Liv Ringheim

Grid Impact from Increased Prosumer Penetration in the Norwegian Distribution Grid

Master's thesis in Energy and Environment
Supervisor: Gerd Kjølle
February 2020

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Norwegian University of Science and Technology
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Problem Description

Electricity production from distributed energy resources leads to new challenges for the power system, as it was originally built to transport electricity downstream from centralized production to distributed consumption. Large growth in installed distributed solar power is expected in the Norwegian power system in the coming years. The grid operators must take this into account to plan and dimension the future power grid.

This thesis aims to investigate what methods, tools, and analyses are needed to map and prevent the challenges caused by solar power in the distribution grid. It will be analyzed and discussed whether, or to what extent, the Norwegian distribution grid is ready for this kind of integration. The focus of the analyses is the effect of distributed solar power on voltage quality in the distribution grid, more specifically voltage level and voltage asymmetry. It is investigated through a literature study, a survey among DSOs and computer simulations.

Simulations are carried out in Netbas and DIgSILENT PowerFactory. They will be used to investigate how different grids can handle the integration, based on grid strength and rated power of the transformer. The effect of battery energy storage, grid improvements and reactive power control is also simulated.

Preface

This master thesis is written at the Department of Electric Power Engineering at the Norwegian University of Science and Technology and concludes my degree in Energy and Environmental engineering. It is written in cooperation with the grid operator Eidsiva Nett AS as a part of FME CINELDI.

I would like to thank my supervisor Gerd Kjølle for her guidance through the work of this thesis. My co-supervisor Lars Helge Narum Furulund in Eidsiva Nett AS has been very helpful throughout the process, and I am grateful. I also want to thank Anders Anseth and Andreas Rosendahl Simonsen in Eidsiva Nett AS for technical help and advice. Moreover, I want to thank Bendik Nybakk Torsæter in SINTEF Energy AS for help with the analysis and grid model in PowerFactory. Thanks to Tonje Kroglund Rian in Powel for a great introductory course in Netbas analysis, and to Malin Eidem in Powel for technical support. I would also like to thank Marie Kolderup in Nelfo for sharing her knowledge of installations and trends for PV in Norway.

Lastly, I want to thank my friends and family for their help and encouragement. Sharing my frustrations and accomplishments with you has been a pleasure.

Liv Ringheim

Liv Ringheim
Trondheim, January 2020

Abstract

This master thesis is a study of the grid impacts from an increased penetration of prosumers in the Norwegian distribution grid. A survey among DSOs has shown a large groth in the amount of prosumers during the last year. Simulations have been carried out in the simulation tools Netbas and DIgSILENT PowerFactory. The simulations are based on different penetration levels of prosumers with 8kW PV systems. Some simulations are also done with a combination of PV and battery energy storage, to see how this affects the results.

The simulations have shown that high production combined with light load can lead to voltages above the tolerated limit an overload of equipment in the grid. Through the simulations, it has been shown that an increased penetration of prosumers in the Norwegian distribution grid is especially challenging in weak grids, where minimum short-circuit currents are low. It has been shown that grid strength and apparent power rating of transformers are the limiting factors for the allowed penetration level of prosumers.

Grid improvements, such as increased transmission capacity in power lines and transformers, can reduce the grid impact from prosumers. Simulations of PV combined with BES has also proven to be an efficient way to reduce the grid impacts from prosumers.

Sammendrag

Denne oppgaven har undersøkt nettpåvirkningen fra en økt penetrasjon av plusskunder i det norske distribusjonsnettet. En spørreundersøkelse blant norske nettselskaper har vist en kraftig vekst i antall plusskunder det siste året. Det er gjennomført simuleringer i Netbas og DIgSILENT PowerFactory med forskjellig penetrasjonsgrad av plusskunder med 8kW solcelleanlegg. Enkelte simuleringer er også gjort med en kombinasjon av solceller og batterier, for å se hvordan distribuert energilagring i batterier kan påvirke resultatene.

Simuleringene har vist at høy produksjon kombinert med lav last kan føre til spenningsoverskridelser og overbelastninger i strømnettet. Gjennom simuleringene er det vist at en økt inntreden av PV i det norske distribusjonsnettet er spesielt utfordrende i svake nett, hvor korslutningsytelsen er lav. Det er vist at nettstyrke, målt i laveste kortslytningsstrøm, sammen med nominell transformatoreffekt er de begrensende faktorene for tillatt penetrasjonsgrad av plusskunder.

Nettforsterkninger, som økt overføringsevne i kabler, kan bidra til å redusere nettpåvirkningen fra plusskundene. Simuleringer med PV kombinert med energilagring i batterier har vist at integrasjon av energilager er et svært godt tiltak for å redusere nettpåvirkningen fra plusskunder.

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Abbreviations

AC Alternating Current

BAPV Building-applied PV

BES Battery Energy Storage

BIPV Building-integrated PV

DC Direct Current

DG Distributed Generation

DSO Distribution System Operator

EV Electric Vehicle

FoL Norwegian Regulation for Quality of Supply

IEA International Energy Agency

IEA PVPS IEA Photovoltaic Power Systems Programme

IRENA International Renewable Energy Agency

IT Isolated Terra

LV Low Voltage

NVE Norwegian Water Resources and Energy Directorate

PV Photovoltaic

TN Terra Neutral

TSO Transmission System Operator

Nomenclature

E	energy	kWh
$E_{battery}$	battery capacity	kWh
I	current	A
I_{SC}	short circuit current	A
P	active power	kW
P_{peak}	peak power	kWp
Q	reactive power	VAr
R	resistance	Ω
S	apparent power	VA
S_{SC}	short circuit power	VA
U	voltage	V
U_L	load voltage	V
U_N	nominal voltage	V
U_{max}	maximum voltage	V
U_{min}	minimum voltage	V
X	reactance	Ω

1 Introduction

1.1 Motivation

Electricity production from solar PV is the fastest-growing power source around the world[1]. Rapid technological improvements combined with decreasing cost helps speed up the process. Solar power in Norway has traditionally been used to cover the electricity need at locations without grid connection, such as cabins. Over the last years, there has been an increase in the amount of grid-connected Photovoltaic (PV) systems in the Norwegian distribution grid. The electrical grid was originally designed to transfer power downstream from centralized production to local consumption. An increased amount of Distributed Generation (DG) from PV in the distribution grid can lead to challenges related to the quality of supply.

1.2 Objective

This master thesis aims to analyze how an increased penetration of distributed PV affects the distribution grid in Norway. The thesis will investigate what kind of analyses must be done to map the effect and which factors are of importance. Available tools and data will be discussed, and the effect on grids of different size and strength is examined.

1.3 Approach and Limitations

Based on the objective some operating points have been made:

- Perform a theoretical study of the grid impact from distributed PV
- Investigate the status for PV and expected growth through literature and a survey among Norwegian Distribution System Operators (DSOs)
- Present measures that can help cope with potential challenges
- Perform simulations on voltage quality in different grid areas with varying penetration of PV
- Analyse how different measures to increase voltage quality can reduce the challenges

The focus of this thesis is on prosumers with PV systems. The systems are typically placed on the roofs of private residences and connected to the low voltage distribution grid. The analysis will demonstrate a worst-case result for the grid with different levels of PV integration. PV technology is not reviewed in this thesis, as it is the grid connection that is of interest here.

To simplify the analysis, it is assumed that the orientation and angle of the panels are ideal in all cases. The size of the roofs is neglected but assumed to be large enough to install the wanted capacity. PV production from industry and other non-residential buildings are not included in the analysis.

Quality of supply concerns many phenomena, and this thesis will focus mainly on voltage magnitude and voltage symmetry/asymmetry. Some other phenomena will also be explained and commented, but not analyzed specifically.

1.4 Thesis Outline

In chapter 2 an introduction to the term prosumers is given, and the rules and regulations for prosumers in Norway is presented. Chapter 3 gives a brief explanation of distributed PV technology and the status and trends for solar power in the world. The Norwegian power system, with a focus on the distribution grid, is presented in chapter 4. In chapter 5 the term quality of supply is explained. The chapter presents the main challenges for the distribution grid regarding distributed generation from PV. Measures to counteract the challenges are also presented in the chapter.

Chapter 6 explains the methodology for the analyses in this thesis. A survey among DSOs is presented and values for the simulations are chosen. The computer simulations in this thesis are carried out in two different simulation tools. In chapter 7 the simulation in Netbas is described and the results are presented. Chapter 8 presents method and results from a simulation in DIgSILENT PowerFactory.

In chapter 9 the results from the simulations and the occurring challenges are summarised and discussed, among the effect of possible improvements or solutions. The conclusion from the analysis is given in chapter 10. Suggestions for further work and analyses are presented in chapter 11.

2 Prosumers

The term prosumer is used to describe customers who both produce and consume electrical energy[2]. This allows for power flow in both directions. The customer can export electricity to the grid when the production is higher than the load and import electricity at times of high load and low production. The difference between a consumer, the traditional electricity customer, and a prosumer is shown in figure 2.1.

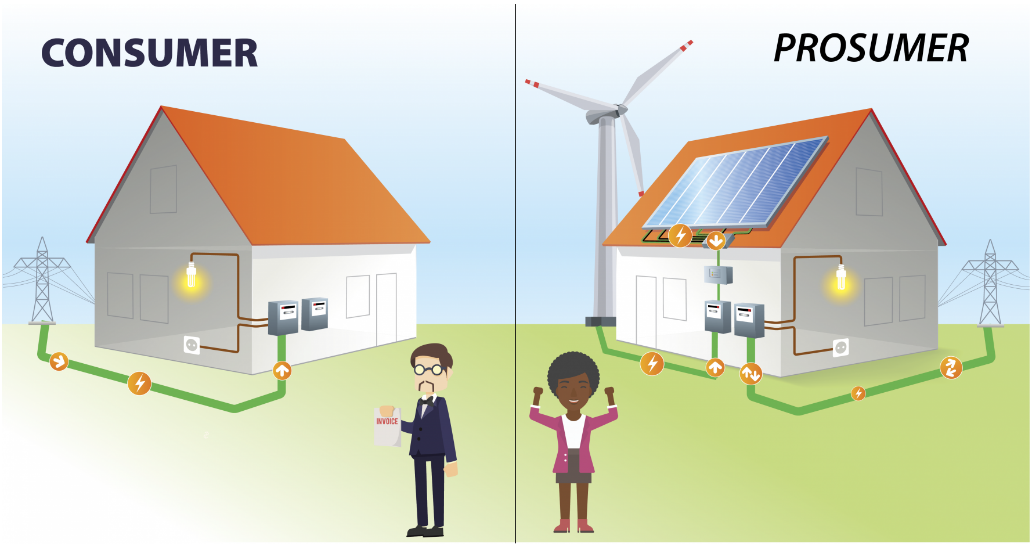

Figure 2.1: Consumer vs. prosumer, from [2]

2.1 Defnition and Regulations

In Norway, there exists a "surplus-customer scheme", in which a plus-customer is defined as an end customer with both production and consumption beyond the connection point, where the production fed from the customer never exceeds 100kW. For the rest of this thesis, the term prosumer refers to such plus-customers. Prosumers choose their own electricity supplier, who buys surplus electricity from the prosumer. They are not allowed to sell electricity on the wholesale market or to other customers, only to their electricity supplier[3].

Customers who want to become prosumers are responsible for informing the DSO about the installation of production equipment. They are required to use equipment with CE certification, i.e. equipment that complies with requirements related to the effect on voltage quality, safety etc[4].

2.2 Cost

Prosumers must pay for their electricity production systems. The most common kind of production systems is PV systems. The total cost depends on the choice of panels and inverter, the size of the system and installation costs. The typical PV system cost for a private residence ranges from 50,000 to 150,000 NOK. The cost of the system is expected to be earned in reduced electricity cost within it's operating period[5].

Enova gives economical support of 10,000 NOK plus 1,250 NOK/kW up to 15kW for installation of PV[6]. This means that the maximum economic support is 28,750 NOK. In order to receive support the requirements in [7] must be fulfilled. From the 1st of April 2020, the fixed support of 10,000 NOK will be reduced to 7,500 NOK. This reflects the reduction in cost for PV, which will be explained in section 3.3.2.

The DSO must allow customers to connect their production systems to the grid. If the connection of the PV system does not require any changes in the customer's over-voltage protection, the DSO can not charge the customer for any needed grid improvements related to the connection. In case of upgrades in the customers over-voltage protection, the DSO can require a construction grant[3].

2.3 Prosumer Penetration

In this thesis, prosumer penetration is defined as the ratio of grid customers with installed PV to total grid customers, as shown in equation (2.1).

$$\text{Prosumer penetration} = \frac{\text{Prosumers}}{\text{Total customers}} \tag{2.1}$$

As seen from equation (2.1) the level of prosumer penetration only deals with the number of prosumers, not the size of the power generation.

3 | Distributed PV

Photovoltaic systems produce electricity by exploiting solar radiation through the photovoltaic effect. The theory behind photovoltaic systems will not be reviewed in this thesis. This chapter will focus on distributed PV systems.

Section 3.1 presents distributed PV technology and grid connection. In section 3.2 the relation between production and consumption for a prosumer is shown. Section 3.3 presents current status and trends for PV in Norway and the rest of the world. Expected growth is shown in section 3.4.

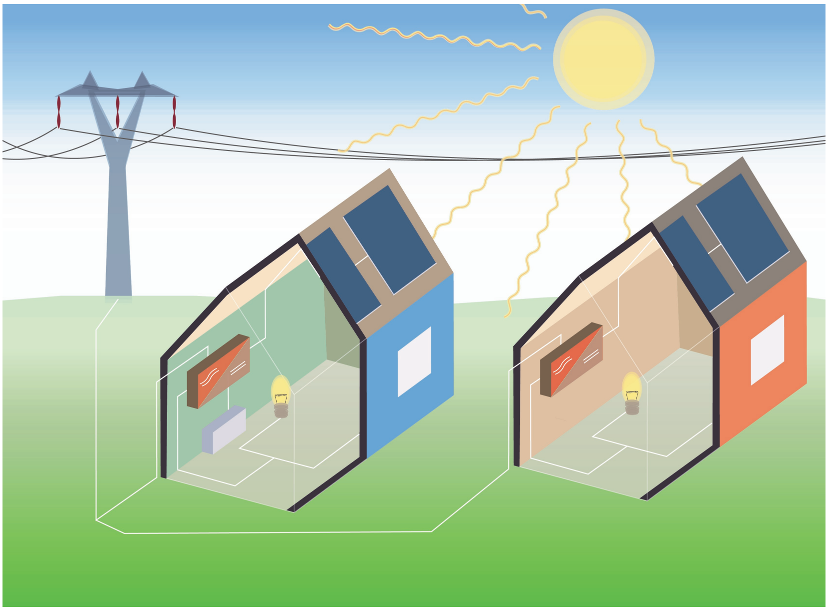

Figure 3.1: Prosumers with distributed rooftop PV systems

3.1 Technology

PV systems can be either central, distributed or stand-alone. Distributed PV systems are usually relatively small and can be placed on walls and roofs of private households, allowing customers to produce their own electricity. PV system produce Direct Current (DC), which must be converted to Alternating Current (AC) before being fed to the grid. Thus, the solar panel is connected to the grid through an inverter, as shown in figure 3.1.

The inverters can be single phase, three-phase or a combination of two or three single-phase inverters. The choice of inverter is an important factor for the grid impacts from the PV system, which will be explained in section 5.2. The AC side of the inverter is connected to the electrical grid and to the residential loads. In this way, the produced electricity can be used directly in the residence or fed to the grid. In some cases specific equipment inside the residence is connected on the DC side of the inverter, i.e. refrigerators. A meter is connected on the AC side of the inverter and measures power flow in both directions.

Common PV panels attached to roofs and walls of buildings are a form of Building-applied PV (BAPV). An alternative to this is Building-integrated PV (BIPV), which means that the solar cells are integrated into the building elements such as roof tiles or glass facades. By choosing BIPV on new buildings the solar cells can replace other building elements, and hence reduce the cost compared to building a house and placing solar panels on it afterward. BIPV is especially relevant in Norway. Since the sun is low in the winter, facades facing south can achieve a high production[8]. Multiconsult reports that there is a potential for as much as 26 TWh of production from BIPV in existing residential and commercial buildings in Norway[9].

Yearly electricity production from PV systems is dependent on many factors, such as angle and orientation of the panels, weather conditions and shading. 1 kWp of installed PV produces about 800-1200 kWh over a year[10].

3.1.1 Integration of Battery Energy Storage

Installation of a distributed PV system can be supplemented by the installation of a Battery Energy Storage (BES). This allows for the produced electricity to be saved for later and utilized when needed. In this way, one can obtain greater self-consumption of produced electricity. The only difference from a conventional distributed PV system is that there is also a battery connected to the DC side of the inverter, as shown in figure 3.2.

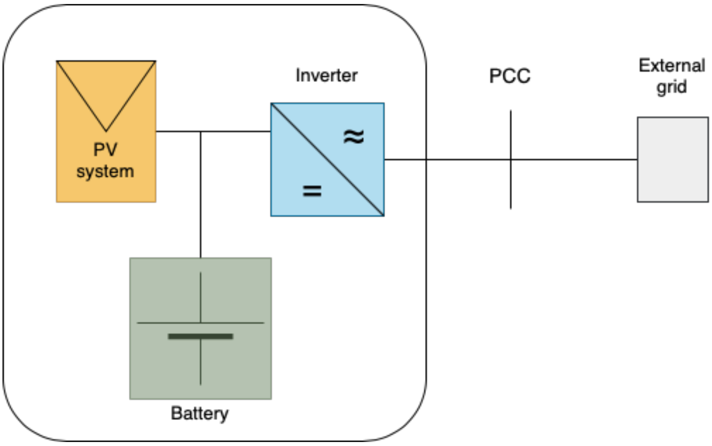

Figure 3.2: System sketch of PV system combined with battery

Installation of batteries can help relieve the local grid from capacity constraints, both at times of high production and high load. To fully utilize this advantage, this requires smart charging that takes grid demand into account[11]. Batteries with smart charging can also be exploited to buy electricity from the grid when prices are low, and export when prices are high, which helps reduce electricity costs for the customers.

3.2 Production and Consumption

The solar radiation in Norway varies a lot throughout the year. Far north, there are many hours of sunlight during the summer and few in the winter, resulting in large seasonal variations in production from solar PV.

About 60% of the electricity consumption in Norway is related to heating[12]. Hence, the load is highest in the winter when temperatures are low. Consumption from households varies with geographical location, size of the house, isolation and heating needs and the consumption pattern of the residents. The largest difference between load and production usually occurs in the middle of the day on business days in the summer. An example of a production and consumption curve from a prosumer is shown in figure 3.3.

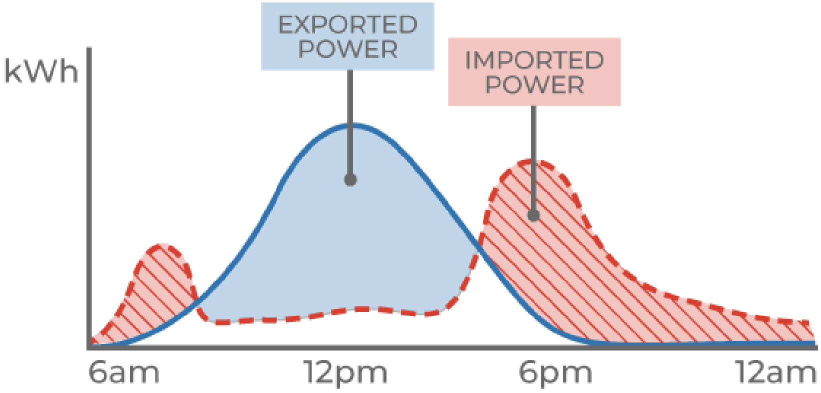

Figure 3.3: Daily variations in load and production for a prosumer[13]

From the figure one can clearly see that the peak production occurs in the middle of the day, while the load is low. Surplus production is fed to the grid. In the afternoon the load is higher than the production, and electricity is imported from the grid.

3.3 Status and Trends

The growth of solar power has increased rapidly during the last years. This is due to a combination of technological development, high learning rates, rapid deployment and price reductions[1]. In addition, the transition towards a greener energy sector based on renewables has resulted in incentives and willingness to invest in solar power. The growth in cumulative installed PV capacity in the world from 2007-2018 is shown in figure 3.4.

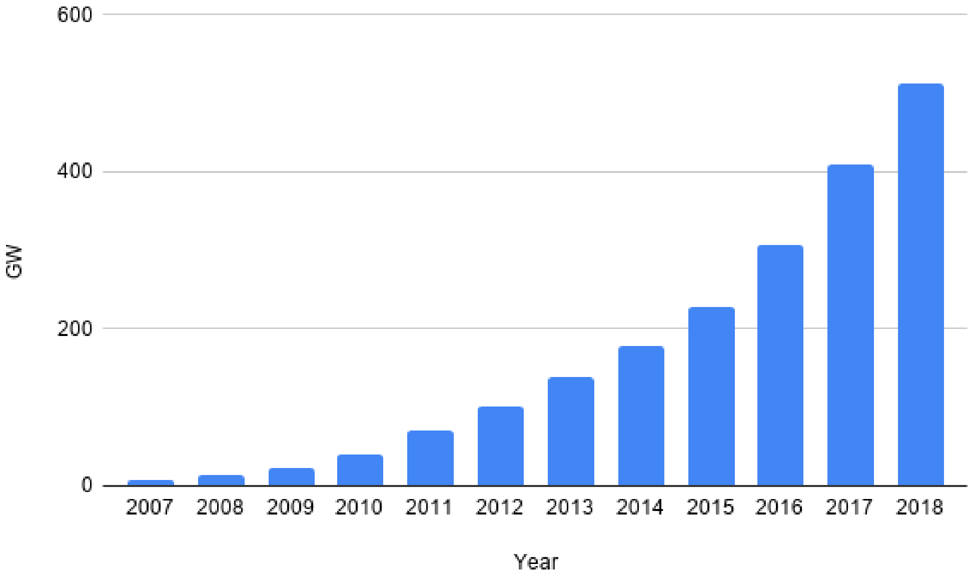

Figure 3.4: Cumulative PV installations in the world 2007-2018, data from [14]

The figure shows that the annual installed capacity has increased, causing a steep growth in cumulative installed PV capacity. By the end of 2018 the total capacity was 512.3 GW. The countries with the highest PV capacity in 2018 were China, USA, Japan and Germany, with installations in China covering 34.2 % of the total PV capacity in the world[14].

According to the International Energy Agency (IEA), distributed solar applications make up almost half of PV capacity growth in the world up to 2014, with residential systems covering 28 % of the distributed systems[1].

The trends for PV in Europe are similar to the rest of the world. Figure 3.5 shows the growth in total installed solar PV capacity in Europe during the last two decades.

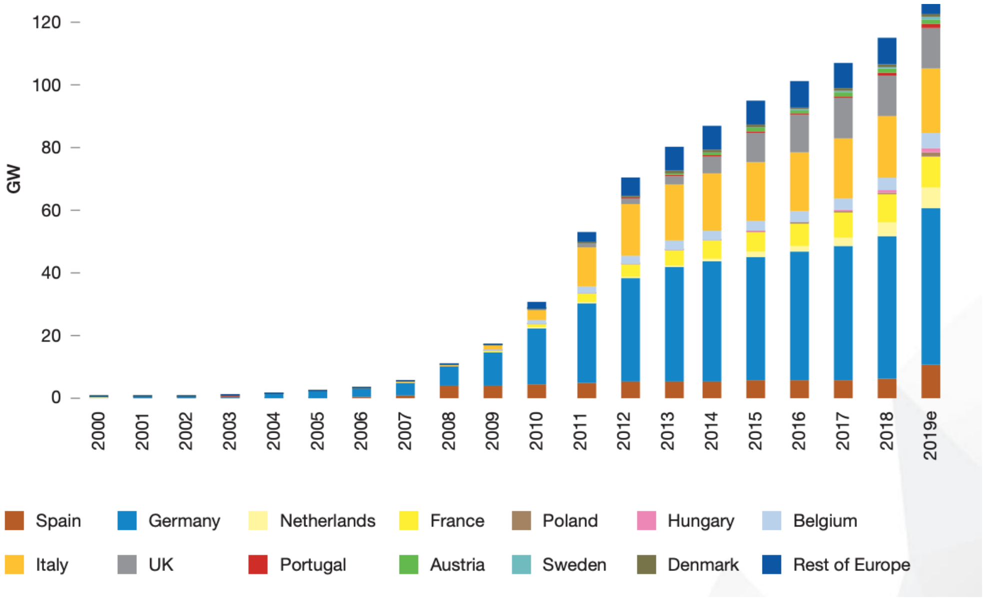

Figure 3.5: Total installed solar PV capacity in Europe, 2000-2019[15]

The figure illustrates a large growth in installed capacity, especially during the last ten years. The total installed capacity by the end of 2019 was 131.9 GW, a 14 % growth from 2018. In 2019 the growth has been largest in Spain, with an added production of 4,680 MW[15].

Germany clearly stands out as the country with the highest PV capacity in Europe, as can be seen in figure 3.5. With a total of 49.9 GW PV, the country has almost 38% of the total capacity in Europe[15]. Approximately 10% of the total electricity consumption in Germany is covered by solar power, and on days with high production the solar power can cover as much as 50% of the consumption. German energy companies are competing to be allowed to install more PV, and the government is criticised for slowing down the growth in installed PV capacity[16].

3.3.1 Status in Norway

Multiconsult has collected data on installed PV capacity in Norway. In 2018 23.5 MWp of PV was installed, which represents a 29% growth in installed capacity from 2017 to 2018[17]. Cumulative installed power from PV from 2004 to 2018 is shown in figure 3.6.

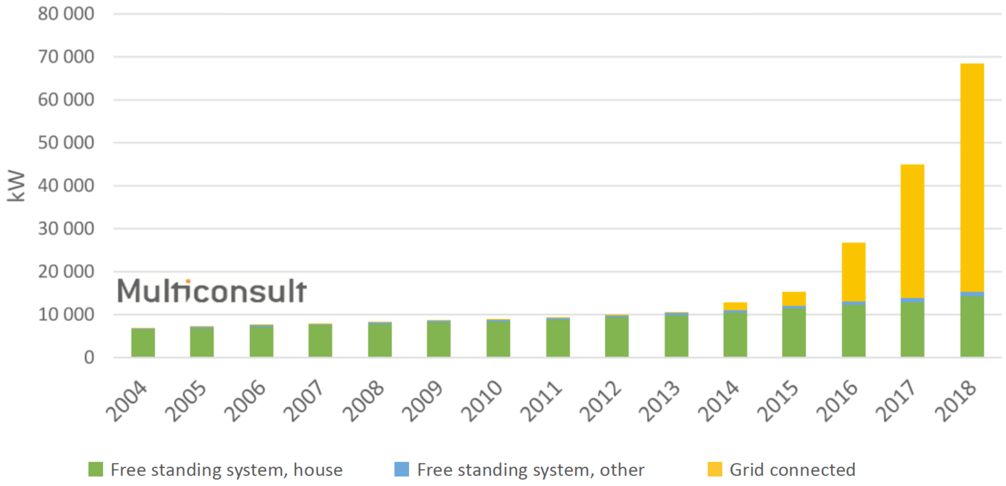

Figure 3.6: Total installed PV in Norway 2004-2018[17]

As seen from figure 3.6, the amount of grid connected PV has increased largely over the last three to four years. Until 2013 the installed capacity was mainly from free standing systems. The total PV capacity reached 68 MW by the end of 2018[17].

According to the Norwegian Water Resources and Energy Directorate (NVE) there were about 2000 prosumers in Norway by the end of 2018[18], and this number is expected to increase rapidly.

3.3.2 Cost

The cost of PV panels has decreased dramatically during the last decades. From 1990 the cost has decreased with as much as 90%[19]. The development in PV price from 2010 to 2018 is shown in figure 3.7.

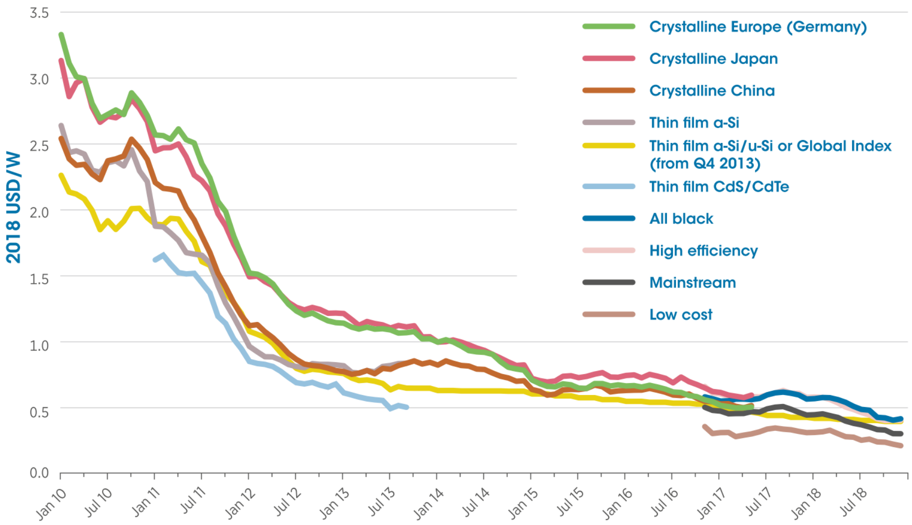

Figure 3.7: Development in price trends for solar PV 2010-2018, average monthly price by module technology and manufacturer[19]

The figure illustrates that the cost has decreased rapidly from 2010 to 2018. Lately it has become competitive to fossil fuels, and IRENA reports that new solar power is expected to cost less than the marginal operating cost of coal fired power plants[19].

While costs have fallen, annual global investments in solar power have been high over the last decade. This has resulted in the large increase in annual installations, as explained earlier. In 2017 as much as 180 billion USD was invested in solar energy[20].

3.4 Expected Growth

There are many different predictions for the growth in installment of PV in the world. The growth is dependent on many factors, such as PV cost, electricity cost, facilitation, and technological development.

According to International Renewable Energy Agency (IRENA), annual Global solar PV additions are expected to reach 270 GW in 2030 and 372 GW in 2050, compared to 94 GW in 2018. This gives a cumulative installed capacity of 2840

GW by 2030 and more than 8500 GW by 2050[21]. IRENA emphasizes the importance of quality infrastructure in order to boost the solar PV markets, to assure performance and durability of the systems[22].

A report from IEA PVPS, which analyses the trends in PV, states that Norway is not expected to be a large PV-market because of low population density, cold climate and high share of cheap hydro power[14].

Research has shown that it is less favorable to produce your own electricity in Norway than in other countries[23]. This is due to the low electricity prices and relatively high installation cost. The introduction of new electricity tariffs for grid rental are also expected to reduce the profit for prosumers[24].

FME CenSES[25] has published a report on prosumers and their role in the future energy system. They claim that existing prosumers in Norway are often motivated more by technological and environmental interest than by economic incentives[26].

For solar power to play an important and central role in the power mix in Norway in 2050, politics, economy, culture and behaviour among different actors are important[27]. The proportion of solar power is expected to increase more rapidly if the electricity cost and/or the total power demand increases.

4 | Power System

This chapter explains how the Norwegian power system is build up, wit a focus on the distribution grid and it's earthing systems. Information about apparent power rating of transformers and grid strength is also given. In section 4.1 the structure of the Norwegian power grid is presented. Section 4.2 presents different earthing systems and its advantages and disadvantages. Grid strength is explained in section 4.3. In section 4.4 the capacity of transformers is explained.

4.1 Norwegian Power System Structure

The power system in Norway consists of three main grid levels: transmission grid, regional grid and distribution grid. The transmission grid is owned and operated by the Transmission System Operator (TSO), Statnett, and has a voltage level of 420 kV and 300 kV. The transmission grid connects Norway to other countries through transmission lines and subsea cables.

The regional grid has a voltage level of 132 kV and 66 kV, and is operated by different DSOs. The lowest voltage level is found in the distribution grid, which connects the end customers to the grid. The distribution grid has a high voltage and a low voltage segment, where high voltage is defined as voltages above 1kV. The high voltage segment has a typical voltage level of 22kV or 11kV, and the low voltage segment is 230V or 400V. Large generating units are connected to the regional or transmission grid, while smaller production plants can be connected to the distribution grid. The structure of the Norwegian power grid is shown in figure 4.1.

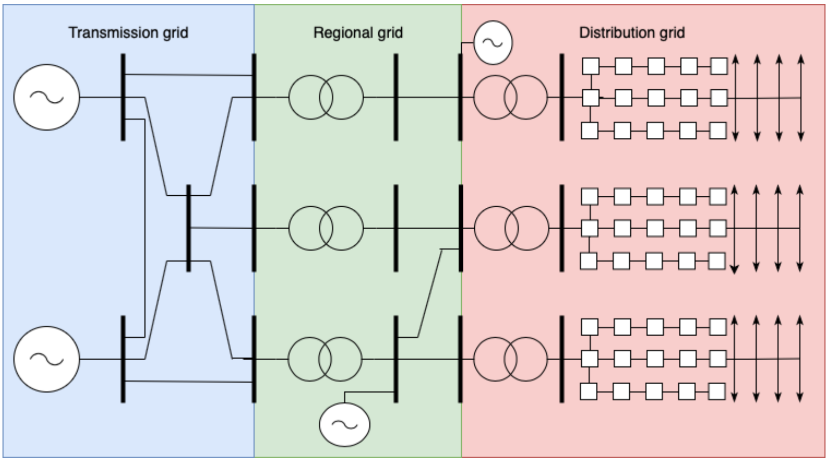

Figure 4.1: Illustration of the structure of the Norwegian power grid

4.2 IT and TN Systems

There are mainly two types of earthing systems that are used in the Norwegian distribution grid: 230 V IT systems and 400 V TN systems. The 230 V IT system is by far the most common, and is used for about 70% of the grid. However, the 400 V TN system is used in new grid areas, and some IT systems are rebuilt to TN systems. The difference between IT and TN systems is explained in the following sections.

4.2.1 IT Systems

In IT systems the supply is isolated from earth. It is either unearthed or connected to earth through a high impedance connection, as shown in figure 4.2. Exposed parts of the system are directly grounded.

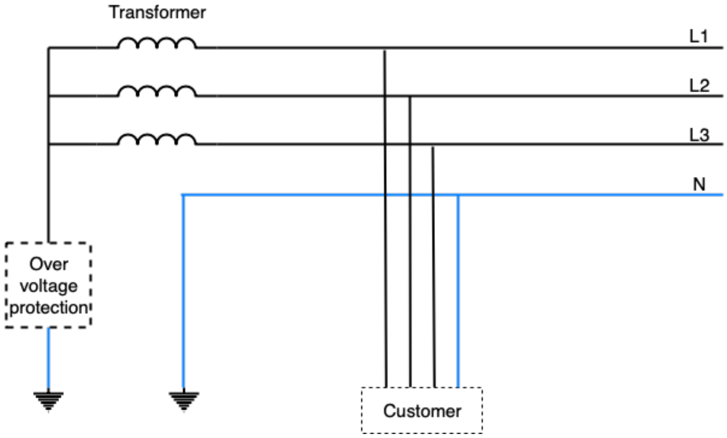

Figure 4.2: IT earthing system

One advantage with IT systems is that the fault current in case of one phase short circuits will go through the ground impedances. This results in small fault currents to ground due to high impedance, so the protection does not trip. Thus, IT systems are well suited for hospitals or other places where power supply is critical[28]. A disadvantage for the IT system is that the line voltage is lower than in TN systems, resulting in larger currents and higher losses.

4.2.2 TN Systems

In TN systems the neutral point of the generator or transformer is directly connected to earth. There are three different types of TN systems:

- TN-C systems
- TN-S systems
- TN-C-S systems

TN-C systems have separate neutral (N) and protective earth (PE) conductors. In TN-S systems there is a combined PEN conductor. TN-C-S systems are a combination of the former, where the PEN-conductor is split into a PE-conductor and an N-conductor. A sketch of a TN-C-S system is shown in figure 4.3, which is the most common TN system in Norway[29].

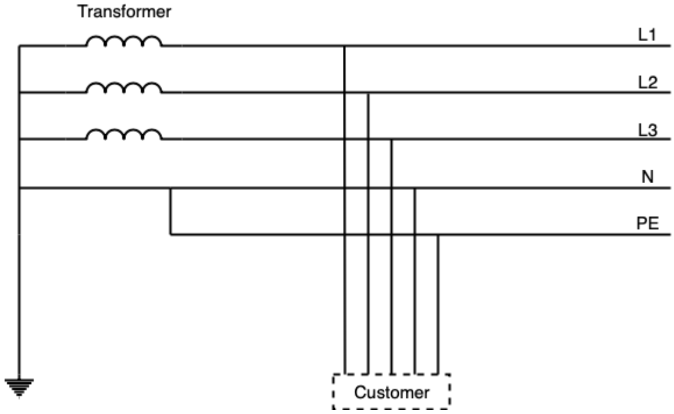

Figure 4.3: TN-C-S earthing system

In TN systems the line voltage is 400V and the phase voltage is 230V. One advantage for 230V/400V TN systems is that the current is lower than in 230V IT-grids, which gives lower losses. However, higher voltage means higher contact voltage, which *can* be dangerous.

4.2.3 Single phase loads

Single phase loads in IT systems are connected between two phase conductors. Therefore, it will affect the voltage in both of the phases it is connected to. In TN systems, single phase loads are connected between one phase conductor and the neutral conductor. The connection will mostly affect the voltage of the phase that it is connected to. Since the voltage is higher in TN than in IT systems, the voltage deviations with the same loads will be larger in IT than in TN systems.

4.3 Grid Strength

Grid strength concerns the grids ability to cope with changes in power flow. Weak grids are often referred to as grids with low short circuit performance[30]. The impedance is large and the X/R ration is low. This means that the resistance of the lines and cables is large compared to the reactance. Weak grids have large voltage drops and losses. In this thesis grid strength is measured in

$I_{k2,\mathrm{min}}$, which is the lowest short-circuit current in IT systems. It can be computed by equation (4.1)[31]:

$$I_{k2,\mathrm{min}} = \frac{c \cdot U_N}{2 \cdot |Z|} \tag{4.1}$$

To take into account that the voltage can be lower than 230V, the factor c is set to 0.95[28].

For the TN system that is simulated in chapter 7, the grid strength is measured by $I_{k1,\mathrm{min}}$. This is because the lowest $I_{k1,\mathrm{min}}$ in a TN system will be similar to $I_{k2,\mathrm{min}}$ for an IT system with the same cables[31]. The values are not directly comparable, but can be used as an indicator of the strength of the grids.

4.4 Apparent Power Rating of Transformers

The apparent power rating of a transformer is based on the amount of current the transformer can handle at its rated voltage. It is normally measured in KVA, and is given by equation (4.2):

$$S_n = \sqrt{3} \cdot U_n \cdot I_n \tag{4.2}$$

Where S is the nominal power [KVA], V is the nominal voltage [kV] and I is the nominal current [A] [32].

The apparent power flow relative to the rated apparent power of a transformer determines the transformer load. The transformer load should not exceed 120% at maximum load[33].

5 | High Installed PV Capacity in the Grid

Increased penetration of PV in the distribution grid can lead to challenges for the power grid. This chapter will take a closer look on quality of supply in the power system and how this is affected by distributed generation and prosumers. Section 5.1 will introduce the term quality of supply. In section 5.2 the challenges related to voltage quality will be explained. Some measures to counteract these challenges are presented in section 5.3.

5.1 Quality of Supply

Quality of supply is a measure of the quality of the electricity delivered to the customers in the power grid. The Norwegian Regulation for Quality of Supply (FoL) defines the rules and regulations for electricity supply in the Norwegian grid[34]. The aim om the regulation is to ensure a satisfactory quality of supply in the power system. Minimum requirements for different phenomena within quality of supply are given in the regulation. Relevant regulations from FoL are included in the description of the challenges.

5.2 Challenges

In distribution grids with high penetration of DG, challenges related to voltage quality can occur. As the power system was originally designed to transport electrical energy from large power plants connected to the transmission grid, connection of smaller power plants in the distribution system may cause problems. The challenges that will be investigated in this thesis are mainly overvoltages and voltage asymmetry, which will be explained in the following sections.

5.2.1 Overvoltages

The voltage magnitude needs to be within a certain level to be useable for the end customers. In FoL the criterion for slow voltage variations is ±10%, measured over a one minute time interval[34]. The allowed interval for the voltage can be computed by equation (5.1).

$$0.9 \cdot U_N \leq U \leq 1.1 \cdot U_N \tag{5.1}$$

Where U_N is the nominal voltage. From equation (5.1) it can be derived that the nominal voltage for all end customers in a 230 V IT system should be within the interval 207 V to 253 V. For a 400 V TN system the allowed interval is 360 V to 440 V.

Feeding of power at a certain point in the grid will cause the voltage to rise. How much the voltage rises depends on the strength of the grid and the amount of power. Voltage rise in a line can be simplified to equation (5.2)[35].

$$\Delta U \approx \frac{P \cdot R - Q \cdot X}{U} \tag{5.2}$$

The distribution grid is originally only designed to handle voltage drops from substation to end customers, not voltage rise. Depending on the existing utilization of the voltage margin, the voltage rise can cause violations of the voltage limit in FoL[36].

In figure 5.1 the solid green and red lines represent voltage drop from substation to end customer during high and low load, typically for winter and summer, respectively. The dashed red line shows how distributed generation combined with low load can cause the voltage to rise above the tolerated limit.

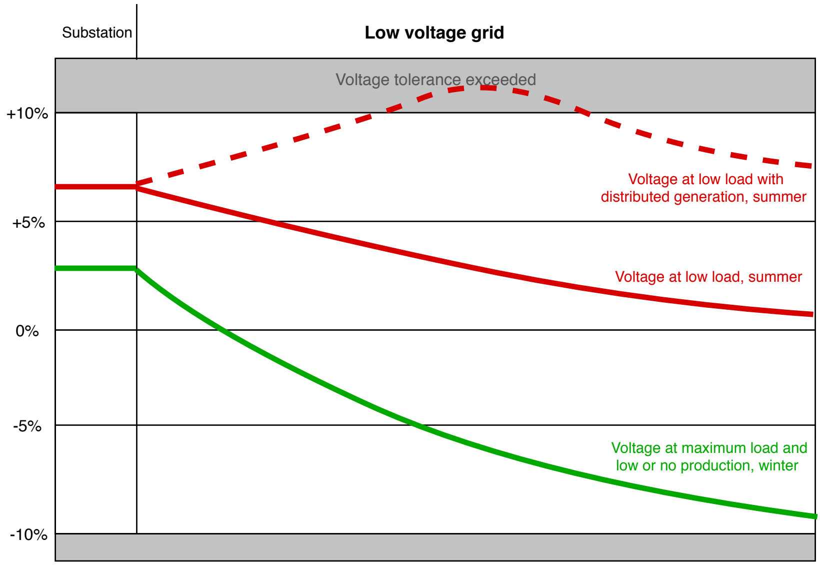

Figure 5.1: Voltage variations in a low voltage circuit, adapted from[35]

To withstand the voltage rise from distributed generation, the grid strength must be adequate to handle both high production combined with low load in the summer and low production combined maximum load in the winter.

In an analysis of future loading scenarios in a Norwegian low voltage network, under-voltage issues due to Electric Vehicle (EV) integration are found much more likely than over-voltage problems caused by PV integration[37]. Nevertheless, it is interesting to analyse how an increase in PV will affect the grid. Both EV and PV integration challenge the grid strength in the distribution grid, since both require large power flows and can cause large voltage deviations.

5.2.2 Voltage Asymmetry

The level of voltage asymmetry, which means difference in voltage between phases, should not exceed 2% at the connection point[34]. Voltage asymmetry measured as the average over ten minutes. It is calculated as the relation between the positive and negative sequential component, U_+ and U_-, respectively, as in equation (5.3).

$$\frac{U_+}{U_-} = \frac{\sqrt{1-\sqrt{3-6\beta}}}{\sqrt{1+\sqrt{3-6\beta}}} \cdot 100\% \tag{5.3}$$

where

$$\beta = \frac{U_{12}^4 + U_{23}^4 + U_{31}^4}{(U_{12}^2 + U_{23}^2 + U_{31}^2)^2} \tag{5.4}$$

and U_{ij} represents the voltage between phase i and j.

Voltage asymmetry is a consequence of unbalanced loads. This can occur if DG is connected to a single phase.

Large PV systems should be connected to the grid through three phase inverters. Earlier, the three phase inverters on the market were not applicable for the Norwegian IT systems. One or more single phase inverters were therefore used to connect the PV systems to the grid. Combining several single phase inverters is expensive and leads to challenges for voltage asymmetry[38].

Data about prosumers in Eidsiva Nett's area show that most new prosumers use three phase inverters, and thereby feed balanced power to the grid. However, a few new PV installations and many of the older ones are connected through single phase inverters. Existing prosumers

5.2.3 Frequency

The frequency in the power system is dependent on load and production. It should at all times be balanced, and in the European power system the balanced frequency is 50Hz. The production is continuously regulated to meet the demand so that the frequency is balanced. The frequency should be within 50Hz ±0.2%, i.e. 49.9 to 50.1 % [39]. The TSO is responsible for controlling the frequency. A balanced frequency is obtained when load and production are equal. An introduction of more DG can affect the frequency due to rapid changes in the power flow[40].

5.3 Measures

There are several measures that can be done in order to enable the integration of grid connected PV systems. The aim of the measures is to counteract the challenges caused by distributed PV. They can also be useful for other grid problems, such as voltage dips due to high power consumption.

5.3.1 Grid Improvements

Grid improvements to strengthen the grid can be done in several ways. One method is by increasing the cross section of the cables, which gives higher transmission capacity and short circuit currents due to lower resistance. Development of more substations closer to the end customers is also a possibility, but this is expensive.

5.3.2 Battery energy storage

Since complications from PV integration are related to correlation between load demand and production, energy storage can be useful. By combining PV installations with BES, one can achieve peak shaving both at times of high load and high production, as explained section 3.1.1.

5.3.3 Reactive Power Regulation

One method for regulating the voltage level in a distribution line is by regulating the reactive power. The voltage can be reduced by reducing the reactive power. For PV systems this can be achieved by using an inverter that consumes reactive power from the grid. Hence, reactive power regulation can contribute to reducing the voltage rise in the grid[41].

Photovoltaic inverters can consume reactive power from the grid to increase the tolerated PV penetration[42]. The effect of reactive power regulation is often better in stronger parts of the grid, where the X/R ratio is high.

5.3.4 Remodeling from IT to TN Systems

Upgrading the existing IT systems to TN systems. This gives higher line voltage, resulting in smaller voltage variations caused by loads or feeding of power. By restructuring the grids to TN systems, this also allows for use of cheaper equipment, such as three phase inverters. Remodeling from IT systems to TN systems is expensive.

6 Methodology

The aim of this analysis is to investigate how an increased penetration of prosumers affects the voltage quality in the distribution grid. This is done through computer simulations, where the input data is based on results from a survey among DSOs and existing literature. The survey maps development, current status and expected growth in prosumers in the Norwegian distribution grid, and is presented in section 6.1. Section 6.2 explains the methodology for the computer simulations. Chosen size of PV systems and batteries is presented and the load assignment is explained.

6.1 Survey about Prosumers

In order to investigate the status and the expected development in prosumers, a survey was sent to different Norwegian DSOs participating in FME CINELDI. The survey's aim was to map the prevalence of prosumers and the growth during the last year. The survey asked for typical size of PV systems, prevalence and size of batteries combined with PV and typical placement in the grid. Expected growth and challenges were also investigated.

Together with available literature the results from the survey will be basis for the analysis in chapter 7 and chapter 8. The survey and a compilation of the answers are attached in appendix C.

6.1.1 Results

Representatives from ten different DSOs have answered the survey. The respondents cover approximately 55% of the total grid customers in Norway. The most important results are shown in table 6.1

Table 6.1: Results from survey among DSOs

Number of customers	1.76 million
Number of prosumers	3500
Number of new prosumers in 2019	1440
Average PV size	7 kW

As seen in table 6.1 the penetration of prosumers in today's grid is low. Almost 3500 prosumers among 1.76 million customers represent less than 0.2%. However, the new prosumers in 2019 cover 41% of the total number of prosumers, which implies a heavily increasing growth.

Average size of PV installation installed at prosumers today is 7kW. The DSOs expect that the size of the installations will increase a little bit during the coming years, but not much. On the other hand, the penetration of prosumers is expected to increase dramatically. This is also in accordance with the prognosis from the literature, see section 3.3. All the DSOs report that it is uncommon for the prosumers to install battery energy storage in combination with PV. There are reported a few prosumers with batteries ranging in size from 6 to 8 kWh.

6.2 Computer Simulations

Simulations of PV production are carried out in two different simulation programs. A comparison of four different low voltage distribution grid is done in Netbas. Simulations are also carried out in one high voltage distribution grid. The goal is to see how grid strength affects the amount of PV tolerated by the grid without exceeding the limits from FoL. Batteries are also simulated, to see how this reduces the impact on the grid.

The simulations in DIgSILENT PowerFactory aims to show how different parameters affect the voltage quality in the grid, more specifically voltage deviations and voltage asymmetry. This is done by varying the amount of prosumers, geographical location and phase balancing of loads. Simulations with reactive power control are also performed.

As mentioned in section 6.1.1 the average size of prosumers PV today is 7kW, and is expected to increase a little. Thus, the size of each PV installation in these simulations is set to 8 kW. This requires a 35-50 m^2 roof area, depending on the choice of panels. An example of an 8 kW PV system is given in appendix A.

In simulations with battery energy storage, which are carried out in Netbas, the charging power is set equal to the rating of the PV systems, i.e. 8kW. This is done in order to investigate whether the introduction of batteries will give the same results as reducing the amount of solar panels. It is assumed that the batteries can charge with full capacity in all simulations.

As explained in section 5.2.1, distributed generation has the highest impact on the grid during low load and high production. From RENblad 3006 regarding grid analysis, this means that the production should be set to 100% and load to 20% for these simulations[43]. Hence, production from the PV systems is set to 100%. The load assignment for Netbas and PowerFactory simulations are explained in sections 7.2 and 8.2 respectively.

7 | Netbas Simulations

7.1 Introduction

Netbas is a network information system delivered by Powel. It is used by grid operators to plan, analyse, build, operate and maintain the power grid[44]. The analysis module of Netbas is used as simulation tool in this chapter. Four low voltage distribution grids and one high voltage distribution grid owned and operated by Eidsiva Nett AS are investigated in the simulations. A brief description of each grid area and its characteristics is given.

7.2 Method

The simulations are done for six different scenarios. Scenario 1-4 tests the grid for different levels of PV penetration. In scenario 5 and 6 BES implementation is tested. A reference scenario with no prosumers is also simulated to see how the normal loading and power flow is for each grid at the assigned date and time. The scenarios are listed in table 7.1.

Table 7.1: Simulation scenarios for Netbas simulations

Scenario	**Prosumer penetration**	**Prosumers with batteries**
Reference	-	-
1	25%	-
2	50%	-
3	75%	-
4	100%	-
5	100%	50%
6	100%	100%

For all simulations in Netbas the PV systems are evenly distributed among the grid customers. This is done manually. As the number of customers in the locations varies and is not always divisible into four, the prosumer penetration also varies a little. Exact penetration for each location and scenario is listed in table C.1 in the appendix.

To achieve light load, the load assignment is set to the day of the year with the lightest load. Predictions for load profiles in Netbas gives lowest expected load in June and July. June is the month with most hours of sunlight throughout the day, and is therefore chosen to obtain the highest production. As explained in section 3.2, the difference between load and production is highest in the middle of the day on business days. Thus, load assignment is set to 12 a.m. in June on a business day, i.e. month 6 and hour 13.

Due to limitations with the battery module for distributed generation in Netbas, load added from EV modules are used to simulate batteries. This choice is not expected to affect the results much. Batteries will only be simulated as loads, they will not be used to feed electricity to the grid. For more information, see appendix D1.

7.3 Location A: Cabled 400V TN-grid in Urban Area

The grid in location A is a 400V TN grid in an urban area. The rated voltage on the Low Voltage (LV) side of the transformer is 415 V. It is connected to an 11 kV high voltage distribution grid. The grid has 46 customers, hereby 45 households, so the maximum number of prosumers is set to 45. The substation transformer has a rated power of 500kVA. The grid is shown in figure 7.1.

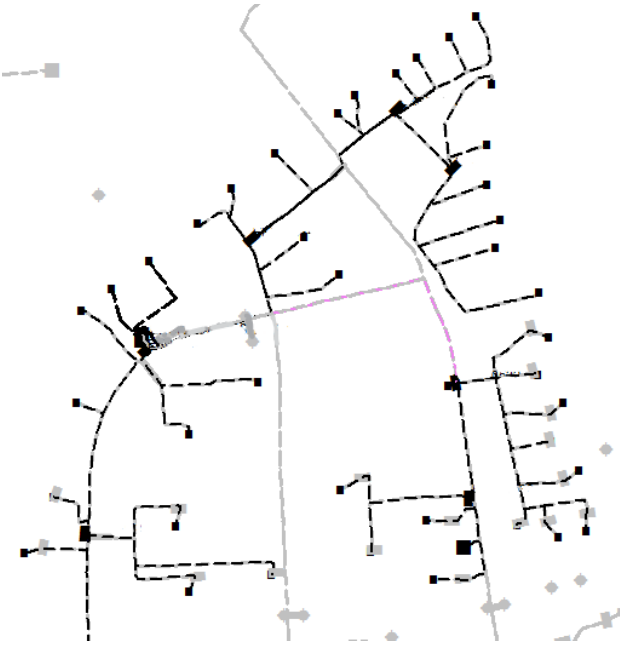

Figure 7.1: Sketch of grid in location A

The lowest short-circuit current in this grid is 1299 A, found at an end customer far from the substation. This implies that the grid is strong. The customers closest to the substation have $I_{k1,\min}$ ranging from 3000 A to 4000A.

Table 7.2: Distribution of short-circuit currents for customers in location B

$I_{k1,\mathbf{min}} < 500$ **A**	**500 A** $\leq I_{k1,\mathbf{min}} \leq$ **1000 A**	$I_{k1,\mathbf{min}} >$ **1000 A**
0	0	45

7.3.1 Simulation Results

The simulation results from location A are shown below. The first table presents the results for the customers, and the second table shows the power flow through the substation and the load of substation and highest loaded line.

Table 7.3: Simulation results for customers in location A

Scenario	**Maximum voltage**	**Voltage rise referred to nominal (400 V)**	**Customers with U > 440 V**
Reference	420 V	5%	0
1	422 V	5.5 %	0
2	423 V	5.75 %	0
3	425 V	6.25 %	0
4	427 V	6.75 %	0
5	423 V	5.75 %	0
6	419 V	4.75 %	0

Table 7.3 shows that none of the customers in this location experience overvoltages due to the installation of PV systems. Even for 100 % prosumer penetration, the voltage only rises 6.75 %. The changes in the substation power flow and loading of lines and transformer are shown in the following table.

Table 7.4: Simulation results for location A

	Substation		
Scenario	**Load**	**Power flow (P+jQ)**	**Max loaded line**
Reference	16.18 %	80.5 + j16.7 kVA	8 %
1	5.2 %	-7.7 + j25.0 kVA	12.0 %
2	21.6 %	-103.2 + j35.6 kVA	13.3 %
3	38.7 %	-190.0 + j46.7 kVA	17.7 %
4	55.9 %	-277.1 + j59.0 kVA	27.7 %
5	26.1 %	-120.5 + j53.7 kVA	13.2 %
6	18.8 %	79.5 + j52.7 kVA	9.4 %

Table 7.4 shows that the power flow is negative for all scenarios 1-5. The

production in the low voltage distribution grid is then higher than the consumption, and power is fed back to the transformer into higher grid levels. The substation is not overloaded in any of the scenarios, and the same goes for the lines.

Since this grid is strong and capable of handling a high penetration of prosumers, it is interesting to see the consequences of introducing larger PV systems. Therefore, simulations are also carried out with 100% penetration of 10, 12 and 14 kW systems. The results are shown below.

Table 7.5: Maximum voltage and loading of substation for 100% prosumer penetration and varying size of PV installations

PV size	**Highest voltage**	**Voltage rise**	**Substation load**
10kW	428 V	7 %	73.2 %
12kW	430 V	7.5 %	90.5 %
14kW	433 V	8.25 %	107.7 %

Table 7.5 shows that the system stays within the voltage limits from FoL, even when the size of the PV systems are doubled. This shows the robustness of a TN system. One can see that the substation is overloaded for 14 kW systems. Hence, the power flow from the low voltage distribution grid is higher than the rating of the transformer.

7.4 Location B - Cabled 230V IT-Grid in Urban Area

The grid in location B is placed in an urban area close to a city centre. It is a 230 V IT system with 38 customers. It is connected to an 11 kV high voltage distribution grid through a transformer with a power rating of 200 kVA. The grid is shown in figure 7.2.

Figure 7.2: Netbas: grid in location B

The transformer has a short circuit power of 154 MVA. The lowest short circuit current is 529 A and the highest is 1369 A. The distribution of short circuit currents for the end customers in this location is shown below.

Table 7.6: Distribution of short circuit currents for customers in location B

I_{k2} < **500 A**	**500 A** $\leq I_{k2} \leq$ **1000 A**	I_{k2} > **1000 A**
0	24	14

7.4.1 Simulation Results

The highest obtained voltages and the number of customers with voltages above 253 V are shown in the table below. The red color marks the scenarios where the limits for slow voltage deviations are exceeded.

Table 7.7: Simulation results for customers in location B

Scenario	**Maximum voltage**	**Voltage rise referred to nominal (230 V)**	**Customers with U > 253 V**
Reference	248 V	7,83%	0
1	252 V	9,57%	0
2	255 V	10,87%	16
3	260 V	13,04%	34
4	264 V	14,78%	38
5	256 V	11,30%	10
6	246 V	6,96%	0

As seen from table 7.7 the voltage limit is exceeded in all scenarios 2-5. However, the highest voltage in the reference scenario is also high, almost 8% higher than the nominal voltage. In table 7.8 the voltage rise relative to the voltage in the reference scenario is shown.

Table 7.8: Voltage rise relative to reference voltage

Scenario	Voltage rise relative to 248 V
1	1,61%
2	2,82%
3	4,84%
4	6,45%
5	3,23%
6	- 0,81%

As seen from table 7.8 the voltage rise is not that high when compared to the reference scenario. Hence, to increase the tolerated prosumer penetration in location B, the voltage level on the low voltage side of the transformer should be reduced.

Table 7.9: Load of line and substation in location B

	Substation		
Scenario	**Load**	**Power flow (P+jQ)**	**Max loaded line**
Reference	36.65 %	72,18 + 15.83 kVA	27.86 %
1	11.59 %	- 7.37 + 22.80 kVA	24.99 %
2	40.60%	- 77.96 + 31.63 kVA	41.02 %
3	77.26 %	- 154.30 + 44.36 kVA	52.49 %
4	110.02 %	- 221.39 + 58.18 kVA	70.91 %
5	52.70 %	- 98.4 + 47.83 kVA	35.49 %
6	41.16 %	72.60 + 46.74 kVA	31.80 %

Table 7.9 shows that the substation is only overloaded in scenario 4, with 100% prosumer penetration. The power flow is negative for all scenarios 1-5, meaning that the local production is higher than the load for all these scenarios. None of the power lines or cables in this grid are not overloaded in any of the scenarios.

7.5 Location C - Grid With Large Share of Overhead Lines

This grid is in a residential area close to a small village. It has a large share of overhead lines and some cables. The substation is connected to a 22kV high voltage distribution grid. The transformer in the substation has a rated power of 200 kVA.

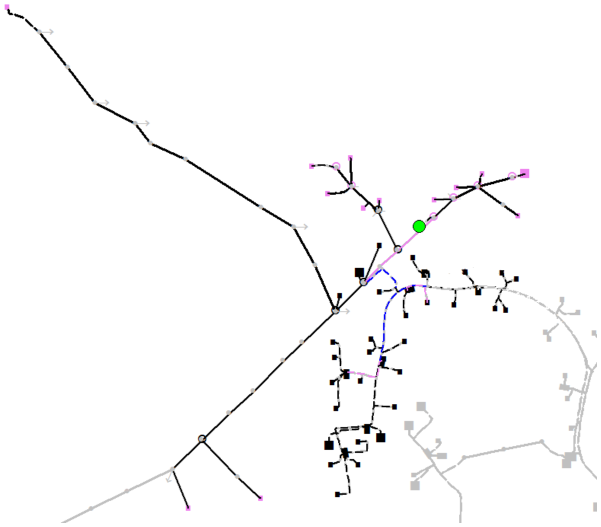

Figure 7.3: Sketch of grid in location C

There are 45 end customers spread over 42 buildings, so the maximum number of PV systems is set to 42. As seen from figure 7.3 most of the houses are located within a small area. The stapled lines in the sketch are cables, and the solid lines represent overhead lines. As seen from the figure there are three customers to the left that are placed far from the substation and are connected by overhead lines.

The lowest short circuit current is 382A, and is found at the customer in the upper left corner. The highest short circuit current is 2321 A. The distribution of short circuit currents shown in table 7.10 shows that this grid has two customers with short circuit currents below 500 A, which were not found for any customers in Location B. However, the amount of customers with short circuit currents above 1 kA is higher than in Location B.

Table 7.10: Distribution of short circuit currents for customers in location C

I_{k2} **< 500 A**	**500 A** $\leq I_{k2} \leq$ **1000 A**	I_{k2} **> 1000 A**
2	18	22

7.5.1 Simulation Results

The simulation results for customers in location C are shown in table 7.11.

Table 7.11: Simulation results for customers in location C

	Maximum	**Voltage rise referred**	**Customers**
Scenario	**voltage**	**to nominal (230 V)**	**with U > 253 V**
Reference	241	4,78%	0
1	245 V	6,52%	0
2	249 V	8,26%	0
3	254 V	10,43%	4
4	259 V	12,61%	31
5	247 V	7,39%	0
6	240 V	4,35%	0

From table 7.11 one can see that the voltage limit is exceeded in scenarios 3 and 4. The introduction of batteries in scenario 5 reduces the voltage, and it is lower than in scenario 2. This is most likely due to different placement of batteries in scenario 5 compared to PV systems in scenario 2, which gives different power flow for the two scenarios. The voltage in scenario 6 and the reference scenario are quite similar.

Table 7.12: Simulation results for location C

	Substation		
Scenario	**Load**	**Power flow (P+jQ)**	**Max loaded line**
Reference	36.39 %	70.20 + 15.15 kVA	34.12 %
1	14.55 %	- 17.03 + 23.19 kVA	21.32 %
2	50.86 %	- 94.84 + 33.37 kVA	44.42 %
3	93.13 %	- 177.79 + 47.82 kVA	80.06 %
4	134.57 %	- 257.77 + 65.69 kVA	123.83 %
5	44.06 %	- 71.02 + 50.41 kVA	38.21 %
6	44.50 %	72.07 + 50.44 kVA	42.74 %

Table 7.12 show that the load of the substation rises above 100% in scenario 4, which is the most extreme scenario. In the same scenario the highest loaded power line experience overload. The power flows from the low voltage grid to the high voltage distribution grid in all scenarios except scenario 6 and the reference scenario.

7.6 Location D - Rural Area with Cabins

In location C a grid in a rural area with many cabins is chosen. It is a 230V IT-grid with a limitation for connections of 3X25A. There are 42 end customers, hereby 38 cabins and four households. The substation transformer has a rating of 100 kVA and is connected to a 22kV high voltage distribution grid.

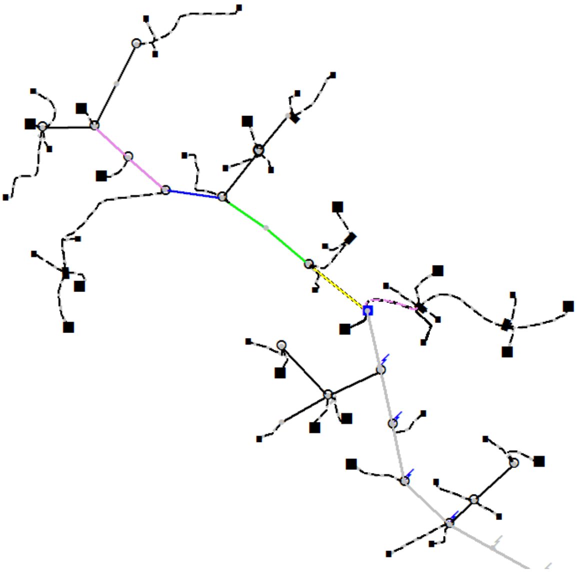

Figure 7.4: Sketch of grid in location D

The customer with the lowest short-circuit current in this grid has $I_{k2} = 351$ A. This value is found at a location far from the substation, as one would expect. The highest short-circuit current is 1897 A, located closer to the substation.

Table 7.13: Distribution of short circuit currents for customers in location D

$I_{k2} <$ **500 A**	**500 A** $\leq I_{k2} \leq$ **1000 A**	$I_{k2} >$ **1000 A**
3	27	13

From table 7.13 one can see that most of the customers have short-circuit currents between 500 A and 1000 A. By comparing this to locations A, B and C, one can see that this is a weaker grid.

7.6.1 Simulation Results

The table below shows the voltages for customers in location D for the simulated scenarios.

Table 7.14: Simulation results for customers in location D

Scenario	**Maximum voltage**	**Voltage rise referred to nominal (230 V)**	**Customers with U > 253 V**
Reference	230 V	0%	0
1	241 V	4.78 %	0
2	254 V	10.43 %	2
3	269 V	16.96 %	16
4	276 V	20.00 %	21
5	252 V	9.57 %	0
6	228 V	- 0.87%	0

Table 7.14 shows that the voltage limit from FoL is exceeded in scenarios 2,3 and 4, i.e. with more than 50% prosumer penetration. The voltage is as much as 276 V in scenario 4, a 20% rise compared to the nominal voltage. Half of the customers experience overvoltages in scenario 4.

Table 7.15: Simulation results for lines and substation in location D

	Substation		
Scenario	**Load**	**Power flow (P+jQ)**	**Max loaded line**
Reference	34.18 %	29.85 + j6.34	21.12 %
1	65.96 %	-56.61 + j16.25	39.77 %
2	149.03 %	-129.52 + j30.56	85.45 %
3	234.74 %	-203.23 + j51.29	142.2 %
4	313.04 %	-269.63 + j73.70	174.75 %
5	154.28 %	-129.18 + j47.85	87.49 %
6	57.06 %	30,676 + j40.68	34.37 %

Table 7.15 shows that the power flow through the substation is negative in all scenarios except the reference scenario and scenario 6. This means that the

production from the PV systems are higher than the total load from the customers in the grid. The substation is overloaded from scenario 2 to 5. In the worst case, scenario 4, the transformer load is more than three times the rated apparent power.

7.7 High Voltage Distribution Grid

In order to see how the higher voltage levels of the grid is affected by increased PV penetration, simulations are also performed in a part of the high voltage distribution grid. This is a 11kv distribution grid connected to a 66kV regional grid. The grid has 47 substations with a total of 1857 customers. The low voltage distribution grids are both 230V IT-grids and 400V TN-grids. The high voltage distribution grid is shown in figure 7.5.

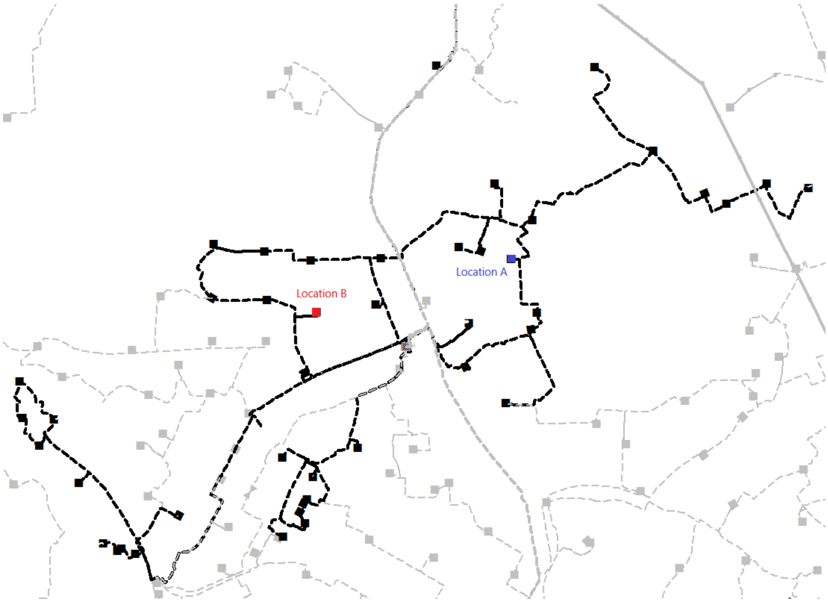

Figure 7.5: Sketch of high voltage distribution grid

In figure 7.5 each square represents a substation. Location A and Location B are marked in the figure.

This grid is large and contains many customers, therefore the simulations have been simplified. Instead of placing the PV systems manually for each scenario, all customers are given 8 kW PV systems and production is set to 25, 50, 75 and 100%, respectively. This will change the results in the low voltage distribution grid since the production is evenly distributed among the customers, but will not have a large effect on the results for the higher voltage level.

Simulations with BES have been done, but are not included here due to uncertainty about the validity of the results. They are attached and discussed in appendix C.4.

7.7.1 Simulation Results

The load and power flow of the LV/MV transformer are shown below. This is the 11/66 kV transformer in the substation between the high voltage distribution grid and the regional grid.

Table 7.16: Apparent power, S, and load of 11kV/66kV transformer

Scenario	**Load**	**Power flow (P+jQ)**
Reference	27.67 %	5.35 + j1.07 MVA
1	9.30 %	1.58 + j0.95 MVA
2	12.54 %	-2.06 + j1.32 MVA
3	30.56 %	-5.59 + j2.15 MVA
4	49.12 %	-9.00 + j3.44 MVA

Table 7.16 shows the load of the LV/MV transformer (11kV/66kV). OThe load of the transformer never exceeds 50%. The power flow through the transformer is negative for scenarios 2 to 5, which means thaht the substation is feeding power to the regional grid. The highest substation load in the 11 kV dsitribution grid is shown in table 7.17 below.

Table 7.17: Maximum substation load in 11 kV high voltage distribution grid

Scenario	**Maximum substation load**
Reference	134.21 %
1	42.69 %
2	118.01 %
3	232.39 %
4	347.61 %

Table 7.17 shows that the highest loaded substation is overloaded in scenario 2, and that in scenario 4 the load is over 300%. The only scenario where no substations are overloaded is scenario 2. Figure 7.6 shows the amount of substations in the 11

kV high voltage disrtibution grid tat are loaded < 50 %, between 50 and 100 % and over 100% for the different scenarios.

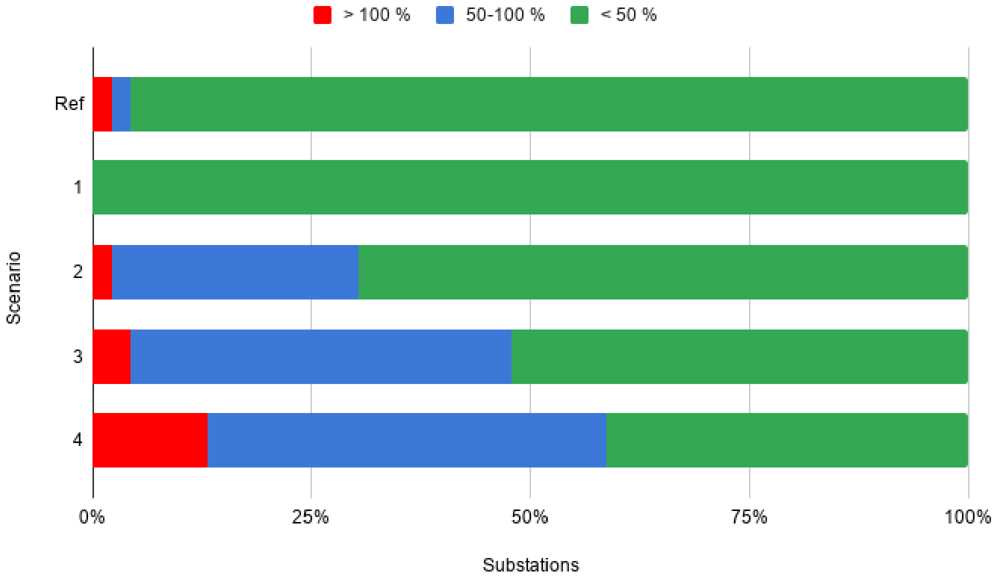

Figure 7.6: Percentage load of substations in high voltage distribution grid

Figure 7.6 shows that about 12 % of the substations in this area are overloaded in scenario 4. More than half of the substations are loaded over 50 % for the same scenario. The only scenario where all substations are loaded less than 50 % is in scenario 1, which means that the local production with a 25 % prosumer penetration covers much of the load in the area. Scenario 1 is also the only scenario where no transformers are overloaded.

7.8 Summary

The simulations have shown that an increased prosumer penetration can result in voltages above the tolerated limit, and that these occur earlier in weak grids than in strong grids.

Figure 7.7 shows the trends for maximum voltage in the different low voltage distribution grids, referred to the nominal voltage. Scenario 0 represents the reference scenario and the black stapled line shows the voltage limit of 10% (1.1 p.u.) from FoL.

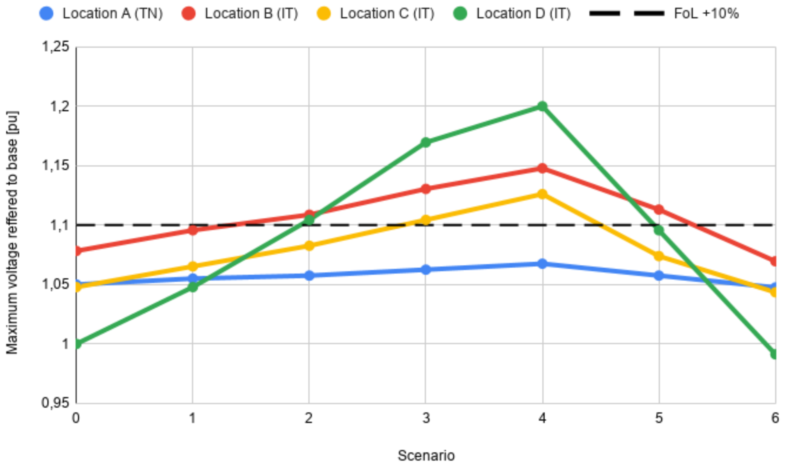

Figure 7.7: Maximum voltage in locations A, B, C and D for all scenarios

The figure clearly shows that the voltage stays most even in the TN grid in location A, represented by the blue line. The grid in location A was by far the strongest, with high short-circuit currents compared to the other locations. This is both due to higher voltage and a combination of stronger and shorter cables.

The voltage in location D is both lowest for the reference scenario and highest for scenarios 3 and 4, as seen from the green line. This is as expected for a weak distribution grid, since the voltage deviations depend on the impedance of the grid and hence the grid strength.

The red and yellow lines, representing location B and D, are of quite similar shape.

The difference in maximum voltage seems to be higher in scenarios 0 and 6 than in scenario 4. This implies that the voltage rise in location B is lower than in C. Due to high output voltage on the LV side of the transformer in location B at no load, the voltage amplitude becomes higher than in C. To avoid voltages above tolerated limit, the output voltage of the transformer should regulated to an appropriate level.

The load of the substations is shown in figure 7.8.

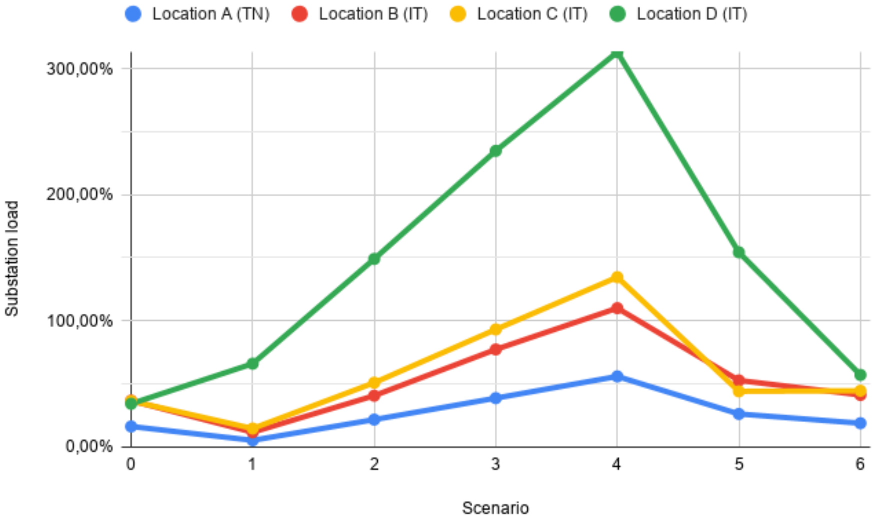

Figure 7.8: Substation load in location A, B, C and D for all scenarios

From the figure it is clear that the load is highest in location D, represented by the green line. Substation D has the lowest power rating (100kVA). Thus, the added load from PV systems constitutes a larger part of the rating of the transformer, resulting in overload. Location D is an area with many cabins. Therefore, it is not very likely that this will be the first place to get a very high penetration of prosumers. However, one should note how strong influence PV integration has on the grid and substation.

Figure 7.8 also shows that the substation in location A is never overloaded. The simulations with larger PV systems in location A have shown that the substation was only overloaded when the size of the PV systems were increased to 14kW.

In locations B and C the substations are overloaded in scenario 4, but much less than location D. The substation in location C has a higher load than B, while both transformers have the same rated apparent power (200 kVA). Location C has four more customers than location B, resulting in 24 kW higher local production, which explains the increased load on the transformer. The use of distributed BES in scenarios 5 and 6 is an efficient way of reducing the transformer load from the PV production.

Transformers in low voltage substations are replaced when the load exceeds 120%[33]. Hence, the transformer in location A would have to be replaced for a prosumer penetration between 25 and 50% with the given PV system size. In location C the limit is only exceeded in scenario 4.

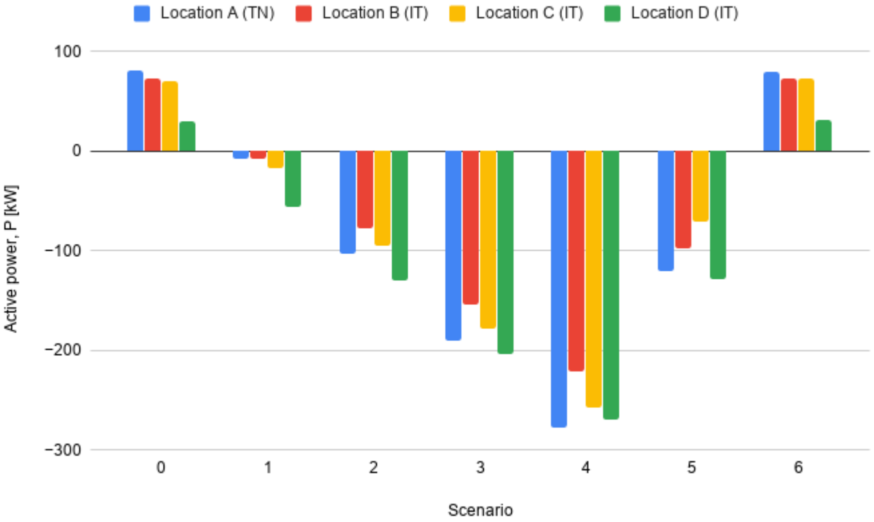

Figure 7.9: Flow of active power (P) in locations A, B, C and D for all scenarios

The active power flow through the substations is shown in figure 7.9. It illustrates that the active power flow is negative in all locations for scenarios 1 through 5. Already at a 25% penetration of prosumers with 8kW PV systems, the local production is higher than the load in the area. Excess electricity production is then transported to higher grid levels.

The effect of introducing BES in scenarios 5 and 6 is clear. By comparing scenario 5 and 2, one can see that the active power flow for 50% prosumer penetration is almost equal as for 100% prosumer penetration, with 50% batteries. The small differences can be caused by different placement of PV systems and batteries in the scenarios. Scenario 6 is also almost equal to the reference scenario.

Simulations on the high voltage distribution grid have shown some of the same trends for load of transformers and power flow as the ones described above. The power flow through the substation is shown in figure 7.10.

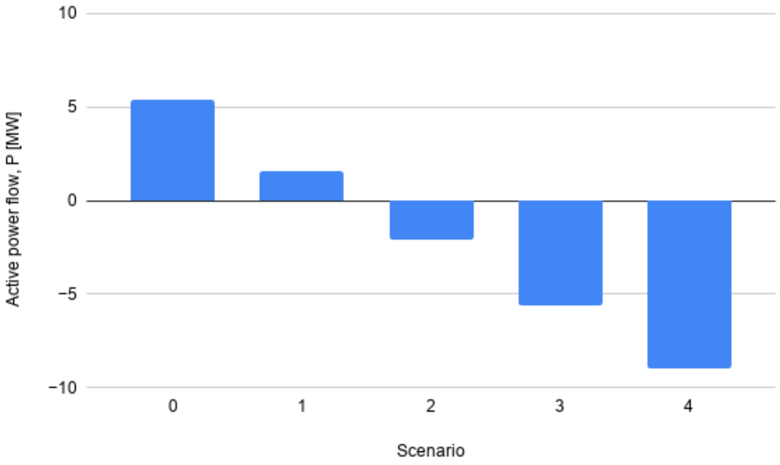

Figure 7.10: Active power flow, P, through LV/MV substation

The most significant difference is that the power flow is positive in scenario 2 for the high voltage substation, while it is negative for all the low voltage substations. Positive power flow in scenario 2 means that the local load of the area is higher than the production from the PV installations.

To summarize, the simulations in this chapter have shown how grids with different characteristics are affected by increased prosumer penetration. It has been shown that grid strength and apparent power rating of the transformers are among the limiting factors for allowed prosumer penetration. Distributed BES has proven to be an efficient way of reducing the customer voltages and the load of the substations. It has also been shown that TN grids are affected much less by prosumers than IT grids.

8 | PowerFactory Simulations

8.1 Introduction

DIgSILENT PowerFactory is a software for power system analysis. It can be used to analyse generation, transmission, distribution and industrial systems[45]. In this thesis it is used to analyse the voltage quality of a distribution grid with installed PV production and batteries. PowerFactory allows for simple editing of the grid data, and is used to see how different parameters affect the results.

This part of the thesis will be similar to a simulation study by Sintef Energy AS from 2017, as part of the SPESNETT project[38], [46]. In the simulation study the PV systems had a size of 4kW, which is half of the size used in this thesis. Therefore, it will be interesting to see how the increased size affects the requirements for the grid strength.

The method of the analysis is described in section 8.2. The analyses and the results are presented in section 8.3 the grid from SPESNETT is analysed. Then, in section 8.4, the grid from Location B in Netbas is build and analysed. A summary of the simulations is given in section 8.5.

8.2 Method

The simulations in this chapter aim to show how PV integration affects the grid in different situations. simulations aim to show how PV integration affects the grid in different situations. Simulations are performed with variations in:

- Grid strength

- Geographical location of prosumers
- Load balancing between phases
- Active and reactive power compensation

By varying these parameters the simulation results can be used to discuss what precautions one should take and what kind of effect the different measures have. In order to easily compare the results with SPESNETT, the same simulation scenarios are used. They are shown in the table below.

Table 8.1: Simulation scenarios for PowerFactory simulations

Scenario	**Prosumer penetration**
1	30 %
2	50 %
3	70 %

8.3 Grid 1: Sample Grid from SPESNETT Project

The grid used in this part of the simulation is the same as in a simulation study from SPESNETT[46]. This grid is used in order to directly compare the results with the results from SPESNETT.

The grid consists of a low voltage cabled grid with four cable distribution cabinets, a transformer and a rigid external grid. The distribution grid is an IT-grid and the voltage on the secondary side of the transformer is set to 240V.

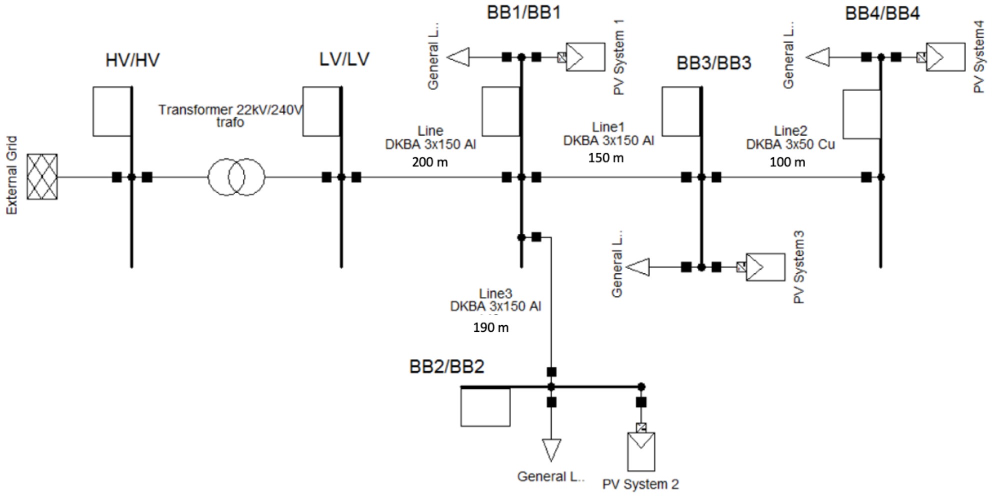

Figure 8.1: Grid used for PowerFactory simulations, $I_{k2,\min} \approx 800A$

As seen from figure 8.1, a general load and a PV system is connected to each of the cable distribution cabinets. The cables from the distribution cabinet to the end customers are neglected, and they are not expected to have a high impact on the voltage losses and quality. The general load at each cabinet is set to 10kW, representing 10 customers with a light load of 1kW[46].

8.3.1 Symmetrical Load - Even Distribution of Prosumers

To obtain symmetrical load the PV is added as a balanced load. In this case the prosumers are distributed evenly in the grid. Since there are 10 customers at each location, the same level of PV production is placed at each cable distribution cabinet. For 30% prosumer penetration, 3 PV systems of 8 kW is added at each point. A balanced AC load flow is then executed. In the first analysis the lowest short circuit current is 805A, at BB4.

Table 8.2: Symmetrical load, even distribution of prosumers, $I_{k2,\text{min}} \approx 800A$

	Cable distribution cabinet ($I_{k2,\text{min}}$)			
Penetration	BB1 (2127A)	BB2 (1096A)	BB3 (1221A)	BB4 (805A)
30%	250	252	253	256
50%	259	263	265	270
70%	267	274	277	284

Table 8.2 shows the simulation results for symmetrical load. One can see that the size and penetration of PV causes the limits from FoL to be exceeded at an early point. Already at 30% the voltage is too high in BB4, and for a 50% penetration the voltage is too high in all points. The relation between voltage and prosumer penetration for this grid is shown in figure 8.2 below. The stapled black line represents the upper voltage limit of 253V from FoL.

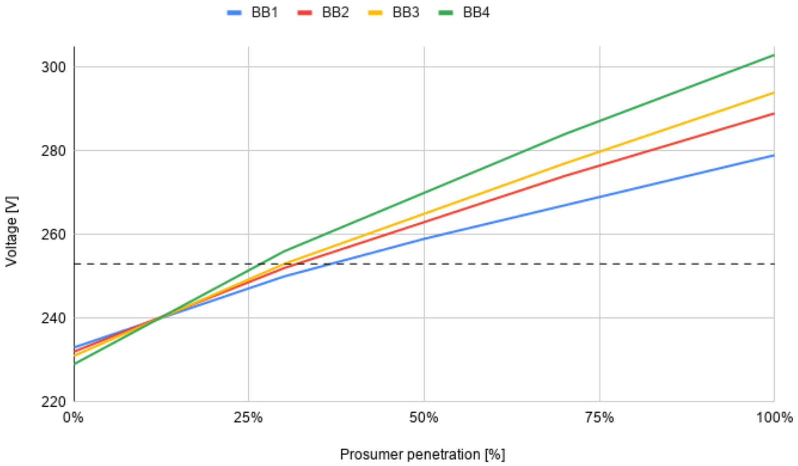

Figure 8.2: Voltage magnitude relative to prosumer penetration, $I_{k2,\min} \approx 800$ A

From figure 8.2 one can see that with no prosumers, the voltage is highest at BB1, which is closest to the substation. The voltage is lowest at BB4, furthest from the substation. This is as expected. By increasing the amount of prosumers this will shift. The shift takes place around 12% penetration, and at that point the voltage is equal at BB1-BB4 ($\approx 240V$). The voltage limit is exceeded at BB4 when the penetration is a little bit higher than 25% and at BB1 before 40% penetration is reached.

Strengthening The Grid

In order to see how a grid improvement can reduce the impact from PV, the short circuit capacity of the grid is increased by shortening the lines. The new parameters are shown in figure 8.3.

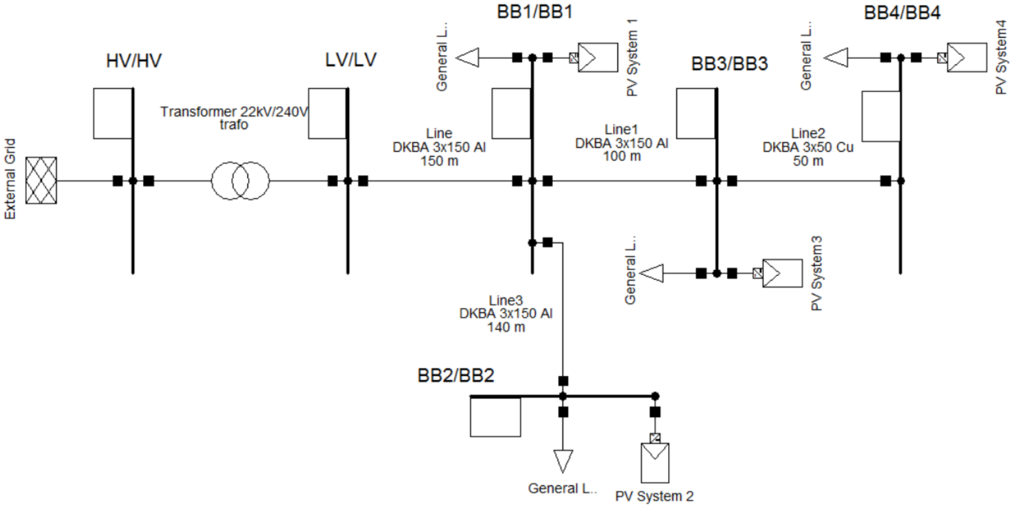

Figure 8.3: Grid used for PowerFactory simulations, $I_{\text{k2, min}} \approx 1250A$

By performing the same analysis on the strengthened grid, the following results have been found:

Table 8.3: Symmetrical load, even distribution of prosumers

	Cable distribution cabinet ($I_{\text{k2, min}}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	247	249	250	251
50%	254	258	259	261
70%	261	266	268	271

As seen from table 8.3 this grid can take a 30% penetration of prosumers with 8kW PV systems. For a 50% penetration the voltage limits are exceeded at all points, and the same goes for 70% penetration. A plot of the results is shown in figure 8.4.

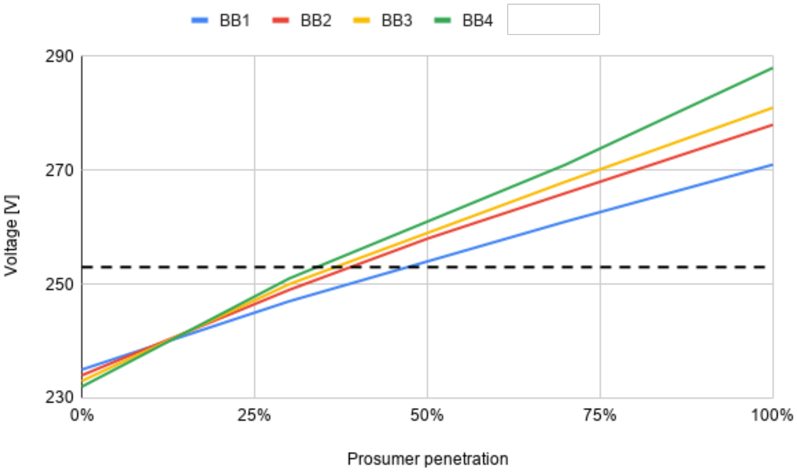

Figure 8.4: Voltage magnitude relative to prosumer penetration, $I_{k2,\text{min}} \approx 1250$ A

As seen from figure 8.4 the voltage limit of 253 V is exceeded around a 35 % penetration. In order to improve the results further, the grid is strengthened again. The cables between the transformer and BB1 and between BB1 and BB3 are changed from DKBA 3x150 Al to DKBA 3x150 Cu, which have lower resistance. The lowest short circuit current is now $\approx 1700A$. The new results are shown below.

Table 8.4: Symmetrical load, even distribution of prosumers, $I_{k2,\text{min}} \approx 1700A$

	Cable distribution cabinet ($I_{k2,\text{min}}$)			
Penetration	BB1 (4339A)	BB2 (2279A)	BB3 (2637A)	BB4 (1709A)
30%	244	245	246	247
50%	249	251	252	254
70%	253	256	257	261

By comparing the results in tables 8.2 to 8.4, it is clear that grid increasing the grid strength helps improve the grid's ability handle an increased prosumer penetration. The voltages at BB4 for the different grids are shown in figure 8.5.

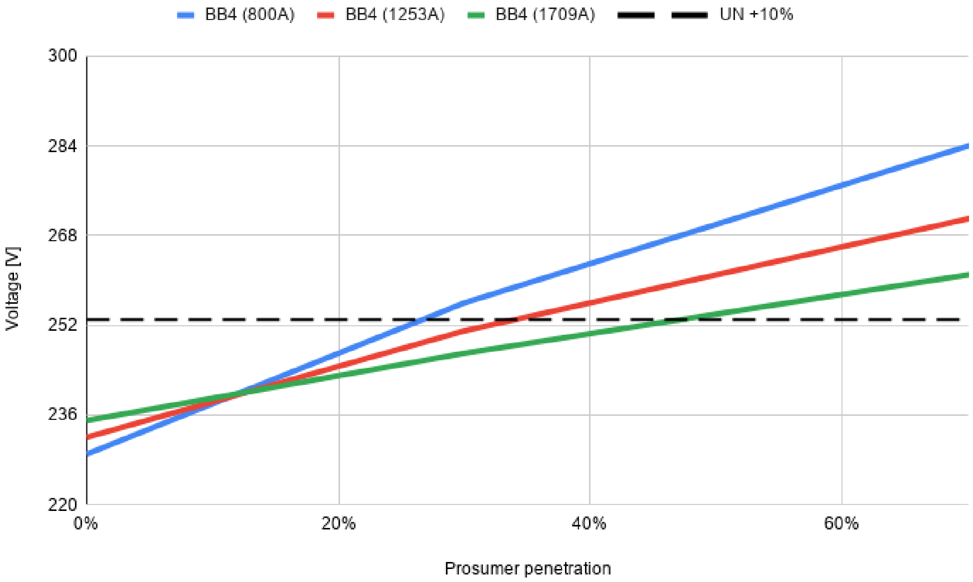

Figure 8.5: Voltage at BB4, $I_{k2,\text{min}} \approx 800$ A, 1250 A and 1700 A

The figure illustrates the importance of grid strength to handle an increased penetration of prosumers.

8.3.2 Symmetrical Load - Geographical Variations

Short circuit currents are higher closer to the substation, and hence the grid is stronger in this area. In order to see how geographical variations affect the results, simulations with prosumers close to substation and far from substation are performed. The grid with $I_{k2,\min} = 1253A$ is used for these simulations.

All PV Connected Close to Substation

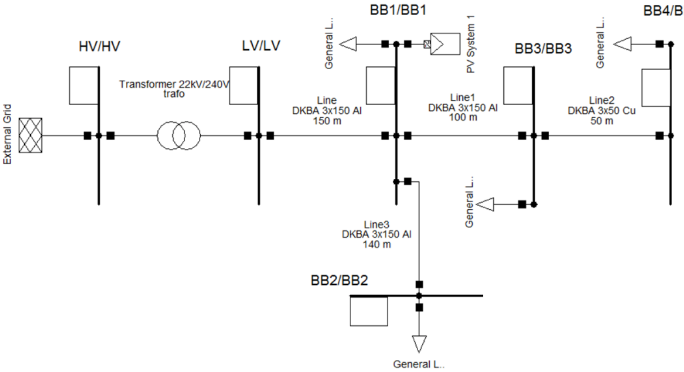

Figure 8.6: PowerFactory grid, all PV connected close to substation, $I_{k2,\min} \approx 1250A$

In this scenario all PV is connected at BB1, as shown in figure 8.6. The size of the PV system at BB1 is now equal to the sum of all PV systems in BB1 to BB4 in section 8.3.1. This is not a feasible scenario since there are only ten customers at this point, but these simulations are performed in order to show how differences in geographical location affects the results. The results from the simulation are shown in table 8.5.

Table 8.5: Symmetrical load, all PV connected to BB1

	Cable distribution cabinet ($I_{k2,\min}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	247	246	245	244
50%	254	253	253	252
70%	262	260	260	259

As seen from table 8.5, the voltage is now highest at BB1, as one would expect. The voltage limit of 253V is exceeded at 50% penetration, but only at BB1. For 70% integration the voltage is too high at all busbars.

All PV Connected far from Substation

To further analyse the effect of geographical variations, all PV is now connected at BB4, furthest from the substation. This is also the point in the grid with the lowest short circuit current. The new grid is shown in figure 8.7.

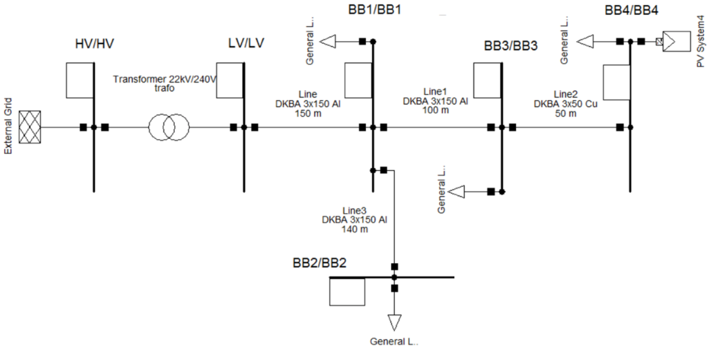

Figure 8.7: PowerFactory grid, all PV connected far from substation, $I_{k2,\min} \approx 1250A$

The results from the simulation are shown in table 8.6.

Table 8.6: Symmetrical load, all PV connected at BB4

	Cable distribution cabinet ($I_{k2,\min}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	248	245	252	259
50%	253	252	264	274
70%	259	258	273	288

As seen in table 8.6, the voltage at BB4 exceeds the limit from FoL already at a 30% penetration of prosumers. In the case with 50% the voltage is also too high in BB3. By comparing table 8.5 and table 8.6 it is clear that the grid is more robust for handling PV at locations with higher short circuit currents, which are found closer to the substation. Thus, the restults are as one would expect.

8.3.3 Reactive Power Regulation

As explained in section 5.3.3 one measure to improve voltage quality is by reactive power compensation. This is tested on the grid in order to see how it affects the voltage. First, each prosumer produces 8kW active power and consumes 1kVAr reactive power. The results are shown in table 8.7.

Table 8.7: Even distribution of prosumers, 1kVAr reactive power consumed by each prosumer

	Cable distribution cabinet ($I_{k2,\text{min}}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	247	248	249	250
50%	253	256	258	260
70%	260	264	266	270

The results in table 8.7 show that consumption of reactive power helps, but that the effect is marginal. By comparing this to the results in table 8.3, one can see that the voltage is a little lower at each location. The same simulations are then done with 2 kVAr reactive power consumed by each PV system. The results for this simulation are shown in table 8.8.

Table 8.8: Even distribution of prosumers, 2kVAr reactive power consumed by each prosumer

	Cable distribution cabinet ($I_{k2,\text{min}}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	246	247	248	249
50%	252	255	256	259
70%	258	263	265	268

Once again, one can see that the resulting voltages are lower, but not much. In figure 8.8 the results are compared to the basecase.

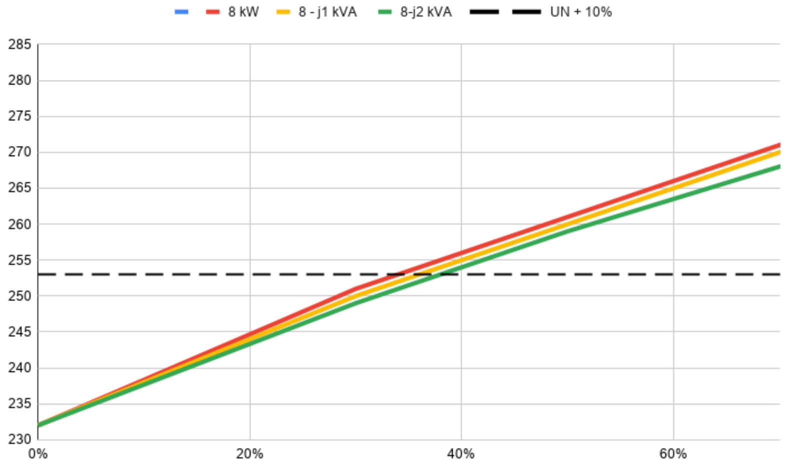

Figure 8.8: Effect of reactive power control on voltage levels, $I_{k2,\min} \approx 1250A$

The figure illustrates that the effect of reactive power consumption from the inverters is minimal, but helpful.

8.3.4 Unsymmetrical Load

The previous simulations have been executed with all PV and load connected as balanced load, i.e. evenly distributed on the three phases. Since PV systems also can be connected through single phase inverters, these simulations are performed to analyse the importance of load balancing. In all the simulations prosumers are distributed evenly throughout the grid, so the same amount of PV is connected at all cable distribution cabinets.

All PV connected on one phase

In these simulations all PV is connected on L1-L2. The resulting phase coltages are shown in table 8.9.

Table 8.9: All PV connected to L1-L2, PV evenly distributed in the grid

		Cable distribution cabinet ($I_{k2,\min}$)			
Pen.	**Voltage**	BB1(2827A)	BB2(1462A)	BB3(1705A)	BB4(1253A)
30%	U_{12}	257	262	263	266
	U_{23}	245	246	247	247
	U_{31}	237	236	236	235
50%	U_{12}	270	277	280	285
	U_{23}	251	254	255	256
	U_{31}	237	237	237	237
70%	U_{12}	282	292	295	302
	U_{23}	257	261	263	265
	U_{31}	238	238	238	239

The table shows that at 30% integration, the voltage U_{12} has exceeded the voltage limit at all locations. A voltage rise relative to the substation voltage is also found in U_{23}, while U_{31} seems unaffected. For 50% integration the voltage limits are also exceeded for U_{23} at all locations except BB1. For these simulations the most important findings are not necessarily the voltage levels, but the voltage asymmetry. The level of voltage asymmetry for this simulation is shown in table 8.10.

Table 8.10: Voltage asymmetry when all PV is connected on L1-L2

	Cable distribution cabinet ($I_{k2,\text{min}}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	4,74%	6,15%	6,35%	7,31%
50%	7,63%	9,15%	9,81%	10,93%
70%	9,95%	12,05%	12,62%	13,89%

The limit for voltage asymmetry is 2%, and as seen from table 8.10 the asymmetry is too high in all locations for the given penetration levels. This shows that it is very important to balance the loads in the grid to avoid problems with voltage asymmetry.

PV connected on two phases

In order to further analyse the effect of load balancing, simulations are also executed with 50% PV connected on L1-L2 and 50% on L2-L3. The simulation results are shown in table 8.11.

Table 8.11: PV connected 50% on L1-L2 and 50% on L2-L3, PV evenly distributed in the grid

		Cable distribution cabinet ($I_{SC,\text{ min}}$)			
Pen.	**Voltage**	BB1(2827A)	BB2(1462A)	BB3(1705A)	BB4(1253A)
30%	U_{12}	247	249	250	252
	U_{23}	251	254	255	257
	U_{31}	240	240	240	240
50%	U_{12}	256	260	261	264
	U_{23}	262	267	270	273
	U_{31}	244	245	245	245
70%	U_{12}	263	269	271	275
	U_{23}	272	279	282	287
	U_{31}	246	248	248	249

As seen from the table, the voltage limit is exceeded already at 30% integration for U_{23} at BB2-BB4. The resulting voltages are lower than in table 8.9, but still too high. Voltage asymmetry is shown in table 8.12.

Table 8.12: Voltage asymmetry for PV connected 50% on L1-L2 and % on L2-L3

	Cable distribution cabinet ($I_{k2,\mathrm{min}}$)			
Penetration	BB1 (2827A)	BB2 (1462A)	BB3 (1705A)	BB4 (1253A)
30%	2.61%	3.30%	3.54%	4.02%
50%	4.15%	5.01%	5.62%	6.29%
70%	5.82%	6.83%	7.44%	8.22%

As seen from table 8.12 the voltage asymmetry is still above the limit of 2% at all locations for all the scenarios. However, by comparing it with the results in table 8.10 one can see that the 50/50 distribution is much better than when all PV is connected between L1-L2. This shows the need for balancing PV in the grid when several systems are installed in the same low voltage distribution grid.

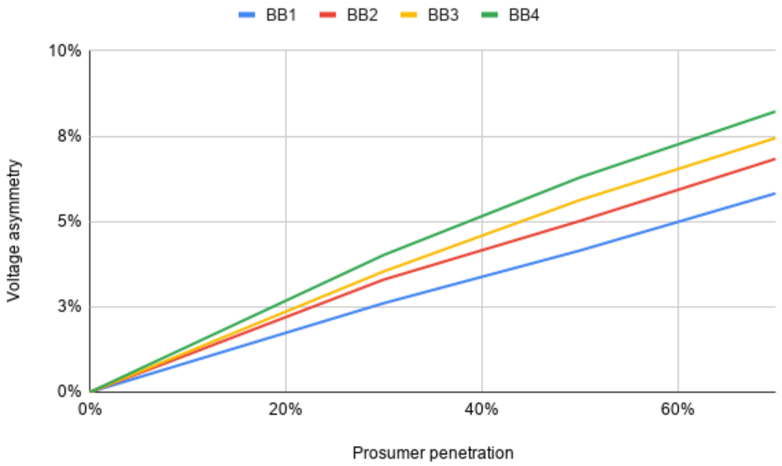

Figure 8.9: Sketch of voltage asymmetry relative to prosumer penetration

Figure 8.9 shows how the degree of voltage asymmetry increases with increased prosumer penetration. The limit of 2% is exceeded at an early stage, and it happens first for the location with the lowest short circuit current.

8.3.5 Comparison with SPESNETT results

In SPESNETT the grids with $I_{k2,\text{min}} = 800$ A and 1200 A were analysed with varying level, placement and connection of PV. The size of the PV systems were set to 4kW. The difference between the voltage in BB4 with 4 and 8kW PV systems is shown in figure 8.10.

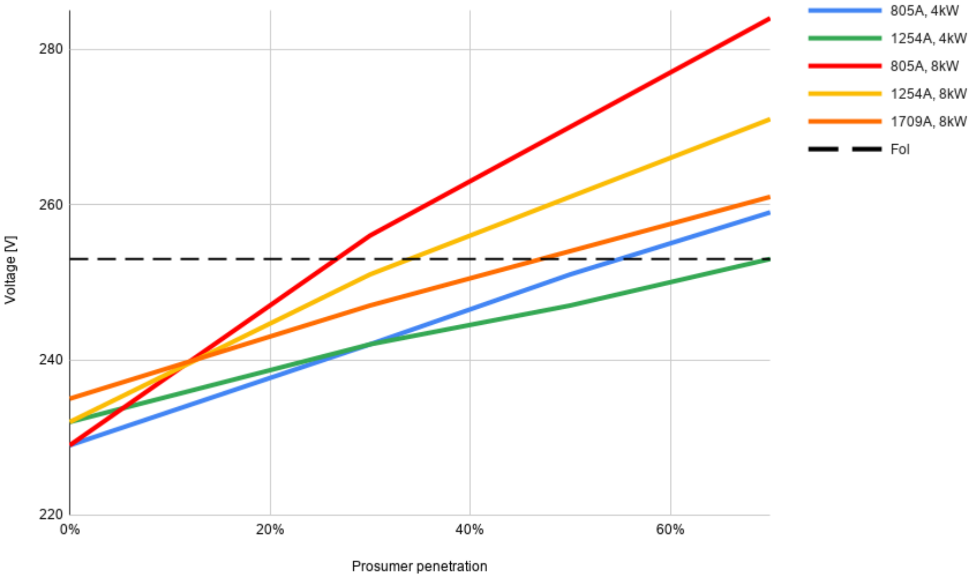

Figure 8.10: Voltage at BB4 relative to prosumer penetration, $I_{k2,\text{min}}$ 805 A, 1254 A and 1709 A, PV systems = 4kW and 8kW

As seen from the figure, the size of the PV system has a large impact on the results. The blue and green lines represent the voltage results from simulations with 4kW solar panels. One can see that the yellow and red lines have a steeper curve. This is easy to understand, a 20% penetration of prosumers with 8kW panels is the same as a 40% penetration of prosumers with 4kW panels. The orange line, with $I_{k2,\text{min}} = 1700$ A, has a flatter curve than the blue one, but a higher starting voltage for 0% penetration.

The results for asymmetric load and variations in geographical location show the same trends as in the SPESNETT project. The only different is the doubled PV size, causing the limits for voltage asymmetry and slow voltage deviations to be exceeded at a much earlier point, as one would expect when the PV systems are larger and the grid strength is the same.

8.4 Grid 2: Location B from Netbas Simulations

In order to test another grid in PowerFactory simulations, the grid from location A is chosen. It has been simplified in a similar manner as grid 1, so all cables from cable distribution cabinets to customers are neglected. The grid is shown in figure 8.11 below.

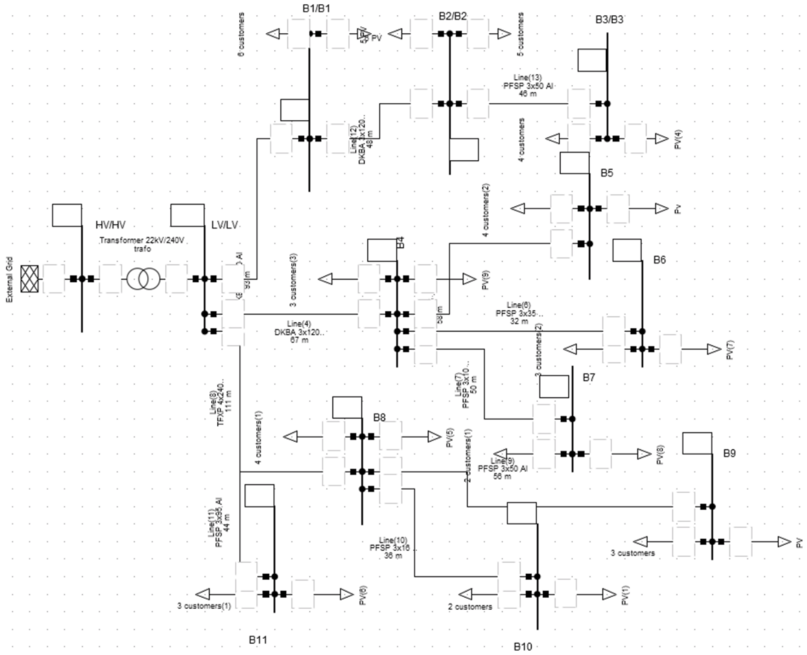

Figure 8.11: Grid 2 in PowerFactory

The low voltage grid consists of an external grid, a transformer and 11 busbars numbered from B1 to B11. Each busbar represents a cable distribution cabinet, and a general load and a PV system is connected at each one. Grid information, including short circuit currents for each busbar, is given in table 8.13

Table 8.13: Information about grid 2 from PowerFactory simulations

Location	$I_{k2,\mathbf{min}}$	**Number of customers**
B1	6858A	6
B2	4339A	5
B3	1840A	4
B4	7958A	3
B5	2208A	4
B6	3283A	3
B7	1346A	2
B8	5761A	4
B9	1800A	3
B10	2224A	2
B11	6269A	3

The short circuit currents shown in table 8.13 are higher than the short circuit currents for location B in the Netbas simulations, which this model is based on. This is because the cables from the cable distribution cabinets to the end customers are neglected, and there are more than one customer at each location.

The lowest short circuit current is 1800 A. This is not much higher than for some of the simulations in Grid 1, where the highest short circuit current was $\approx$ 1700 A. However, since the amount of customers in each location is lower here than in Grid 1, this grid is relatively much stronger.

8.4.1 Simulation of Increasing Prosumer Penetration

Simulations have been performed with an even distribution of prosumers. The resulting voltages for each location are shown in table 8.14 below.

Table 8.14: Voltage at each busbar with even distribution of prosumers

	Prosumer penetration				
Location ($I_{k2,\mathbf{min}}$)	0 %	30 %	50 %	70 %	100 %
B1 (6858A)		241	242	244	245
B2 (4339A)		242	243	245	247
B3 (1840A)		242	245	247	250
B4 (7958A)		241	242	242	243
B5 (2208A)		241	243	245	247
B6 (3283A)		241	242	243	245
B7 (1346A)		240	241	244	247
B8 (5761A)		241	241	242	244
B9 (1800A)		242	242	244	247
B10 (2224A)		242	242	243	245
B11 (6269A)		240	240	241	241

From the table one can see that none of the voltages are higher than the limit of 253 V from FoL, which means that the grid can handle this level of PV integration.

Table 8.15: Maximum voltage, even distribution of prosumers

Prosumer penetration	**Maximum voltage**	**Voltage rise***
30 %	242 V	0.8%
50 %	245 V	2.1%
70 %	247 V	2.9%
100%	250 V	4.2%

$*$ voltage rise referred to low voltage side of transformer (240V)

The highest voltage in all scenarios is found in B3, which has a short circuit current of 1840 A. Four customers are connected at this location.

8.5 Summary

The simulations have shown that sufficient grid strength is crucial for handling an increased penetration of prosumers. The importance of balanced connection of load have been shown through symmetrical and unsymmetrical load connections. Even though most new prosumers nowadays use three phase inverters for connection of load, it is useful to see how weak IT grids react to unbalanced connection of systems.

It has also been shown that consuming reactive power from the grid can reduce the voltage rise caused by PV penetration. This kind of compensation is expected to be more useful in a stronger grid with higher X/R ratio.

By comparing the results from grid 1 with results from SPESNETT[46], one can see that the increased size of PV systems have a large impact on the resulting voltages. Even for the strongest grid ($I_{k2,\text{min}} = 1700$ A), voltages were higher than in SPESNETT with $I_{k2,\text{min}} = 800$ A.

Analyses of grid 2, which is adapted from Location B in Netbas, have shown that by neglecting the cables from cable distribution cabinets to the end customers the voltage rise is lower than obtained in the Netbas analysis. To use this kind of simplification for analyses, one might therefore need to reduce the accepted interval for voltage level.

9 | Discussion

9.1 Method

The survey about prosumers was sent to 13 Norwegian DSOs participating in FME CINELDI. There are currently a total of 123 DSOs in Norway[47], so the selection is small. However, the recipients cover more than 50 % of the total grid customers in Norway.

The chosen size of 8kW PV systems was based on the replies regarding average size of PV systems and expected growth from the survey. The power output from future prosumer PV systems might be larger than anticipated here. Both increased power density and more extensive use of BIPV can lead to larger systems in the future.

Simulations have been carried out without taking the angle, orientation or size of the roofs into account. This will give unrealistically high values for simultaneously produced power in the areas. In a more realistic simulation one would assume that some houses would have high production in the beginning of the day, while others have higher production in the afternoon. This means that the resulting voltages in the simulations are worse than they would be in real life when installing PV systems of the same size.

The prosumer penetration in the scenarios might not seem completely realistic if one is looking at the whole power system as one. A 100% prosumer penetration will probably never for the foreseeable future be the case. However, it is not impossible that this occurs for some substations. "Neighbor effect", i.e. that neighbors are inspired by each other, can lead to high prosumer penetration in certain areas.

9.2 Results

9.2.1 Voltage Magnitude

The computer simulations have shown that, in grids with low short-circuit currents, the voltage limit from FoL is exceeded at a much lower penetration level than in stronger grids. Simulations in Netbas have also shown that the TN grid that was analysed had a much higher tolerance for prosumer penetration.

The comparison with the SPESNETT project, which had 4kW PV systems, have shown that the increased size of systems has a large impact on the results. The voltage level at the weakest point in the grid is much higher, causing the limits from FoL to be exceeded at a much earlier point.

9.2.2 Voltage Asymmetry

Simulations of unbalanced loads in PowerFactory have shown that the need for balancing between phases is crucial for the new sizes of PV systems. The limits for voltage asymmetry in FoL are exceeded at an early stage, and load balancing is therefore crucial. Most new installations are connected through three phase inverters. In case of connection through three phase inverters, voltage asymmetry is not an issue.

9.2.3 Substation Load

Reverse power flow through the substations occurred at an early point in the simulations in Netbas. For all simulations in different low voltage distribution grids, local production was higher than the consumption for scenarios 1 to 5, i.e. from 25% prosumer penetration. For the transformer in location D, with the lowest rated apparent power, this led to a heavy overload of more than 300% in the worst scenario (scenario 4).

The reverse power flow is not an issue as long as the grid operators take this into account and balance the production and consumption. If the total production from PV systems in an area is higher than the rated apparent power of the transformer, overload can occur.

9.3 Impact of Different Measures

9.3.1 Battery Energy Storage

BES has proven to be an efficient way of reducing the capacity constraints of the grid. The simulations have shown that adding a battery with the same charging power as the power output from the PV system, eliminate the effect of the PV system on the grid. Investment in BES can be an alternative to grid upgrades.

9.3.2 Reactive Power Regulation

The simulations in PowerFactory have shown that if the inverters consume reactive power, the voltage level in the grid can be relieved. This was only carries out in one grid with a minimum short circuit of 1200 A. Since the effect of reactive power regulation is expected to have more impact in stronger parts of the grid, simulations should also have been done on stronger grids.

9.3.3 Grid Improvements

By strengthening the grid in the PowerFactory simulations, the obtained results were improved. This was done by reducing the length if cables and by switching the cables with other that had lower resistance. Other ways to improve the grid are by adding more substations closer to the customer. Restructuring from IT to TN grids to achieve higher voltage is also a possibility, but this is expensive.

10 | Conclusion

The amount of prosumers in Norway has icreased largely during the last years, and is expected to continue growing. Rapid technological development and heavy price reductions speeds up the process. Through a survey among Norwegian DSOs it has been found that the amount of prosumers has increased by more than 40% in 2019. An increased prosumer penetration in the distribution grid can lead to challenges related to quality of supply and load of equipment. The highest production from PV systems occurs at times with low load, and can cause voltages above the tolerated limit and overload of equipment.

Computer simulations with different penetration levels of prosumers with 8kW PV systems have been carried out. Netbas and DIgSILENT PowerFactory are used as simulation tools. The simulations have shown that the minimum short-circuit current and apparent power rating of transformers are among the limiting factors for the allowable prosumer penetration.

The computer simulations have that strong grids can handle a much higher penetration of prosumers without exceeding the voltage limits given in FoL. Connection of several prosumers in the same weak low voltage distribution grid is likely to cause voltages above the tolerated limit. If the total installed PV capacity is higher than the rated apparent power of the transformers, overload of transformers can also occur.

Grid improvements to increase minimum low voltage currents in the grid can improve the allowed prosumer penetration. By increasing the transmission capacity of the power lines or the rated apparent power of the transformers, the grid can handle a higher prosumer penetration.

The simulations have shown that distributed BES can help relieve the grid from capacity constraints by reducing the power flow of surplus production from prosumers to the grid. This both reduces the load of the transformer and power lines, and reduces the voltages. BES is therefore very useful in grids with high prosumer penetration. Investing in BES can therefore be an alternative to investing in grid improvements if it is financially profitable.

11 | Further Work

This thesis has simulated the worst case scenario for integration of prosumers in the distribution grid. The focus has been on voltage level, voltage asymmetry and complications related to load of lines and transformers. To further analyse the effect of increased prosumer penetration in the grid, it can be interesting to do the following:

- Simulations with more realistic production data for prosumers based on location, roof area, angle and orientation, e.g. by using PVsyst or similar programs.
- The socioeconomic cost of required grid upgrades to handle an increased prosumer penetration.
- Analyses with PV and BES over time, to see how much self-consumption one can achieve and how this can relieve the grid from capacity constraints.

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A | Example PV System

A PV system can for instance be made by combining panels of the type REC295TP2. Technical data for these panels are given below.

Table A.1: Technical data for REC TwinPeak 2 (REC295TP2)[48]

Nominal power	295 Wp
Area	1.67 m^2

The PV system should have a size of 8kW. The number of panels is computed as follows:

$$\frac{8000W}{295Wp} = 27.1$$

Thus, one needs 28 panels of this type to achieve an 8kW system. This requires a roof area of:

$$28 * 1.67m^2 \approx 47m^2$$

B | Survey about Prosumers

The following survey was sent to different DSOs in order to map the status and expected growth in prosumers in Norway. The survey is in Norwegian. Answers will be presented in English in section B.1

Kartlegging av plusskunder hos ulike nettselskaper

Section 1 ...

Plusskunder i dagens nett

1. Hvilket nettselskap representerer du?

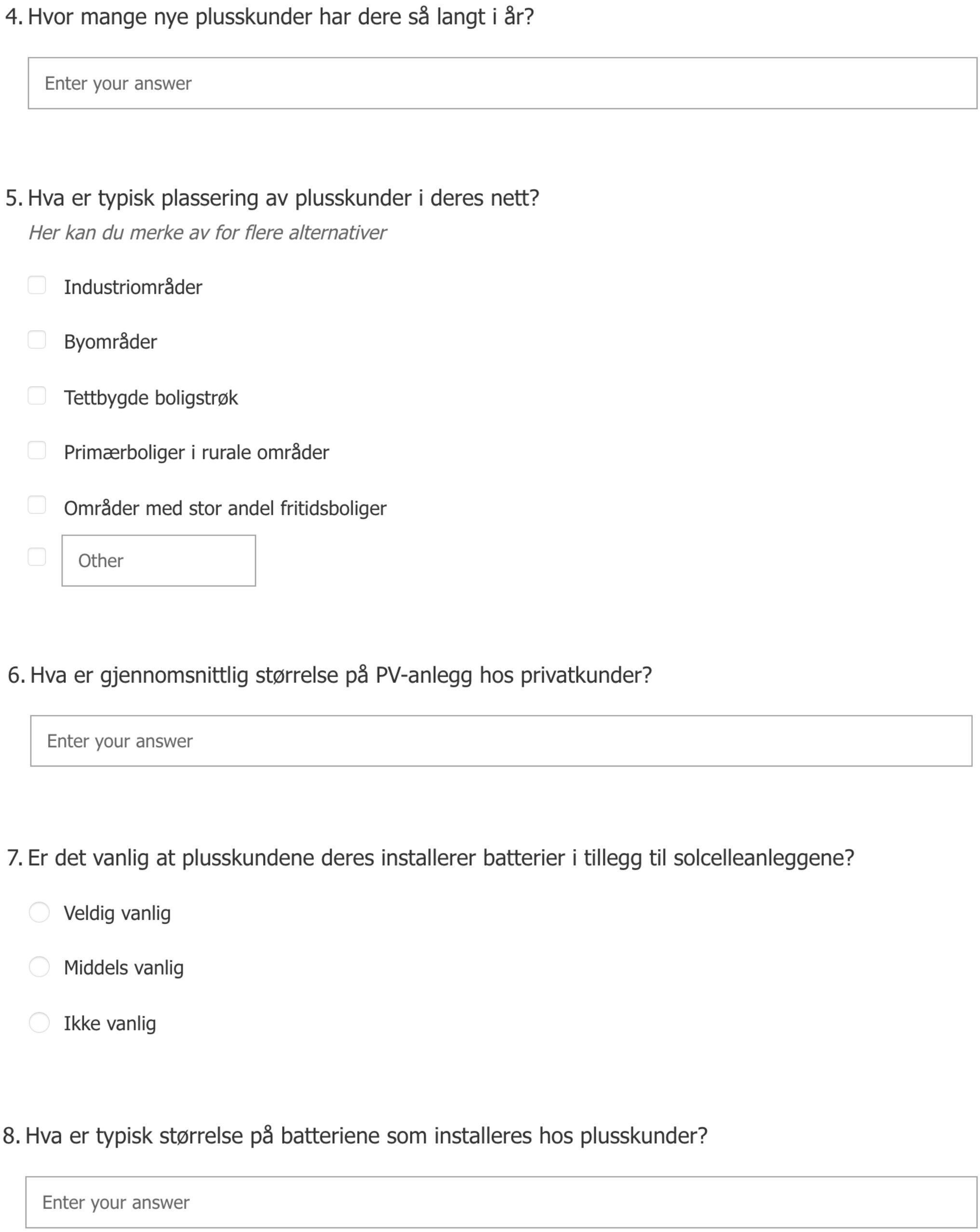
Enter your answer

2. Hvor mange nettkunder har dere?

Enter your answer

3. Hvor mange plusskunder har dere?

Enter your answer



4. Hvor mange nye plusskunder har dere så langt i år?

Enter your answer

5. Hva er typisk plassering av plusskunder i deres nett?

Her kan du merke av for flere alternativer

☐ Industriområder

☐ Byområder

☐ Tettbygde boligstrøk

☐ Primærboliger i rurale områder

☐ Områder med stor andel fritidsboliger

☐ Other

6. Hva er gjennomsnittlig størrelse på PV-anlegg hos privatkunder?

Enter your answer

7. Er det vanlig at plusskundene deres installerer batterier i tillegg til solcelleanleggene?

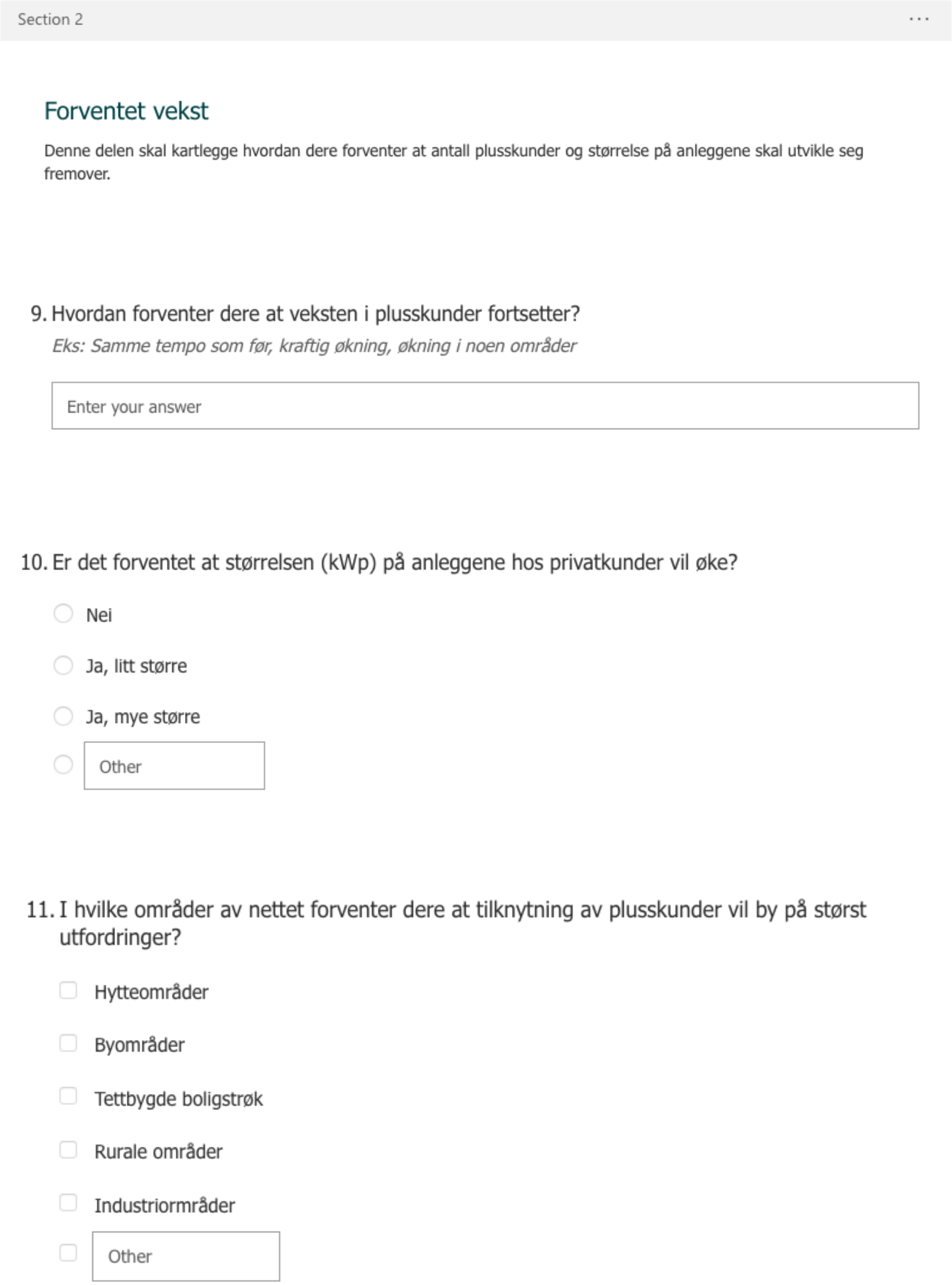
○ Veldig vanlig

○ Middels vanlig

○ Ikke vanlig

8. Hva er typisk størrelse på batteriene som installeres hos plusskunder?

Enter your answer



Section 2 ···

Forventet vekst

Denne delen skal kartlegge hvordan dere forventer at antall plusskunder og størrelse på anleggene skal utvikle seg fremover.

9. Hvordan forventer dere at veksten i plusskunder fortsetter?

Eks: Samme tempo som før, kraftig økning, økning i noen områder

Enter your answer

10. Er det forventet at størrelsen (kWp) på anleggene hos privatkunder vil øke?

○ Nei

○ Ja, litt større

○ Ja, mye større

○ Other

11. I hvilke områder av nettet forventer dere at tilknytning av plusskunder vil by på størst utfordringer?

☐ Hytteområder

☐ Byområder

☐ Tettbygde boligstrøk

☐ Rurale områder

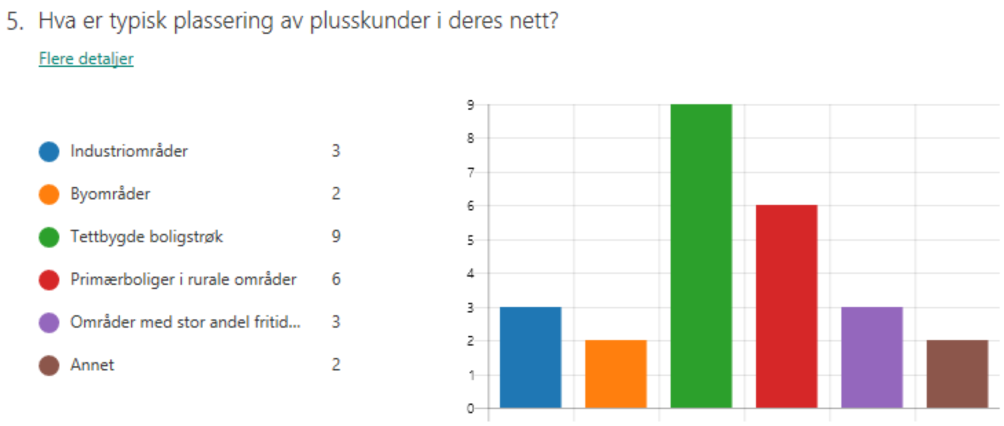
☐ Industriormråder

☐ Other

B.1 Answers

Representatives from ten DSOs participating in FME CINELDI have answered the survey. They cover a total of 57% of the grid customers in Norway. A compilation of the answers is shown below. Due to privacy issues some answers are excluded.

1. Excluded
2. Total number of customers: 1.76 millions
3. Total number of prosumers: 3489
4. New prosumers in 2019: 1441
5. Mostly in densely populated areas and residential houses in rural areas, see figure B.1.
6. Average size ranges from 5 to 14 kW for different DSOs, several report that the average size is 7 kW.
7. All the DSOs report that is is not common for prosumers to install batteries.
8. Typical battery size ranges from 6 to 8 kWh.
9. There has been a large growth over the last years. It is expected that this will continue increasing, and then flat out.
10. The size of the PV systems are expected to rise a little, but not much. See figure B.2.
11. Grid areas where connection of prosumers will cause challenges are mostly in areas, cabin areas and densely populated residential areas. See figure B.2.

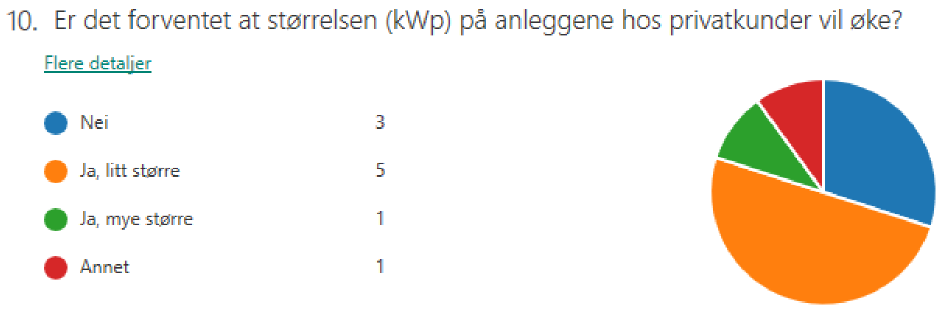


5. Hva er typisk plassering av plusskunder i deres nett?

Flere detaljer

● Industriområder	3
● Byområder	2
● Tettbygde boligstrøk	9
● Primærboliger i rurale områder	6
● Områder med stor andel fritid...	3
● Annet	2

Figure B.1: Answers to question 5



10. Er det forventet at størrelsen (kWp) på anleggene hos privatkunder vil øke?

Flere detaljer

● Nei	3
● Ja, litt større	5
● Ja, mye større	1
● Annet	1

Figure B.2: Answers to question 10

11. I hvilke områder av nettet forventer dere at tilknytning av plusskunder vil by på størst utfordringer?

Flere detaljer

● Hytteområder	5
● Byområder	2
● Tettbygde boligstrøk	4
● Rurale områder	7
● Industriormråder	1
● Annet	2

Figure B.3: Ansnwers to question 11

C | Netbas

C.1 Short Circuit Currents

C.1.1 Location A

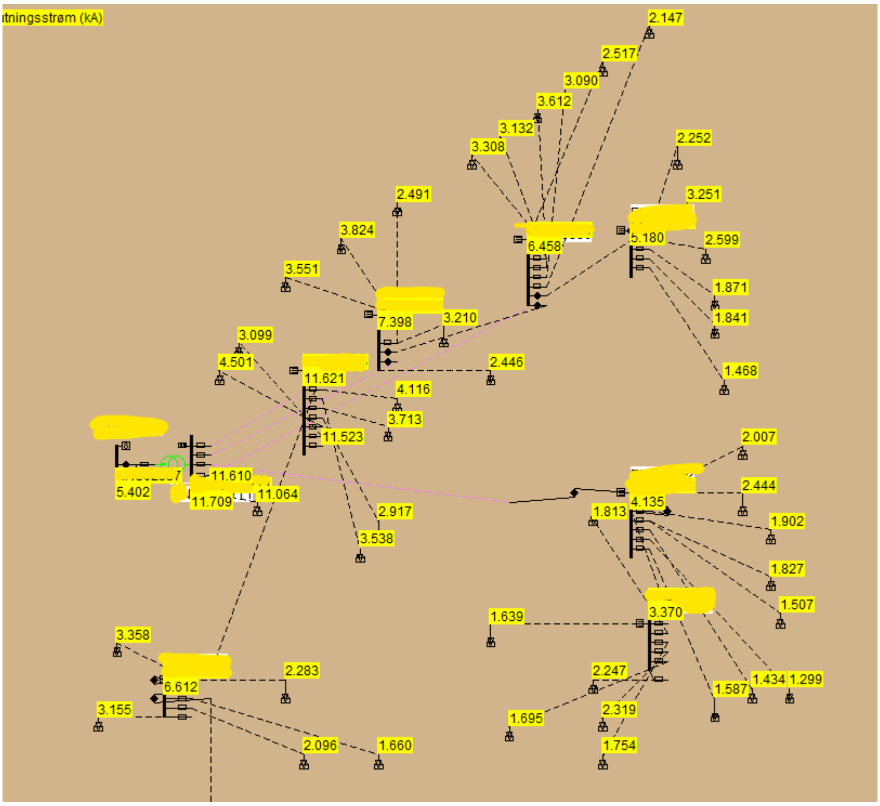


Figure C.1: Short-circuit currents ($I_{k1,\min}$) for location A

C.1.2 Location B

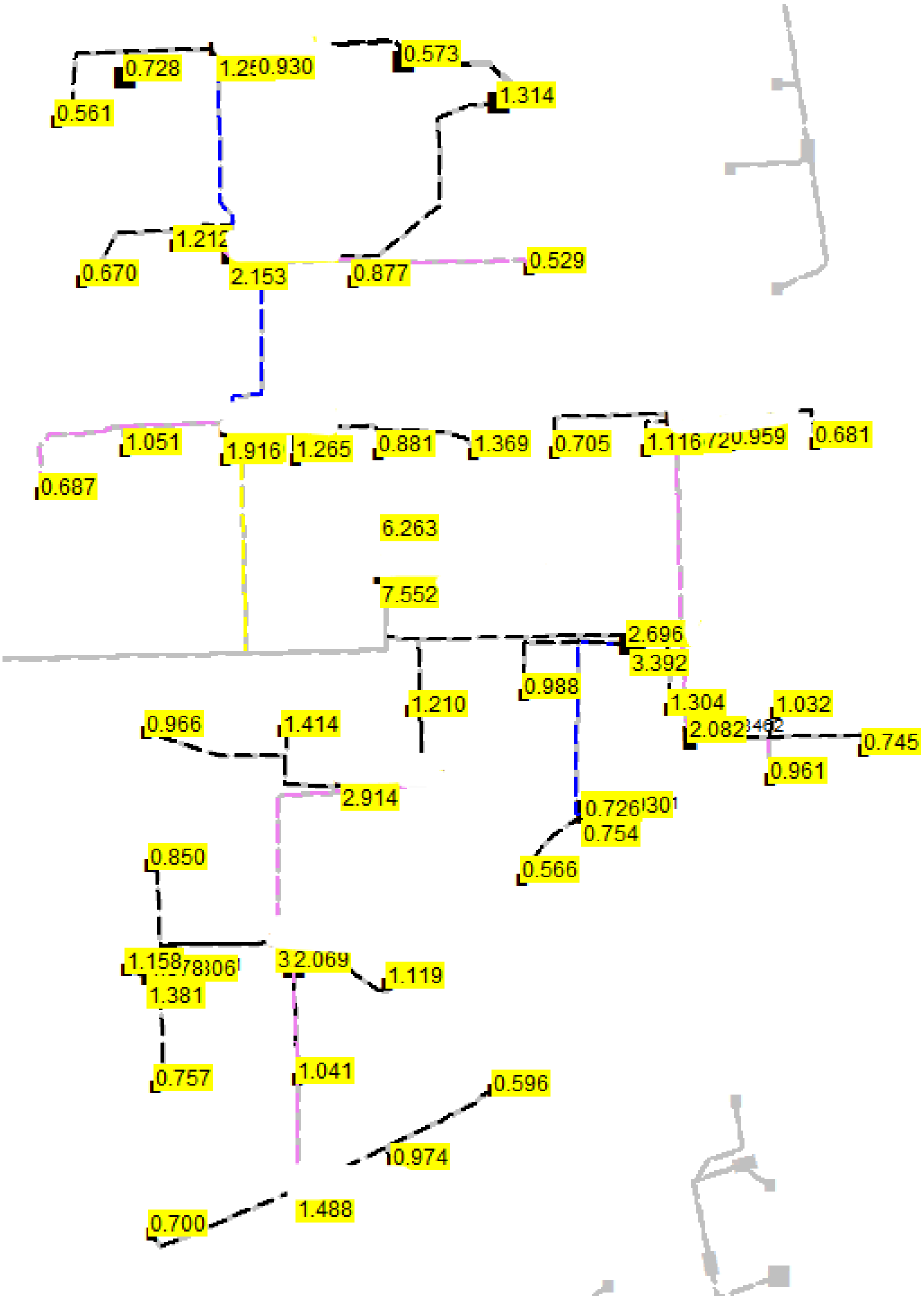


Figure C.2: Short-circuit currents ($I_{k2,\min}$) for location B

C.1.3 Location C

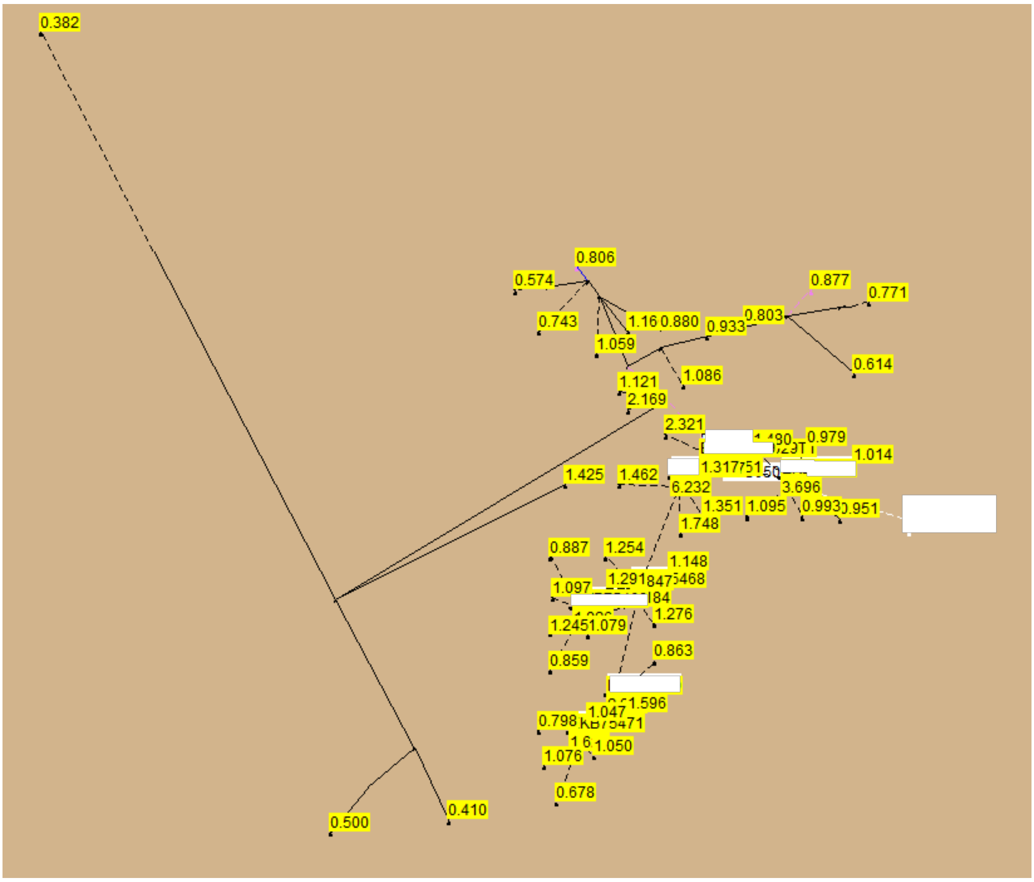


Figure C.3: Short-circuit currents ($I_{k2,\mathrm{min}}$) for location C

C.1.4 Location D

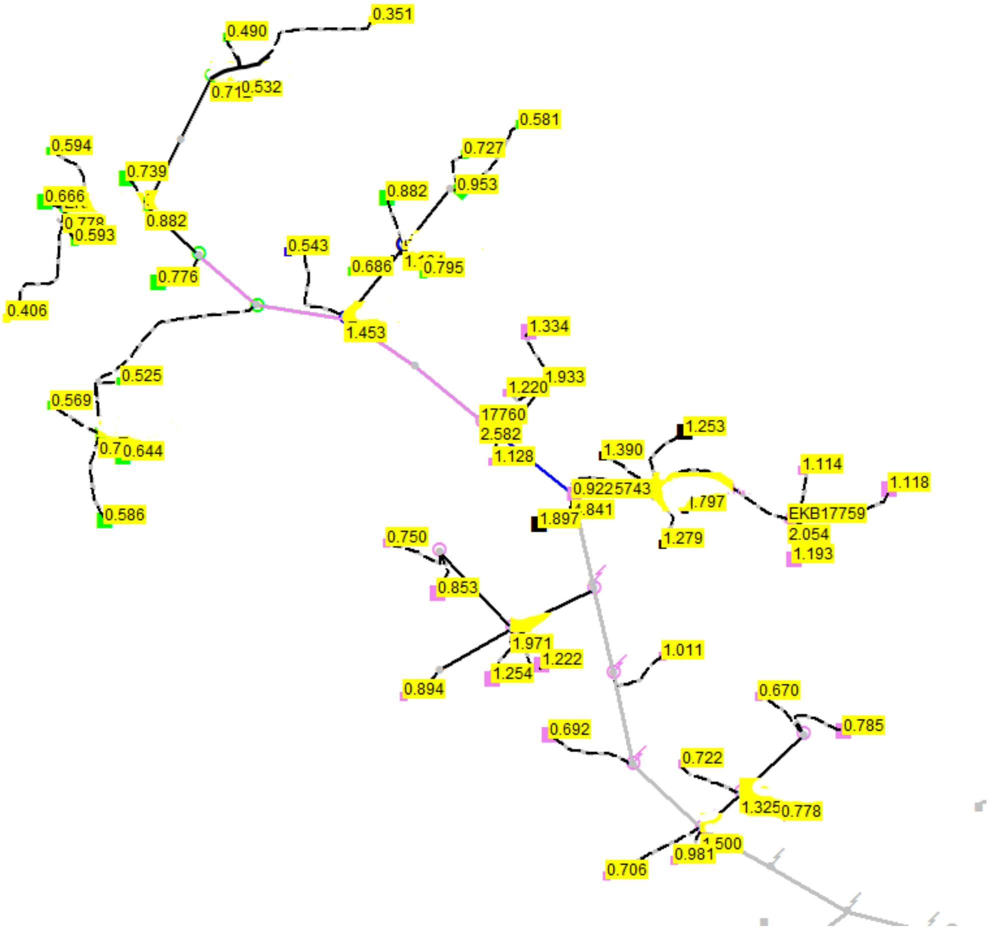


Figure C.4: Short-circuit currents ($I_{k2,\min}$) for location D

C.2 Prosumer Penetration in Low Voltage Distribution Grids

The accurate prosumer penetration and number of prosumers for the simulations in Netbas are given in table C.1. For battery simulations in scenario 5, the number of batteries are set to the same level as the number of prosumers in scenario 2. Scenario 6 had 100% integration of both PV and batteries, i.e. the same numbers as in scenario 4.

Table C.1: Accurate prosumer penetration in Netbas simulations

	Penetration level [%] (number of prosumers)			
Location	Scenario 1	Scenario 2	Scenario 3	Scenario 4
A	24.4% (11)	51.1% (23)	75.6% (34)	100% (45)
B	26.30% (10)	50% (19)	76.3% (29)	100% (38)
C	25.58% (11)	48.84% (21)	74.42% (32)	100% (43)
D	26.19% (11)	50% (21)	76.19% (32)	100% (42)

C.3 Battery Simulation

Some limitations in the battery plugin for distributed generation in Netbas occurred. Therefore, simulations were performed by using EVs instead of batteries.

For batteries input data are:

- Maximum production [kW]
- Maximum charging [kWh]
- Capacity [kWh]

Similarly, for EVs the input data are:

- Maximum charging [kW]
- Power consumption [kWh]

By choosing the same level for maximum charging, and setting the power consumption for the EV equal to the capacity of the battery, one can replace the batteries with EVs. It is not expected that the use of EV instead of batteries affects the results of the simulations in chapter 7, since both are pure loads. This assumption has been confirmed by employees in Powel.

C.4 Battery Simulation in High Voltage Distribution Grid

Table C.2: Load and power flow of 11kV/66kV transformer

Scenario	**Load**	**Power flow (P+jQ)**
Reference	27.67 %	5.35 + j1.07 MVA
1	9.30 %	1.58 + j0.95 MVA
2	12.54 %	-2.06 + j1.32 MVA
3	30.56 %	-5.59 + j2.15 MVA
4	49.12 %	-9.00 + j3.44 MVA
5	23.39 %	-3.77 + j2.61 MVA
6	21.98 %	3.56 + j2.47 MVA

Table C.2 shows load and power flow of LV/MV transformer. The results for scenarios 2 and 5 should be quite similar, and the same goes for scenario 1 and 6. Since this is not nearly the case the simulation results were excluded from the man part of this report. The table below shows the maximum loading of lines and substations in the 11kV high voltage distribution grid.

Table C.3: Maximum load of substations and cables in high voltage distribution grid

Scenario	**Maximum loaded substation**	**Maximum loaded line**
Reference	134.21 %	129.57 %
1	42.69 %	129.34 %
2	118.01 %	129.42 %
3	232.39 %	175.35 %
4	347.61 %	257.30 %
5	186.28 %	141.25 %
6	105.93 %	130.52 %

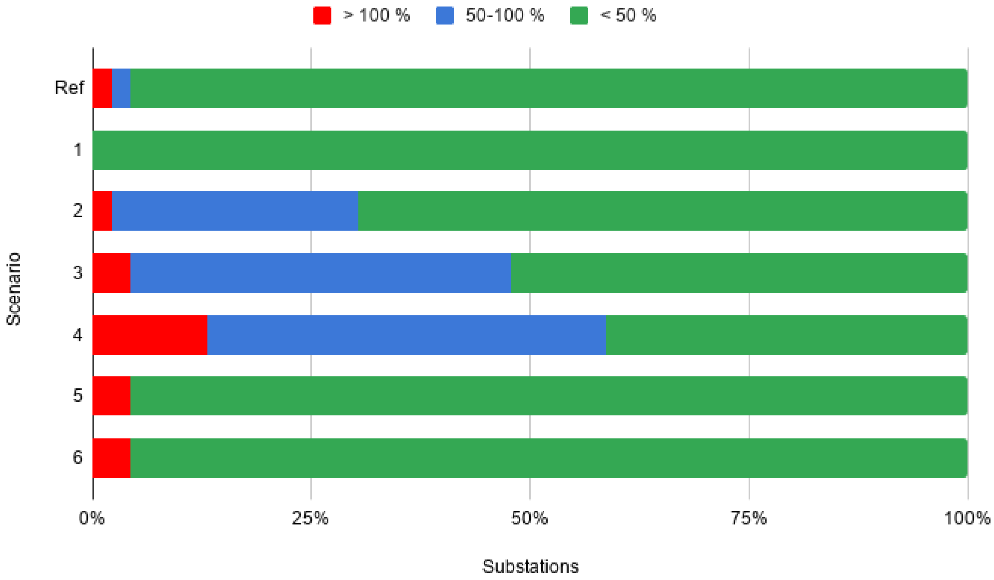


Figure C.5: Percentage load of substations in high voltage distribution grid

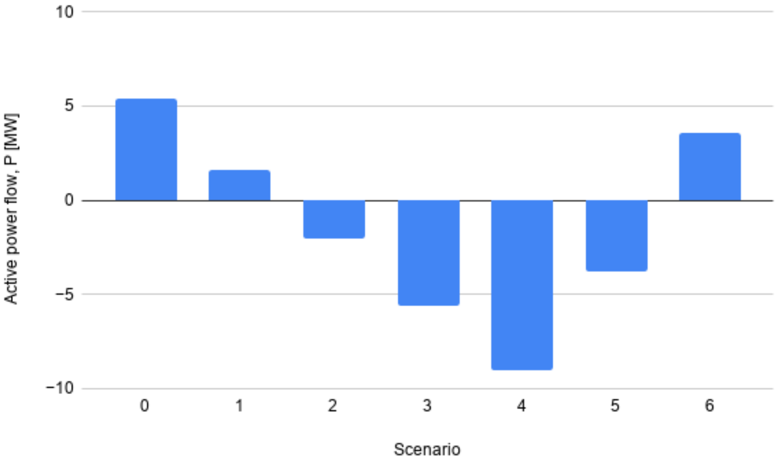


Figure C.6: Active power flow through LV/MV substation

D | PowerFactory

D.1 Grid 1

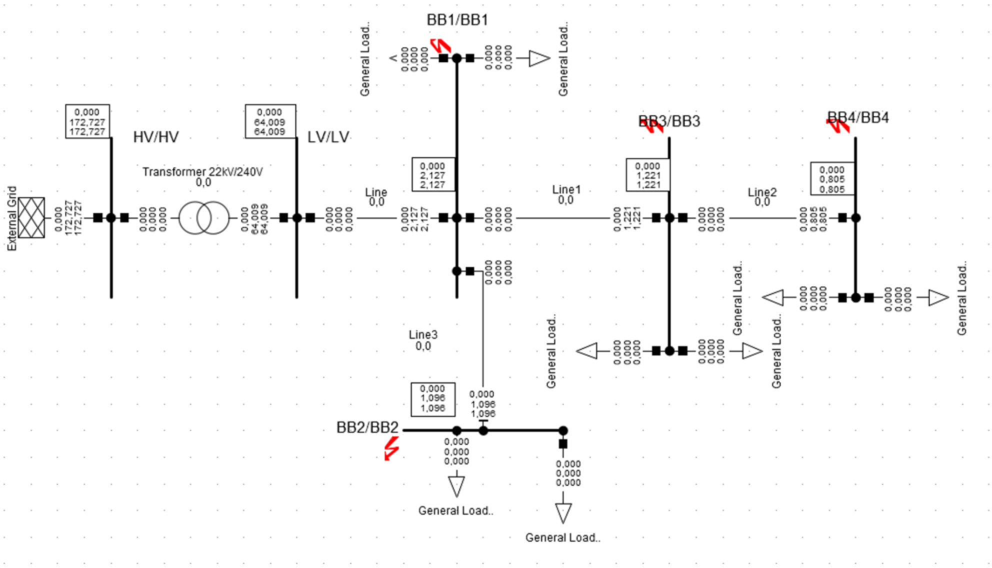


Figure D.1: Short circuit currents in grid 1

D.2 Grid 2

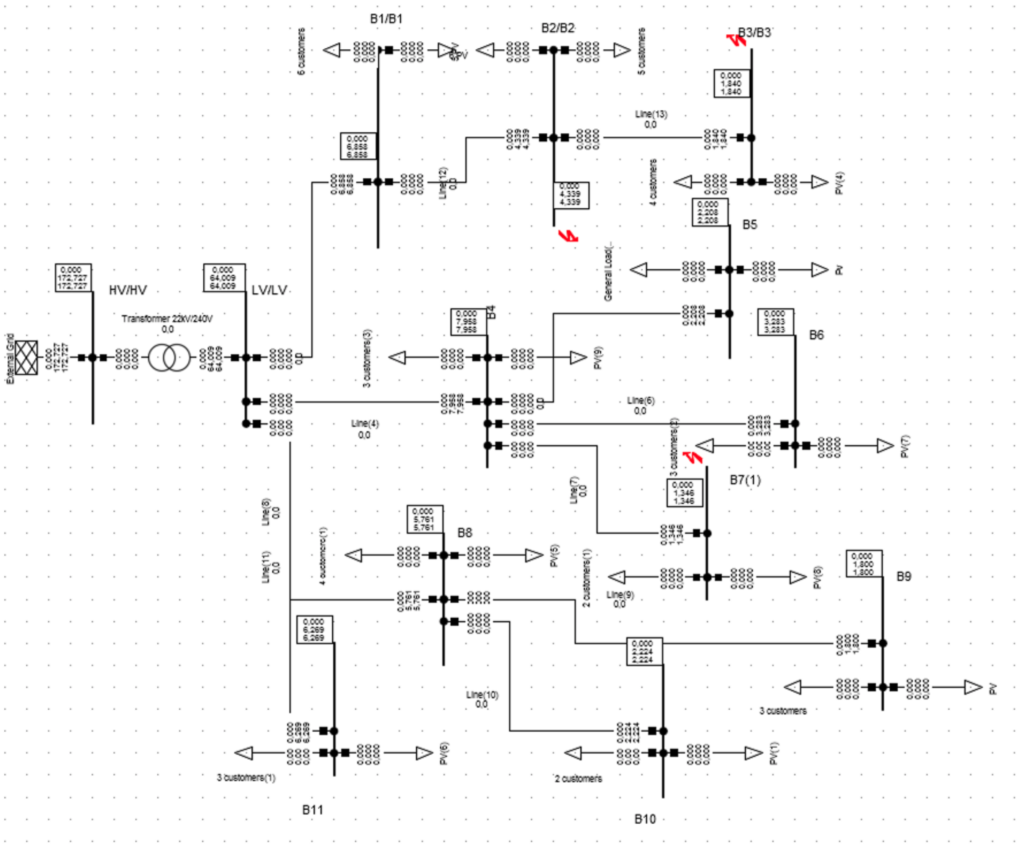


Figure D.2: Short circuit currents for grid 2

Table D.1: Distribution of prosumers at each location for different simulation scenarios

Location	**Prosumer penetration**			
	30%	50%	70%	100%
B1	2	3	4	6
B2	2	3	4	5
B3	1	2	3	4
B4	1	2	2	3
B5	1	2	3	4
B6	1	2	2	3
B7	0	1	1	2
B8	1	2	3	4
B9	1	1	2	3
B10	1	1	1	2
B11	1	1	2	3
Actual penetration	30.77 %	51.28 %	69.23 %	100 %

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Grid Impact from Increased Prosumer Penetration in the Norwegian Distribution Grid

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