate TSO-DSO voltage interaction.

A economic aspect of DERs can be implemented to observed how DERs perform in different types of markets which market optimizes their ownings.

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