Local voltage control in a low voltage grid with high photovoltaic penetration

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Abstract

This thesis examines how active power control (Volt-Watt control) and reactive power compensation (Volt-VAr control) can help limit voltage increases on the low voltage grid due to high photovoltaic (PV), installations. Due to the large increase in interest to install small scale PV-systems within residential areas the Distribution System Operator E.ON, has noticed problems concerning high voltage levels on the customer side as the amount of PV installations increase. To limit the voltage increases the Distribution System Operator can upgrade the grid with newer and thicker cables and a new transformer, which takes time and costs money. In some cases it might also lead to relatively new cables being excavated. Another possible solution would be to use the existing grid in an optimal way.

To test how the different control methods behave and to quantify how the overall impact would be for the PV-system owner, a model of an existing substation in the south of Sweden was built in PowerFactory. Once the model was built, local Volt-Watt and Volt-VAr controls were implemented on each PV-system. The system was then simulated for a full year using real load data from the customers and real solar irradiation values from SMHI where focus was on the aggregated behaviour over time. The simulations using Volt-Watt control found that, depending on where within the grid they were located, there was a large disparity between the different customers in terms of how much they would have to be curtailed. The figures ranged from 0 percent up to almost 20 percent of all yearly production in a scenario where 70 percent of all household had a PV-system installed. Volt-VAr was not as effective in decreasing the voltage magnitude as Volt-Watt due to the high R/X ratio but showed promise in cases when the voltage levels were not that prominent. Volt-VAr could help lower the voltage magnitude by a few volts if needed, and serve as way to delay the eventual need to curtail active power.

This thesis also showed that there are many grid characteristics that influence how effective the voltage control can be. If situated in a weaker part of the overall grid, the voltage magnitudes in the local grid will become higher, leading to more active power curtailment if Volt-Watt is used, and limited chances that Volt-VAr could work. Another finding was that the tap position of the transformer makes a large difference in terms of curtailment of the PV-systems.

Acknowledgements

I would like to thank my supervisor at E.ON, Thomas Pettersson, for coming up with the idea for this project and for allowing me to pursue it. I would also like to thank him, and all other people at E.ON, for the help along the way and for providing me with the information needed. I would also like to thank my supervisor, Richard Pates, at LTH for all of his help and support along the way. Special thanks for listening to and helping me sort out my thoughts when needed.

Finally, I would like to say thank you to my wife, Ellinor, for supporting me through all hurdles in life. Without you this thesis would not be possible.

List of Abbreviations

DER Distributed Energy Resources

PV Photovoltaics

VVC Volt-VAr control

VWC Volt-Watt control

Contents

1

Introduction

1.1 Background

In recent years, there has been a significant increase in Photovoltaics (PV) system installations in residential areas across Sweden. This plays an important role in the transition towards a renewable energy system. The Distribution System Operator, E.ON, is the largest electricity grid owner in Sweden and they have also noticed a large increase in new installations [E.ON, 2023]. In 2022 they had 29 000 new requests regarding installations and in 2023 there were 23 806 new requests. This trend is further demonstrated on a national scale by figure 1.1. High electricity prices in recent years are one major driver of this trend, another factor is the "Green incentive" deal where the government pays for 20 percent of the PV installation costs [Energimyndigheten, 2023]. On top of this there is also a tax incentive of 0.60 SEK/kWh when selling electricity back to the power grid for small scale renewable electricity [Skatteverket, 2023].

In many ways this expansion is a good thing, but there are also some challenges that arises from this development. Before the introduction of Distributed Energy Resources (DER), the power grid in Sweden had basically operated in a constant manner. The power grid is divided in multiple voltage levels, from the highest of a phase to phase voltage of 400 kV_{ph-ph}, down to the lowest level of 400 V_{ph-ph} at the connection point in a residential area. At the highest levels we have the large generating units and at the lower levels we have the loads. As can be seen in figure 1.2 this led to a unidirectional power flow where power went from the high voltage level, down towards the low. In a residential area the power grid is divided into groups of around 20 connection points on each, one substation consists in general of approximate 5-7 groups. In the traditional power grid these households might have a main fuse of 20-25 ampere where the loads where not nearly fully utilised at the same time. When one load is high, the others might be lower. The distribution grid, like cables and transformers, are in large designed and dimensioned around this operation.

Figure 1.3 shows how the modern power grid operates. One clear difference to the traditional power grid is the multitude of generating units. Another important difference is the location. With generating units now situated within the low voltage parts of the grid, power can now flow in both directions. This is something that E.ON experience today when more and more PV-systems are being installed on the low voltage side. Now E.ON notices large reversed power flows when many PV installations are on the same group and in contrast to before when the loads where relatively low, the PV-systems output full power in the middle of the day when the owners are usually not home. For a PV installation of 17 kW, this often leads to a net power from the PV-system of over 16 kW since the standby load in the households are often around 500 W. This has also been confirmed in studies such as [Sadeghian and Wang, 2020]. This trend is exacerbated when more PV-systems are installed on the group.

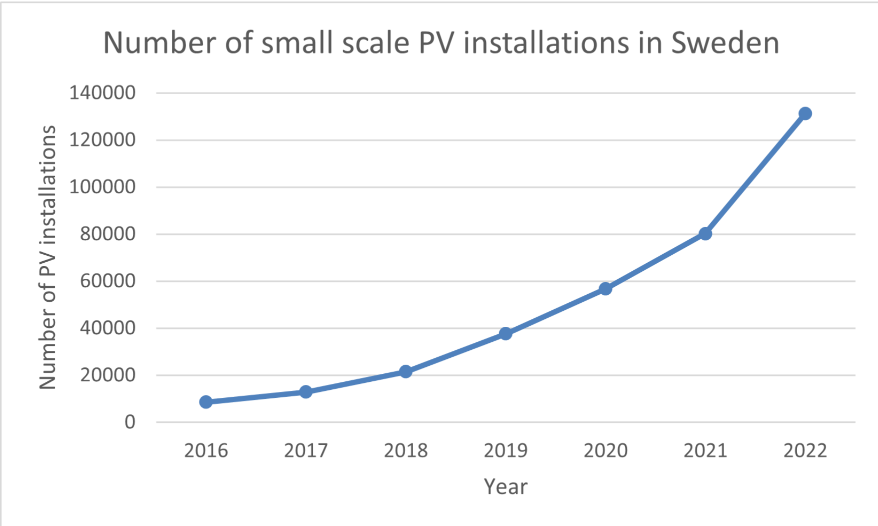

Figure 1.1 The number of small scale PV installations in Sweden from year 2016 until 2022. The data for this plot was collected from the Swedish energy departments statistical database [Energimyndigheten, 2024]

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One of the reasons why this is a problem is that we get a voltage increase on the sending part of a transmission line if we increase the active power while keeping the reactive power Q constant [Anderson, 2020]. This is exactly what happens in groups with many PV installations. We get a large active power flow from the PV-systems towards the higher voltage parts of the grid. At the same time the PV-systems are run at a power factor of 1. This is a problem since the grid owner must by law always keep the voltage at 230 $V_{ph-line}$ ± 10 percent, this means that the voltage always has to be kept below 253 V. If the voltage deviates outside of this region the inverter over-voltage protection will trip and the inverter will turn off. Another possible problem is that the transformer that in previous operation were well dimensioned, all of a sudden might be under dimensioned during periods of high PV production. Both of these problems can lead to the Distribution System Operator being forced to perform costly and time consuming grid strengthening measures in terms of new cables and new transformers.

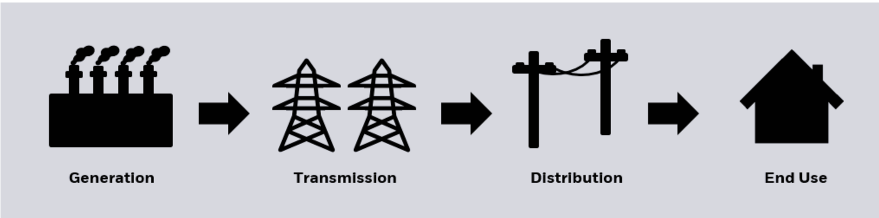

Figure 1.2 Sketch of the traditional power grid where the arrows indicate power flow and voltage decreases from left to right [Department of Energy, 2017]

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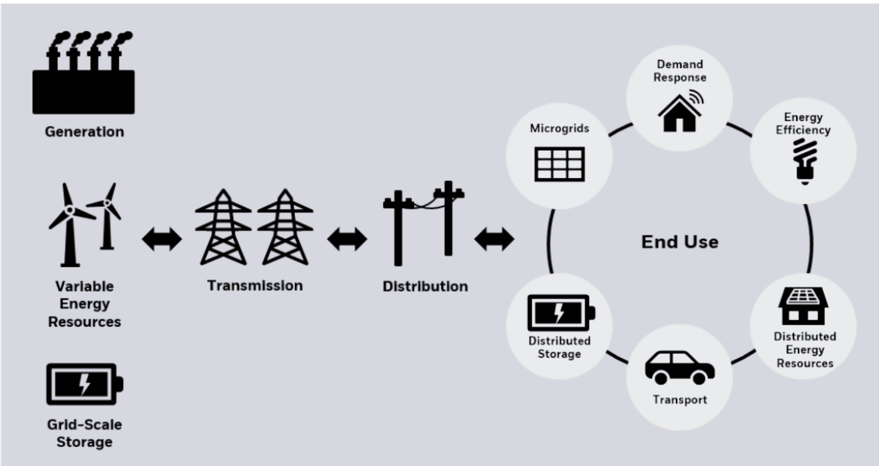


Figure 1.3 Sketch of the modern power grid where the arrows indicate power flow and voltage decreases from left to right [Department of Energy, 2017].

1.2 Objective and limitations

The main goal of this thesis is to quantify the impact of different control methods on the overall voltage profile of the local grid and to determine the extent of active power curtailment required for voltage regulation. By evaluating the different control methods and what different parameters impact the voltage magnitude, this might be a supplement for grid strengthening measures. In Sweden, there is no requirement or incentive for small scale producers to control the voltage at the connection point [Energimarknadsinspektionen, 2018]. There is also no viable option for the Distribution System Operators to decline a request to connect a small scale PV-system. From the producers point of view they want to output as much active power as possible. But from a societal point of view this will come at a great cost since large grid reinforcements has to be made, leading to higher prices for all since the costs of these reinforcements will be put on the customer collective. It will also lead to longer waiting times for connection of PV-systems so to be able to connect as many PV-systems as possible in a reasonable time frame there will be a need to solve this problem. Another consideration relates to environmental sustainability, where, in many cases, cables with more than 40 years of their life cycle remaining have to be dug up and replaced by newer and thicker ones.

An alternative approach would be to fully utilise the grid we have in a smart way. This thesis will attempt to address this challenge. Since there is no legal way for a Distribution System Operator to limit the output of a grid connected PV-system, one important part of this project will be to examine the local grid behaviour for different legislature cases. This will include reactive control and active control of the PV inverter. Another important aspect will be to evaluate the unfairness part, where the PV-system furthest away from the transformer station always will get the largest voltage rise. This unfairness occurs since the voltage rise is directly proportional to the cable resistance and the resistance of the cable increases with length. The transformer loading will also be noted for the different parts of this thesis. The main objectives will be to answer the following questions:

- Could reactive power compensation in the form of Volt-VAr control (VVC) on the PV side be used to limit the need for grid strengthening measures in the examined local grid?
- Could active power control in the form of Volt-Watt control (VWC) on the PV side be used to limit the need for grid strengthening measures in the examined local grid?
- How large is the difference in curtailment between a connection point far away from the transformer in comparison to one close to the transformer?
- What is the hosting capacity for PV installations before the transformer gets overloaded?

To accomplish this a model of an existing grid in the south of Sweden will be build in PowerFactory where different irradiation and PV penetration cases will be considered. The voltage levels at the different connection points of the local grid will then be observed. These cases, without any voltage control on the PV side, will then be compared with different types of voltage control on the PV side. In this thesis focus will be on a residential area with a substantial amount of households, this substation will be a good representative of a typical neighbourhood. The same type of voltage problem can also occur in a rural area with few connection points but with further distances between each other. In these cases the problems can occur with only a few PV installations due to the long distances while the problems in the residential area occur due to many simultaneous connections. This report focuses on the local voltage behaviour caused by high PV penetration. Potential problems concerning frequency deviations caused by high production variability and a lack of inertia will not be a part of this report. As a simplification a set temperature of $25°$ will be used.

Another limitation is that this thesis will not analyse any dynamic behaviour. Full focus will be on analysing the aggregated behaviour over time, with a timescale of 1 hour. This means that no focus will be put on what happens at the exact moment when there is a change in irradiation or load, but instead focus will be on how the system behave on average over time.

1.3 Disposition

In chapter 2 the relevant theory for this thesis will be presented. Focus will first be on the relevant components of the power grid, the focus will then shift to be more about voltage requirements and then different voltage control methods. Chapter 3 will describe the method used in this thesis. First, the choices made will be described, then the thesis will be divided into different parts. The first step involves building and verifying the PowerFactory model, and the second part involves simulations. The results of this thesis will be found in chapter 4 which will follow the same structure as described in chapter 3. Chapter 5 contains a discussion of the results. In the final chapter, chapter 6, the main conclusions drawn from the work will be presented. At this stage the answers to the questions asked in the introduction will also be summarised.

2

Theory

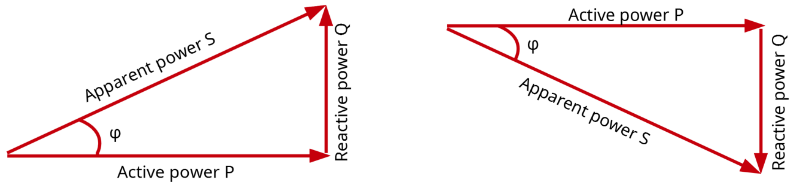
In this chapter of the thesis the theoretical background will be found. In sections 2.1 and 2.2 the reader will find basic power systems theory and an introduction to PV-systems that is included for completeness. Readers with prior knowledge in these areas can skip directly to section 2.3 for the theoretical background about voltage control requirements on generating units and later in section 2.4 information on voltage requirements on the low voltage grid. In section 2.5 theory about the different control strategies considered in this thesis is described, followed by section 2.6 that includes a description of the programs used in this thesis.

2.1 Power system

Power factor

The power factor tells the ratio between active power and apparent power according to equation 2.1. A power factor of 1 means that there is only active power present and a power factor of zero means that the circuit is purely reactive. The angle ϕ is called the power angle and can be either positive or negative. For a purely inductive load the current lags the voltage by 90° and the power factor is said to be lagging. For a purely capacitive load the opposite is true, the current leads the voltage by 90° and the power factor is said to be leading. Figure 2.1 shows the power triangle for both a leading and a lagging power factor. The horizontal axis is the real axis and the vertical axis is the imaginary.

$$powerfactor = \frac{|P|}{|S|} = cos(\phi) \tag{2.1}$$



(a) Lagging , or inductive, power factor **(b)** Leading, or capacitive, power factor

Figure 2.1 Power triangles for leading and lagging power factors

Transformers

A transformer consists of a core with a high permeability material, often iron. On each side of the material there are conductive coils that are wound around the iron core. Faraday's law of induction is given by equation 2.2. It states that a change in magnetic flux ϕ induces an Electromotive force, e, in an electric circuit. The Electromotive force is the energy supply to a charge that maintains the potential difference, the magnitude of the Electromotive force also depends on the number of loops, N, that the coil consists of. From Amperes circuital law we know that a varying current will induce a varying magnetic field.

$$e = -N \cdot \frac{d\phi}{dt} \qquad [V] \qquad (2.2)$$

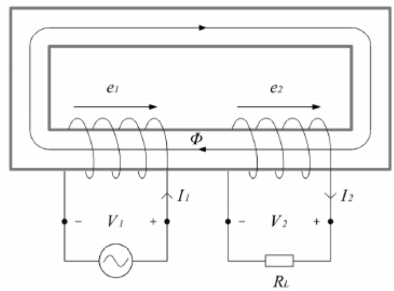


Figure 2.2 Sketch of an ideal transformer [Björnstedt, 2017]

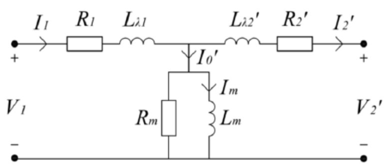


Figure 2.3 Circuit diagram of a non-ideal transformer [Björnstedt, 2017]

From this information we can conclude that if we feed an AC current I_1 through the primary winding in accordance to figure 2.2, this will induce a varying magnetic flux, Φ within the iron core. This varying magnetic flux will in turn induce an Electromotive force on the secondary side. For an ideal transformer there are no resistive losses and the magnetic flux is the same on both the primary and the secondary side. This means that Faraday's law can be combined for both sides resulting in equation 2.3. For an ideal transformer the voltages V_1 and V_2 equals the Electromotive forces e_1 and e_2 and can be decided by the number of turns on the windings. If N_1 is larger than N_2 we have a step down transformer since the voltage is higher on the primary side, if N_1 is smaller than N_2 we have a step up transformer. This also mean that the current scales inversely with the turns ratio $\frac{N_1}{N_2}$ in accordance to equation 2.4.

$$\frac{d\phi}{dt} = \frac{e_1}{e_2} = \frac{N_1}{N_2} \tag{2.3}$$

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{2.4}$$

A transformer however, is not ideal. There are resistances within the windings, R_1 and R_2 that lead to a voltage drop. All of the magnetic flux that is induced is not transferred to the other side. There are some leakage flux that is modeled as an inductive voltage drop due to the inductance $L_{\lambda 1}$ on the primary side and $L_{\lambda 2}$ on the secondary side. I_0' is the idle current needed for magnetisation where the prime sign indicates that the value is recalculated from primary to the secondary side values to get rid of the transformer from the circuit diagram, L_m is the magnetisation inductance and R_m represents the hysteresis losses. Figure 2.3 shows the circuit diagram of a non-ideal transformer. The recalculations from primary to secondary side is performed in accordance to equations 2.5 to 2.7 [Björnstedt, 2017]. Figure 2.2 shows a conceptual one-phase two-winding transformer, in practice a three-phase two-winding transformer is often used.

$$V_2' = V_2 \frac{N_1}{N_2} \tag{2.5}$$

$$I_2' = I_2 \frac{N_2}{N_1} \tag{2.6}$$

$$Z_2' = Z_2 \left(\frac{N_1}{N_2} \right)^2 \tag{2.7}$$

In practice this can be used in multiple ways on the power grid. Transformers of course is used as the main component of reducing or increasing the voltage on the grid. When it comes to the voltage increases due to high PV penetration On-Load Tap Changer could be part of the solution where the turns ratio can be changed while the transformer is still operating.

Transmission cables

In equation 2.8 the DC-resistance, $R_{DC,T}$, of a transmission cable at temperature T, is shown. It can be seen that it is uniform, meaning that the current uses the whole cross-section of the cable equally. Also shown is that the resistance is influenced by the resistivity of the cable material, ρ_T, the cable length, l, and the cable cross-sectional area, A. The resistivity of a material is the temperature dependant part. For AC-current the skin effect has to be taken into account when calculating the resistance of a cable. The skin effect means that for an AC-current the current does not flow uniformly through the whole cross-section of the cable. With increased frequency, a larger portion of the current flow towards the outer shell of the cable and less current flow in the middle of the cable. How large the skin effect is depend on the frequency and the material of the cable. For frequencies relatively low as 50 Hz, this effect is not larger than a few percent and the AC-resistance, $R_{AC,T}$ has a similar dependency on cable length, resistivity and cross-sectional area as the DC-resistance. An increased cross-sectional area will decrease both $R_{DC,T}$ and $R_{AC,T}$ and the resistances will increase with increased length of the cable. [Glover et al., 2015].

$$R_{DC,T} = \rho_T \frac{l}{A} \qquad [\Omega] \qquad (2.8)$$

The total impedance, Z, of a cable also has a reactive part, X. This reactance consists of bot an inductive part and a capacitive part.

Power flow

When performing power flow analysis the main goal is usually to find the absolute voltage levels, voltage angle, active power and reactive power for all of the buses. In simulations of a power system the buses are usually divided into three different categories, PV-bus, PQ-bus and slack-bus. For the different types of buses, different parameters are known in accordance to table 2.1. For large power grids, this means that there will be a large amount of non-linear equations that needs to be solved which can not be done analytical. For this reason numerical methods are used and in the case of DIgSILENT PowerFactory the Newton-Raphson method is used to approximate the solutions. For a general problem with only one equation to solve, Newton-Raphson is performed in accordance to equation 2.9 where the approximation gets better for each iteration. For a large power system with many equation to solve, the matrix form of Newton-Raphson is used for the approximations in accordance to equation 2.10 where J is the Jacobian matrix [Glover et al., 2015].

$$x_{n+1} = \frac{f(x_n)}{f\prime(x_n)} \qquad (2.9)$$

	Slack-bus	PV-bus	PQ-bus
|V|	Known	Known	Unknown
δ	Known	Unknown	Unknown
P	Unknown	Known	Known
Q	Unknown	Unknown	Known

Table 2.1 Table showing what parameters are known for the different types of buses.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \left[\begin{array}{cc} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \hline \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{array}\right] \begin{bmatrix} \delta \\ V \end{bmatrix} = J \begin{bmatrix} \delta \\ V \end{bmatrix} \tag{2.10}$$

Voltage change

The voltage increase on the sending part of a transmission line is described by equation 2.11. It can be seen that it is proportional to the factor between active power and resistance of the cable connecting the two buses and the factor between the reactive power and the reactance of the cable. This implies that to limit the voltage increase, one can either restrict the active power transfer, reduce the resistance, limit the reactive power, or limit the reactance of the cable. When strengthening the grid, thicker cables are usually installed, resulting in reduced cable resistance. From equation 2.11 it is clear that the R/X ratio is of importance when it comes to voltage changes. A high R/X ratio means that the reactance on the grid is low in comparison to the resistance. When analysing equation 2.11 with this knowledge it is clear that a high R/X ratio means that the active power influence the voltage change more in relation to the reactive power.

$$\Delta V = \frac{PR + QX + j(PX - QR)}{V_{ref}} \approx \frac{PR + QX}{V_{ref}} \quad [V] \tag{2.11}$$

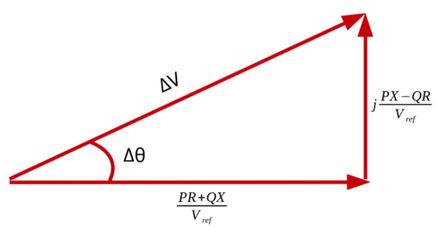


Figure 2.4 Conceptual figure of the vectors of equation 2.11 in the complex plane. In reality the angle $\Delta\theta$ is generally quite small and represent the change in voltage angle.

2.2 PV-systems

A solar cell is basically a pn-junction that transforms solar irradiation to electricity. A pn-junction is created when two doped semiconducting materials, often Silicon, are put together. One side is doped with a material that has five valence electrons like Phosphorus. This creates an n-type material since it has an excess of negative charge carriers called donors. This material is put together with a p-type material. This is a semiconducting material that is doped with a material that has three valence electrons like Boron. The resulting material has an excess of positive charge carriers, also called acceptors. Both materials are however electrically neutral. When they are put together a depletion layer is created around the boundary of the materials. This happens since some of the negative charge carriers on the n-type materials are attracted to the holes on the p-type material side and vice versa. This creates an electric field at the boundary that is positive on the n-side and negative on the p-side. This phenomenon continues until the electric field is large enough to prevent the electrons on the n-side to overcome the electric field and vice versa. This results in an electric field with an approximate voltage of 0.7 V over the pn-junction, the exact voltage depends on the materials used.

When the depletion region is hit by photons from the solar irradiation that has more energy than the bandgap, E_g, electrons from the negative side of the depletion region will be exited to the other side of the pn-junction, leaving a hole behind. When connecting a load to the two terminals the excited electrons on the n-side will be attracted by the hole on the p-side. Because of this electrons will flow through the load and recombine with the hole at the other side of the load. The bandgap of Silicon is 1.11 eV, so every photon with more than 1.11 eV of energy will contribute to a flowing current. All excess energy above E_g will be lost as heat.

In figure 2.5 the solid curves are the IV curves and the dashed curves are the power that is delivered by the solar cell. The IV curve has two extreme points. One is I_{sc}, which is the short circuit current, at this point the voltage is zero and no power is delivered by the solar cell. The other is V_{oc} which is the open circuit voltage, at this point no current goes through the solar cell and no power is delivered. From the picture it is clear that there is one point where the maximum amount of power is delivered, this is called the maximum power point, P_{MP}. This is important to keep track of in a PV-system. For this reason a maximum power point tracker (MPPT) is used. What is clear from figure 2.5, and important for this report, is that the solar irradiation determines the active power output of the solar cell. In practice there is also a temperature dependence but in figure 2.5 the temperature is assumed constant, just as will be assumed in this report.

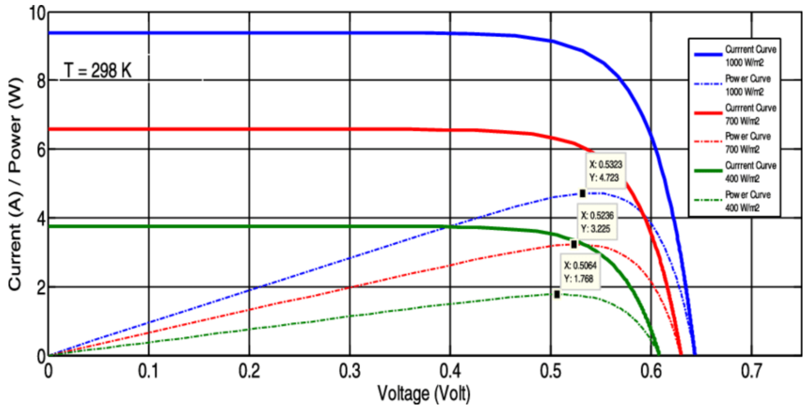


Figure 2.5 IV curve of a solar cell displaying the maximum power point for various solar irradiation cases [Dash et al., 2015].

Figure 2.6 shows a block diagram of a typical PV-system. The PV array and MPPT control was mentioned in the previous paragraph while the DC-DC converter is a boost converter that raises the DC input voltage of the inverter. In this report the inverter operating point will be of great interest. As can be seen i figure 2.6 the inverter output is directly connected to the grid. This means that the active power output, and the inverter voltage will influence the grid behaviour. If there is more active power production than there is load within the internal grid of the connection point, there will be a reversed power flow and a voltage increase on the sending part of the line, in this case on the connection point where the PV-system is connected.

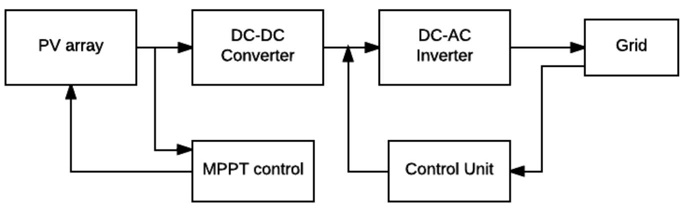


Figure 2.6 Block diagram of a general PV-system [Argyrou et al., 2017].

2.3 Voltage requirements on generating units

In the Commission Regulation (EU) 2016/631, the regulations for generators that are connected to the power grid is collected. This document has been revised for Swedish conditions in EIFS 2018:2 [Energimarknadsinspektionen, 2018]. In this document the different types of generators are divided into type A, B, C and D. Type A applies for generating units $\geq 0.8kW < 1.5MW$, type B applies to generators $\geq 1.5MW < 10MW$, type C applies to generators $\geq 10MW < 30MW$ and type D applies to generators $\geq 30MW$. The document specifies clear requirements regarding frequency support for all four types.

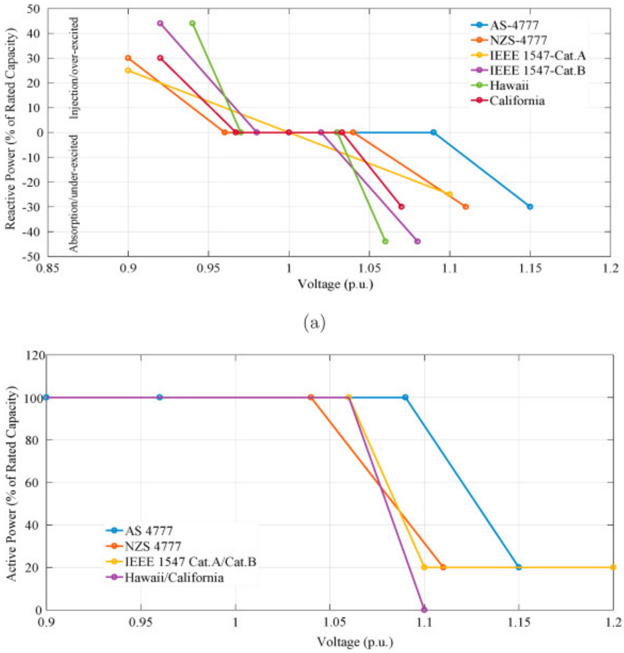
When it comes to voltage requirements type A have no requirements at all. For type B, C and D there are however requirements when it comes to non synchronous power generators, both when it comes to voltage levels and when it comes to the ability to provide and absorb reactive power. In chapter five of EIFS 2018:2 it is stated that a non synchronous generator of type C and D should, in the voltage interval of 95-105 percent of nominal, be able to absorb reactive power in the magnitude of one third of the instantaneous active power output. It is also stated that type C and D should be able to, in the voltage interval of 90-102 percent of nominal, provide reactive power in the magnitude of one third of the instantaneous active power output. There are also rules that requires the generators to have automatic voltage control and that when the voltage drops below 95 percent of nominal at the connection point the generator should support the voltage with reactive power.

2.4 Voltage requirements on the low voltage grid

In a low voltage grid the Distribution System Operator have full responsibility to keep the voltage within 230V $\pm$ 10 percent. The PV systems in the low voltage grid typically fall into the type A category, which means that there are no requirements on the PV-system when it comes to managing the voltage at the connection point . This means that legally all voltage control efforts have to be made by the Distribution System Operator. According to SEK Svensk Elstandard (2019) there is a legal limit where an installation within the customers internal grid can have a voltage change of up to 5 percent of the nominal voltage. This implies that if the PV-system is installed at a separate building from where the connection point is located, there could be a voltage increase of up to 11.5 V between the connection point and the point where the inverter is connected. Legally this is not the responsibility of the Distribution System Operator but has to be taken into consideration.

Grid codes

Even though there are no requirements on the Swedish grid, there are some places around the world where the PV-system owner is required to limit the voltage at their own connection point. What most of these grid codes have in common are that they rely on VWC and VVC as will be further described in section 2.5. Figure 2.7 shows an example of different grid codes when it comes to VVC and VWC of PV-systems. In California there is a mandate that VWC has to be active if a PV-system owner would like to connect their system to the grid, while Hawaii have a system where the control activation is decided upon from case to case. In Hawaii the VWC control is activated at 1.06 per unit (p.u) voltage and the active power is fully curtailed ad 1.10 p.u voltage. As for the reactive power compensation Hawaii has a deadband between 0.96 p.u and 1.04 p.u while Q_{max} is output at 0.94 p.u and Q_{min} is absorbed at 1.06 p.u.



(a)

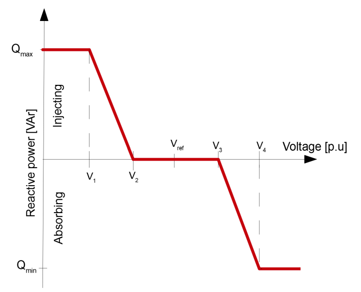
(b)

Figure 2.7 Figure (a) shows different grid codes for reactive power compensation and figure (b) shows different grid codes for active power control [Chathurangi et al., 2021].

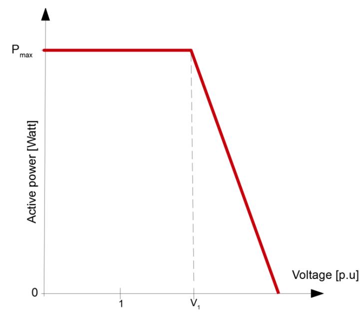
2.5 Voltage control

The Distribution System Operator has some options that can be utilised even though the PV inverter can not be controlled directly. One is to install automatic tap changers, or On-Load Tap Changer on the transformer. This is a good way to limit (or increase) the voltage at the transformer side, with the down side that it will also influence the voltage at other levels of the grid. With a lower voltage at the transformer side, the voltage increase that occurs because of equation 2.11 when the PV-systems output active power to the grid, will not be as significant as if the voltage at the transformer side is higher. By lowering the voltage on the transformer side the voltage on the PV side can be moved away from the upper voltage level, but at the same time the voltage pushes closer to the lower limit on the transformer side, resulting in less margins to the lower limit. On-Load Tap Changer can be used to some extent but there are clear limitations. E.ONs approach has primarily been to install On-Load Tap Changer at the higher voltage levels.

The Distribution System Operator can also try to reconfigure the feeder to be able to connect more PV-systems. This can for instance be if there is a group with many PV installations and another with less. If possible, it could be beneficial to reconfigure the groups in a way that the PV installations are more evenly distributed between the groups. Another possible solution would be to strengthen the grid by installing new cables. This is time consuming and expensive and would preferably be avoided. Another solution would be to fix the problem where it originate, at the PV side. Even though there is no legal obligation to do so in Sweden most inverters on the market today have the capability to manage the voltage at the PV side. Figure 2.8 shows two examples of control strategies that can help to accomplish this.



(a) Sketch of Volt-VAr control behaviour



(b) Sketch of Volt-Watt control behaviour

Figure 2.8 Volt-VAr and Volt-Watt control of an inverter

Volt-VAr control by the inverter

VVC means that the reactive power, Q, is a function of the voltage at the connection point. In figure 2.8a the typical VVC sought behaviour is shown. It can be seen that below the voltage V_1 maximum amount of reactive power will be injected to the power grid. The reactive power then decreases linearly until reaching zero when the voltage is at V_2. Between V_2 and V_3 is a deadband where no reactive power is injected or absorbed. When the voltage is then increased above V_3 reactive power is absorbed by the inverter, the amount of reactive power that is being absorbed increases linearly with increased voltage. Above V_4 maximum reactive power is absorbed by the inverter. From equation 2.11 we can see that a negative reactive power will help mitigate the voltage rise due to the active power flow, how much this will help depend on the R/X ratio. The apparent power rating of the inverter, S_{inv}, sets the limit for what the inverter can provide in terms of power. This means that the maximum reactive power that can be absorbed or injected by the inverter is given by equation 2.12 where P_{pv} is the instantaneous active power output from the inverter. This means that as long as the active power output is below the inverter rating, reactive power can be absorbed or injected to the grid by the inverter [Almeida et al., 2021]. This means that the voltage is not guaranteed to stay within the voltage levels of the grid but there will be no active power curtailment.

$$Q_{max} = \sqrt{S_{inv}^2 - P_{pv}^2} \tag{2.12}$$

By inspecting figure 2.8a one can see that there are some variables that can be influenced by the controller and some that can not. Q_{max} is a set figure that depend on the inverter specification and the active power loading while V_{ref} is the voltage reference of the grid. In the local grid of this report $V_{ref} = 230V_{ph-line}$. The size of the deadband can however be changed by moving voltages V_2 and V_3. This will make the reactive compensation start either at a lower or a higher voltage. Another approach would be to influence the inclination by changing the gain of the P-controller. A sharper inclination would give a more aggressive controller and would move V_4 closer to V_3 and V_1 closer to V_2. For the case when V_4 move closer to V_3 this would mean that the inverter absorbs maximum amount of reactive power for a lower voltage. Another interpretation of moving V_4 closer to V_3 is that the controller starts to resemble an on/off controller as the inclination derivative move towards infinity. There is also a limit on Q_{max} that is set by the grid code. The reason for this depend on the availability of reactive power on the grid that could potentially be absorbed. This can for instance be seen when comparing the California and Hawaii grid codes where Q_{max} is 44 percent of rated capacity in Hawaii and 30 percent i California.

Volt-Watt control by the inverter

The behaviour of VWC can be seen in figure 2.8b where it is shown that the active power output is a function of the voltage at the connection point. This means that for voltages below a certain threshold level, u_{red}, the inverter outputs P_{inv} and above this voltage the active power output is curtailed in a piecewise linear fashion until the active power is completely curtailed when the voltage has reached u_{max}. There is no absolute rule that the active power needs to be 100 percent curtailed at u_{max}, for instance when grid code IEEE 1547 Cat.A/Cat.B is implemented the active power is 20 percent of rated power at u_{max}. For this thesis however, where the Hawaii grid code will be used, 100 percent curtailment is implemented. P_{inv} is controlled by the MPPT algorithm of the PV-system and is the maximum active power the PV-system can output given the operating conditions. Local VWC control on all PV-systems in the local grid will theoretically do a better job with limiting the voltage rise but with the drawback that during the periods when the control has to be active, the active power output will be limited. Equation 2.13 shows how the VWC should behave for different voltage levels.

$$P(t) = \begin{cases} P_{pv}, & \text{if } voltage \leq u_{red} \\ P_{inv} - P_{inv}\frac{voltage - u_{red}}{u_{max} - u_{red}}, & \text{if } u_{red} < \text{voltage} \leq u_{max} \\ 0, & \text{if voltage} > u_{max} \end{cases} \tag{2.13}$$

2.6 Software

The programs that will be used in this thesis are Matlab for plotting and for sorting data in excel-files, dpPower as the tool used by E.ON and DIgSILENT PowerFactory to build the model. Powerfactory and dpPower will be presented below.

Digpro dpPower

Digpro dpPower is a grid modelling tool where a grid owner can model their grid. E.ON uses dpPower to model their local grid and to perform grid calculations. These simulations are then used as a complement when deciding what measures needs to be taken on the grid. In dpPower all components of the grid can be implemented and it is easy to add for instance a PV-system to a connection point when a new installation has been introduced to the grid. One limitation in terms of this project is that the PV-system that can be added has a static output power. This means that when performing the grid calculations the active power output is fixed. The power factor can be changed manually for each calculation, but there is no way to implement any control of the power output dependant on the characteristics of the grid. When it comes to dpPower all voltage levels are shown as integers without any decimal. Another limitation in dpPower is that all calculations only take local behaviour into consideration. For this reason the upper voltage limit in dpPower calculations has been set to 244 V. This value comes from experience on E.ONs part where simulation results above 244 V will potentially lead to measured voltages exceeding the actual legal limit of 253 V.

DIgSILENT PowerFactory

Since the main objective of this report is to investigate how different voltage control methods can be used to limit the voltage rises due to increased PV penetration there is a need to use another simulation tool than dpPower. For this reason PowerFactory was used as a modelling tool. PowerFactory can be used in a similar way as dpPower, but with PowerFactory comes more degree of freedom to implement changes to each module in the program. Another important feature for this report is the function of Quasi-Dynamic simulations where multiple load flow calculations can be performed within a single simulation. This means that the user for instance can input solar irradiation data of a full year and perform load flow calculations for the entire year. If for instance the data is input on an hourly scale there would be 8760 data points for each calculation. In practice the Quasi-Dynamic simulation will perform 8760 separate load flow calculations in a single simulation. While a single load flow calculation is a good tool when analysing for instance the worst case scenario, Quasi-Dynamic simulation can give a good figure of the aggregated behaviour over time with varying conditions. This means that the user can input different time characteristics from a .csv file (Comma separated values) and then perform the Quasi-Dynamic simulations dependant on these. The user could then for instance input the solar irradiance data to the PV module and a load profile to the different loads and get the voltage behaviour for each node in the grid for all different data points in the time characteristics. With this information one can get figures such as how much a PV-system generate during each part of the simulation time, how much power is transferred back to the transformer at each instance of time, the voltage profile for any given time and of course the aggregated behaviour during the full simulation time.

While this data is important there is still a need to change the output of the PV-system dependant on the grid data. With the approach in the paragraph above the active power output will always follow the solar irradiance and only be limited by the power factor setting and the rated size of the inverter. The reactive power output will only be influenced by the fixed value of the power factor. In PowerFactory there are multiple already implemented control strategies for the PV module as is illustrated in figure 2.9. There is however not any Volt-Watt control option.

There are multiple ways of implementing your own control logic in PowerFactory. One of these methods are to implement a QDSL model that is a tool to create user defined load flow and Quasi-Dynamic models. Figure 2.10 shows the procedure of how the QDSL model works. PowerFactory uses two distinctions for data types in general. It uses 'Type' data and 'Element' data. The difference is that the type stores the electrical characteristics as the cable resistance for a cable, while the element stores the specific equipment data as the cable length for the same cable. When creating a QDSL model the same approach is used. A type (TypQdsl) is created that includes the structure of the model and the control. Besides this an element (ElmQdsl) is also created that includes for instance information about which PV module voltage should be measured and what limitations should apply to the QDSL model [DIGSILENT, 2022].

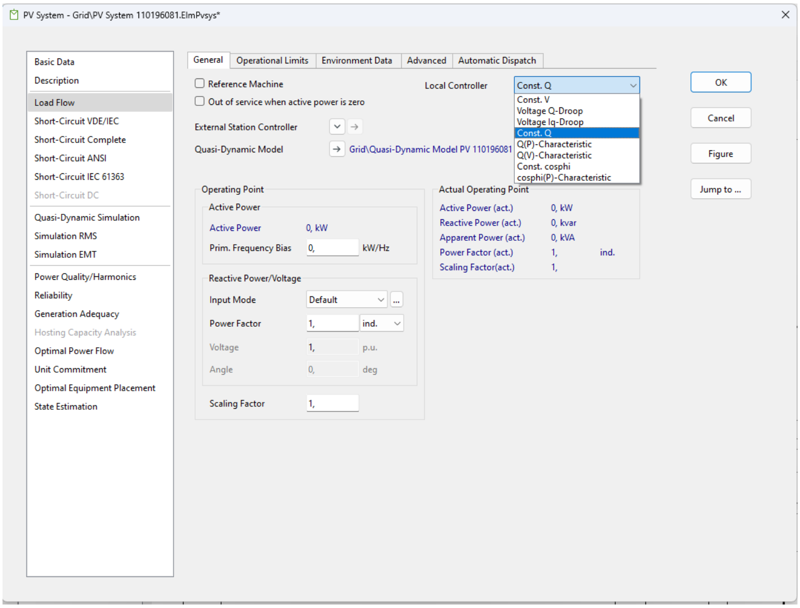


Figure 2.9 Visualisation of different PV controllers implemented in PowerFactory.

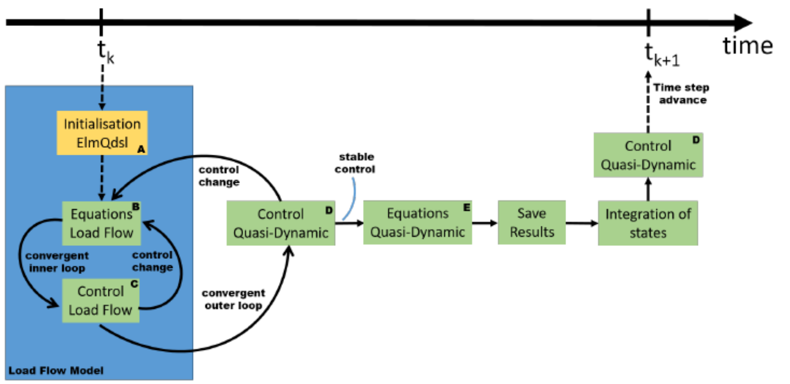


Figure 2.10 Simulation procedure of QDSL models in PowerFactory [DIGSILENT, 2022].

3

Methodology

This part of the report can be divided into two main cases. The first part, explained in section 3.1 to 3.3 consists of validating that the same behaviour that occurs in dp-Power also occurs in the PowerFactory model created for this report. PowerFactory will later be used in the simulations since dpPower has limitations when it comes to implementing control of the PV-systems. Since dpPower does not take the regional grid impact into consideration, only the local behaviour will be considered in the first part of the report. When the model behaviour has been validated, sections 3.4 will describe how the controls and the other parts of the model were implemented in PowerFactory while section 3.5 will describe how the different simulations were performed.

3.1 Choice of substation

In this report the analysed substation is VKT-003. This is a substation located in the south of Sweden. It is a relative new part of E.ONs local grid that where beginning to take shape in 2006, before PV production on the low voltage grid in large numbers where introduced and planned for. This area could be described as a typical residential area with a combination of small houses and apartment buildings. The substation have a transformer rated at 800 kVA and in total 7 groups connected to it. The area have, in accordance to table 3.1, 25 installed PV-systems today and experience problems related to voltage increases, especially on group 5. This has led to the point where grid re-enforcement's are already being performed. This means that cables that still have more than 40 years of economic lifetime left has to be dug up and replaced to limit the voltage increases due to PV installations and this at a point with a PV penetration below 20 percent. Figure 3.1 shows an overview of the area connected to VKT-003 in dpPower.

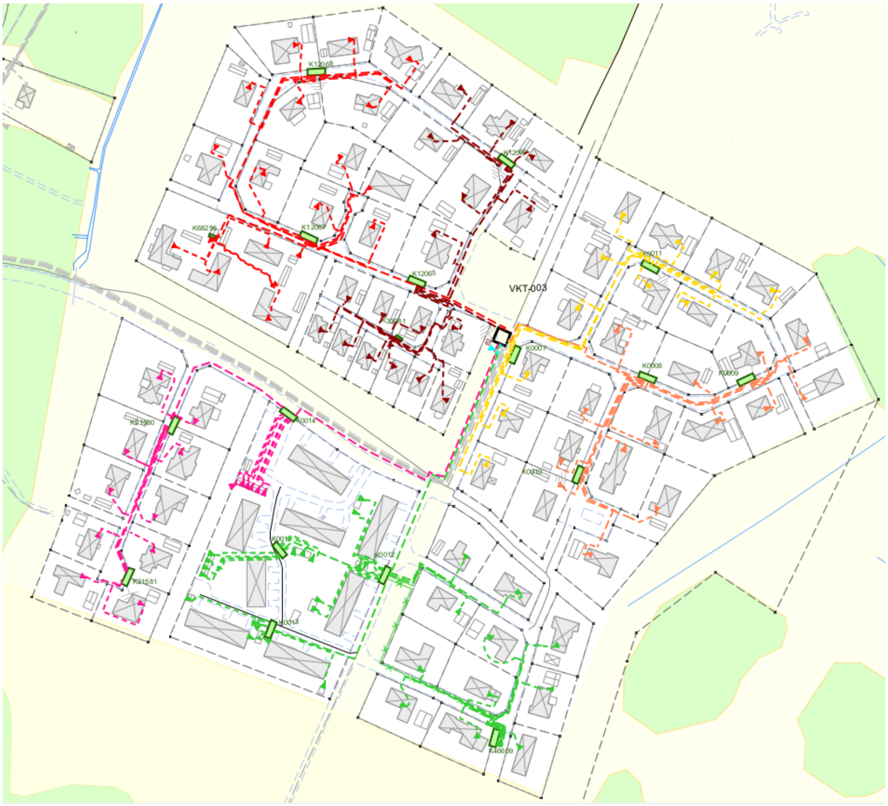


Figure 3.1 A view of the substation VKT-003 and the connected households.The orange dashed lines are group 1, the yellow are group 2, the pink are group 4, the green are group 5, the brown are group 6 and the red are group 7. The black square box illustrates the transformer station. Group 3 only contains one connection point and this is not a residential home, this group will be discarded in the rest of the thesis.

3.2 Model of substation VKT-003 in dpPower

In the first step, before the building of a model in PowerFactory, all relevant information from dpPower had to be collected. In this part, all cable lengths, cable types, connection points, loads, PV installations and transformer data were extracted. Another choice that was to be made was what group to analyse. Group 5 had both the highest input-impedances of the groups and the most connection points. With equation 2.11 in mind it is fair to assume that this means that group 5 will represent a worst case scenario when it comes to voltage increases due to PV installations and was chosen for this reason. In figure 3.1, the green lines on the lower right part of the figure represent group 5.

At this stage, the reference simulations in dpPower were also conducted. Three scenarios were chosen for the verification simulations. The first was the scenario of how the grid operates today. The second was the scenario where all connection points within the substation had PV-systems installed. This scenario is a somewhat academic case since the transformer would be loaded far above the rated kVA when the power factor is kept at 1. On the other hand, this might not be the case when VWC is implemented. In the third scenario, 70 percent of all connection points on each group had PV-systems installed. For the case with a 70 percent PV penetration the amount of connection points to install PV-systems on where first calculated, then what connection points to install PV-systems on were decided randomly. In all cases the already installed PV systems were left as they where, while all new PV-systems were assumed to be 11 kW with a power factor of 1. The reasoning behind the 11 kW was that this is the average new PV installation size on E.ONs local grid. The scenario of 70 percent PV penetration was chosen since at this point the transformer loading were beginning to close in on the rating of 800 kVA. This means that at 70 percent PV penetration the transformer will be needed to be replaced, if no control is used. To achieve 70 percent PV penetration, 4 new PV units were installed on group 1, 5 new units were installed on group 2, 11 new units were installed on group 4, 16 new units were installed on group 5, 9 new units were installed on group 6 and 7 new units were installed on group 7. Table 3.2 shows the cable types that are used in this part of the grid.

When performing production calculations in dpPower the main reason is to examine high voltages when there is high PV production on the low voltage side of the transformer. This typically occurs during summertime in the middle of the day. In Sweden this means that production is high when the demand is low. The load is low since the house owners usually are not home in the middle of the day, and there is no heating required in the middle of the summer. For this reason a typical reference load of 10 percent of the connection points maximum load during the last year is used during the load flow calculations in dpPower, while the PV-system output is at the rated power, P_{rated}. Table 3.1 shows which connection points have PV-systems installed today, the sizes of these, and the input-impedance of the connection points.

Connection point	**Group**	$P_{rated}(kW)$	**Input-impedance** (Ω)
110095296	1	13	0.19
110142095	1	7	0.19
110124377	1	12	0.36
110115897	1	11	0.13
110181570	2	17	0.35
110103175	2	9	0.24
110115933	2	11	0.36
110105887	2	10	0.33
110096280	2	12	0.21
110106919	2	15	0.25
110185273	5	12	0.31
110185132	5	13	0.24
110185135	5	14	0.49
110196081	5	16.8	0.42
110189870	5	8	0.39
110118017	6	7	0.36
110154380	6	12	0.26
110125996	6	11	0.23
110121053	6	13	0.43
110152869	7	14	0.15
110152868	7	14	0.22
110135882	7	14	0.28
110161793	7	14	0.34
110116583	7	7	0.12
110116670	7	10	0.28

Table 3.1 Installed PV systems on substation VKT-003

3.3 Model of substation VKT-003 in PowerFactory

In PowerFactory, a detailed model of each connection point in group 5 was built, while the other groups were modelled as a single node with one point load and one point PV unit that represent the whole group. From all the cable data the equivalent impedance was calculated and used for each group when connecting to the transformer. The choice to only study one of the groups in this part of the thesis was first and foremost made due to PowerFactory license limitations of 50 nodes. The data such as cable types, cable lengths, PV-systems, loads, and transformer data from dpPower were used when creating the PowerFactory model. To verify that the voltage behaviour between the two models was similar, the same approach was taken as in section 3.2, where only the local behaviour were considered.

Cable type	**Cable area (mm)**	**Resistance (Ω/km)**	**Reactance (Ω/km)**	**R/X ratio**
SE-N1XE-AS4G240	240	0.125	0.0691	1.81
SE-N1XE-AS4G150	150	0.206	0.072	2.86
SE-N1XE-AS4G95	95	0.32	0.0722	4.43
SE-N1XE-AR5G25	25	1.2	0.0722	6.9
SE-N1XV-U5G16	16	1.15	0.085	13.56
SE-N1XV-U5G10	10	1.83	0.091	20.09

Table 3.2 List of cable types that are installed in VKT-003. The data is collected from dpPower.

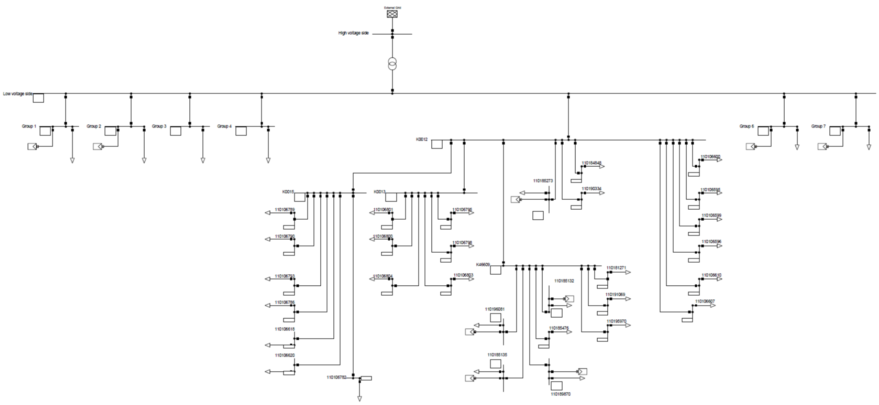


Figure 3.2 A single line diagram of the model in PowerFactory with today's PV penetration. The different models used in this thesis are shown in larger format in figures A.1 and B.1

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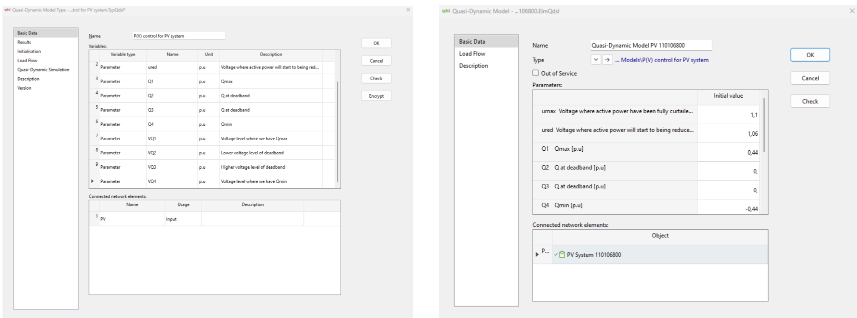
To compare the power flow calculations with dpPower, the PV-systems in PowerFactory were set to have an active power output of the rated power, P_{rated}. The loads were set to 10 percent of the maximum load of each individual connection point, and the low voltage side of the transformer, where set in accordance to the transformer voltage calculations in dpPower. Figure 3.2 shows the single line diagram in PowerFactory when today's PV penetration where used.

3.4 Voltage control

When the model in PowerFactory has been verified to behave in a similar manner as the dpPower model, voltage control is to be implemented. The main focus of this part is not the dynamic behaviour, but instead the aggregated behaviour over time is focused on. As described in section 2.4 there are no requirements on voltage control for small scale PV-system owners in Sweden, but there are grid codes active around the world to combat these problems with voltage rises due to high PV penetration. In an optimal situation, field tests would be performed to determine what a grid code could look like in Swedish conditions. This would make sure that the grid code is manageable within the Swedish power grid. Since this is outside the scope of this thesis, the Hawaii grid code is deemed as a good starting point since it is a well tested grid code during many years. Another good argument for why the Hawaii grid code is a good choice is that the Hawaiian electrical companies have collaborated with inverter manufacturers for years regarding this issue, resulting in most of the inverters on the market today having the feature as an option within their inverter software [Giraldez et al., 2017]. For this part, a QDSL model were created. Figure 3.3 shows part if the interface of this QDSL model.



(a) Figure of QDSL type for a PV system **(b)** Example of how the QDSL element look.

Figure 3.3 QDSL type and element example in PowerFactory.

Active power control

In figure 3.3b it is shown that the active power will start to curtail when the voltage is at 1.06 p.u and will be completely curtailed at 1.10 p.u. In all simulations where active power curtailment will be used, the PV panel installation will be over-dimensioned by 20 percent in relation to the inverter size as is common practice on the Swedish market. This is done since the Swedish solar condition does not allow the PV-system to operate at, or close to, rated power for that many hours of the year. This means that for a PV-system with an inverter rated at 11 kVA, 13.2 kW of solar panels will be installed.

Reactive power compensation

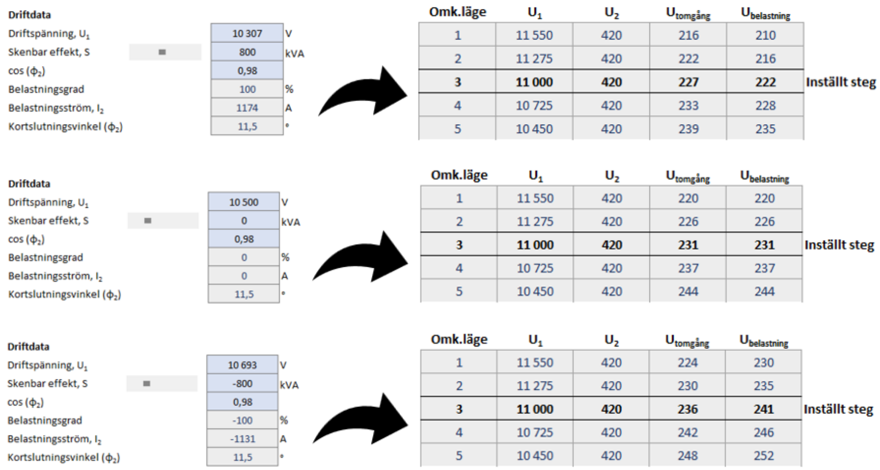
According to the Hawaii grid code there should be a deadband between 0.96 and 1.04 p.u, while Q_{max} is set to 0.44 p.u and Q_{min} is set to -0.44 p.u. This means that for a PV-system with a rated apparent power of 10 kVA, the reactive power injection or absorption will never exceed 4.44 kVAr. These settings are illustrated in figure 3.3. It will be assumed that there are enough reactive power on the external grid to absorb.

Transformer voltage

Figure 3.4 shows the excel provided by E.ON to calculate the transformer voltage during different operational situations. E.ON also provided operational data of U_1 as it is today. During full load U_1 were 10 307 V. With this setting at full load conditions and a power factor of 0.98, the secondary side voltage of the transformer during load, $U_{belastning}$, was calculated to be 222 V. Unfortunately as it is today, there is not that much PV installed on VKT-003 so the upper limit of U_1 had to be approximated. Assuming that U_1 increases at full production as much as U_1 decreased during full load, U_1 were approximated to be 10 693 V during full production, resulting in a secondary side voltage $U_{belastning}$ of 241 V. In between these extreme values of U_1 we have the no-load voltage. At this stage U_1 equals 10 500 V, resulting in a secondary side voltage of 231 V.

As shown by the figure, if setting the tap position to position 4, the no-load voltage would be 237 V. which is above the limit that E.ON has when setting up their transformers. In tap position 2 the transformer voltage would instead be to low, which could lead to voltages below the allowed limit during full load hours. For this reason the data for tap position 3 were used as a starting point in this thesis. Also worth noting is that within the values of U_1 is an average impact of approximate 1.1 percent of the overlaying parts of the grid, this was not the case in the dpPower calculations. If only local behaviour were taken into consideration U_1 would for instance be 10 412 V during full load. This value of 1.1 percent is an average value during a year and will be higher at some time instances and lower at some time instances. In general the overlaying grid impact is allowed to be up to 3 percent so in a weaker part of the grid, $U_{belastning}$ could be quite a bit higher during full production and lower during full load.

To account for the varying voltage on the transformer, a QDSL script were created that changed the transformer voltage, dependant on the loading of the transformer. By implementing this code, the transformer voltage assumed a linear relation between the transformer voltage and the loading. This means that the voltage increases linearly from 222 V when the load is 800 kVA, up to 241 V when the load is -800 kVA, meaning full production. In practice the QDSL script changes the tap position in PowerFactory between -8 and +8 with a voltage change of 1.1875 V per tap position change with a no-load voltage of 231 V.



Driftdata		
Driftspänning, U_1	10 307	V
Skenbar effekt, S	800	kVA
cos (ϕ_2)	0,98	
Belastningsgrad	100	%
Belastningsström, I_2	1174	A
Kortslutningsvinkel (ϕ_2)	11,5	°

Omk.läge	U_1	U_2	$U_{tomgång}$	$U_{belastning}$	
1	11 550	420	216	210	
2	11 275	420	222	216	
3	**11 000**	**420**	**227**	**222**	**Inställt steg**
4	10 725	420	233	228	
5	10 450	420	239	235	

Driftdata		
Driftspänning, U_1	10 500	V
Skenbar effekt, S	0	kVA
cos (ϕ_2)	0,98	
Belastningsgrad	0	%
Belastningsström, I_2	0	A
Kortslutningsvinkel (ϕ_2)	11,5	°

Omk.läge	U_1	U_2	$U_{tomgång}$	$U_{belastning}$	
1	11 550	420	220	220	
2	11 275	420	226	226	
3	**11 000**	**420**	**231**	**231**	**Inställt steg**
4	10 725	420	237	237	
5	10 450	420	244	244	

Driftdata		
Driftspänning, U_1	10 693	V
Skenbar effekt, S	-800	kVA
cos (ϕ_2)	0,98	
Belastningsgrad	-100	%
Belastningsström, I_2	-1131	A
Kortslutningsvinkel (ϕ_2)	11,5	°

Omk.läge	U_1	U_2	$U_{tomgång}$	$U_{belastning}$	
1	11 550	420	224	230	
2	11 275	420	230	235	
3	**11 000**	**420**	**236**	**241**	**Inställt steg**
4	10 725	420	242	246	
5	10 450	420	248	252	

Figure 3.4 This figure shows how different operational conditions impact the transformer voltage on the secondary side. By varying the operational voltage, U_1, a calculated value of the secondary side voltage $U_{belastning}$ can be found. The data in the blue cells, to the left of the arrows is the input data and the data to the right of the arrows is the output data. The top part of the figure shows the conditions during full load, the middle part shows the conditions during no-load and the bottom part of the figure shows the situation during full production.

3.5 Simulations

In this part the main focus is to emulate the real local grid as much as possible. For this reason real irradiance values from STRÅNG, and real loads of the connection points will be used as input data. STRÅNG data used here are from the Swedish Meteorological and Hydrological Institute (SMHI), and were produced with support from the Swedish Radiation Protection Authority and the Swedish Environmental Agency. Each PV-system where assumed to have a 30° roof inclination and oriented towards south. In reality there will be a distribution here where the maximum production time for the different connection points will differ somewhat. With the setup chosen in this thesis a worst case scenario will be presented. By using the same data for all connection points it makes it easier to compare the different nodes, which is a large part of this thesis.

Control verification

The first part of the simulations consisted of confirming that the PV-system output active and reactive power as expected with the control activated. For this part focus was on connection point 110196081, and examining the solutions to the load flow calculations for different cases. The active power control were verified first by changing the irradiation until the voltage at the examined connection point reached 1.06 p.u. Up until this point no active power curtailment should be present. The irradiation were then increased until the voltage reached 1.08 p.u. At this point it was verified if the PV-system had been 50 percent curtailed. For this verification irradiation data from 2023-06-05 were used since this day captured the sought behaviour in a good way. There was no need to evaluate more connection points since they all use the same control. For the reactive control it was important to evaluate that no reactive power were absorbed when the voltage was below 1.04 p.u. It was also important to verify that Q_{min} were never exceeded, both when the limit was set by the grid code and when the limit was set by the rated power of the inverter. To accomplish this simulations of 2023-06-05 were performed, but this time with the reactive power control activated. From the simulations it could be observed at what point in time there were no reactive power absorption and what the maximum reactive power absorption were. It could also be observed how the reactive absorption reacted when the rated apparent power of the inverter was reached.

Simulations without control

As a reference the different scenarios were first simulated without any control activated. The case with today's PV penetration, 70 percent PV penetration and 100 percent PV penetration were all simulated and the results were saved. Solar irradiance data from 2023 was collected from SMHI and input as a .csv file to each PV-system. The measured loads from 2023 for each connection point were also input as a .csv file to PowerFactory. The simulations gave, among other data, the voltages, active power production and transformer loading during each hour of the year.

Simulations with active control

In this part Quasi-Dynamic simulations were performed with an hourly scale during a full year with VWC activated. This gave the voltages and active power production during each hour of the year. These values could then be compared to the case without any control to get the aggregated active power curtailment for the full year for each connection point in group 5. Just as in the case with no control, these simulations were performed for all three scenarios of this thesis.

Simulations with reactive control

In this part Quasi-Dynamic simulations were performed in the same manner as in the previous section, with the difference that VVC were activated during these simulations. The voltage levels were observed together with the reactive power absorption during all hours of the year and the transformer loading. Just as in the previous sections all three scenarios of the thesis were simulated.

Simulations of all groups

Because of the limited license it was not possible to model the whole substation in detail. It was however possible to increase the size from the previous of a single node to model each cable box within each group. This extended the groups from the previous of 1 node to between five and eight nodes. At this stage model 4 could be modelled completely, while group 5 was modelled in the same manner as the rest of the groups. Group 4 could be completely modelled since it consisted of only 16 connection points in comparison to the 30 of group 5. The thinking was that this would give a good approximation of the average behaviour of each group. Once this model was in place different scenarios concerning transformer settings and grid strengths could be tested. A figure of this PowerFactory model can be seen in figure B.1.

4

Results

In section 4.1 the model built in PowerFactory for this thesis is compared to the model in dpPower that E.ON uses to simulate substation VKT-003. The comparison takes into account the three different PV scenarios used in this report. Section 4.1, just as done in dpPower, only takes local behaviour into consideration. In section 4.2 the results from the simulations in PowerFactory will be shown, at this point in time the overlaying impact will be included as described in section 3.4. This part consists of a control verification that will show what the output of the PV-systems are for different voltage conditions.

The simulation part will also consist of simulation results for all three scenarios for all three control cases, VWC, VVC and no control. In this section focus will be on showing the voltage, active power and reactive power for two of the connection points, namely the one with the most severe voltage increases and the one with the least voltage increases. The transformer loading will also be plotted for each simulation case. As a final part of the simulation section the aggregated active power curtailment for the different PV penetration cases will be presented to show how much each connection point would have to be curtailed in each case.

4.1 Model verification

Figure 4.1 shows how the voltages in dpPower and PowerFactory correlate to each other. The red dashed line shows the ideal behaviour where the voltages are identical for both programs. Each dot represent a single connection point in group 5 of VKT-003 and the different colours represents the different cases that were studied. From the figure it is clear that the two programs behave in a similar manner when it comes to the voltage levels. This is also confirmed by the correlation coefficients. The correlation coefficient of the voltages between the two models in the scenario of today's PV installation is 0.9804, the correlation coefficient for the scenario of 70 percent PV installations is 0.9936 and the correlation coefficient for the scenario of 100 percent PV installations is 0.9910. One clear source of a small error is that dpPower presents the voltages without any decimals. This can lead to errors on the magnitude of 1 volt in either direction on any given node.

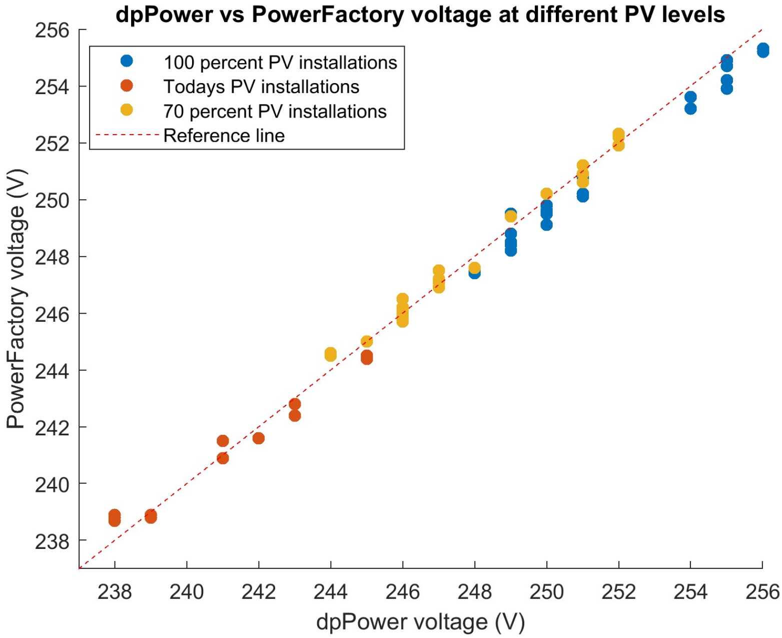


Figure 4.1 Plot of the voltage levels in dpPower and PowerFactory for different scenarios. Each dot represents a connection point. On the x-axis the calculated voltage in dpPower is shown and on the y-axis the calculated voltage in PowerFactory is shown. The red dashed line shows the ideal position of the connection points where the voltages are the same in both models. Each colour represent a different PV penetration scenario.

4.2 Simulations

Control verification

For this part of the simulation connection point 110196081 were analysed in more detail. Figure 4.2 shows the voltage and active power behaviour without any control. This shows that the voltage level continue to increase as the solar conditions for the PV-system continue to get better. In the middle of the day, the voltage has reached far above the upper limit of 1.10 p.u, while the active power output is at approximate nominal power. Figure 4.3 and 4.4 shows the behaviour with VWC activated. In figure 4.3 the results at 12.00 is made visible. At this point in time the voltage is 1.082 p.u. According to section 2.5 the active power should be 55.0 percent curtailed at this stage. As shown by figure 4.3 the PV-system is curtailed by

9.1 kW, or 54.95 percent. In figure 4.4 the results at 08.00 is made visible. At his point in time the voltage is at 1.073 p.u According to section 2.5 the active power of the PV-system should be curtailed by 32.5 percent. As shown by figure 4.4 the active power is curtailed by 3.43 kW, or 32.9 percent. The small deviations are there due to the rounding of the voltage level. Also shown by figures 4.3 and 4.4 is that there is no curtailment when the voltage is below 1.06 p.u.

Figures 4.5, 4.6 and 4.7 show the reactive power behaviour for connection point 110196081 on 2023-06-05. From all three of the figures it is clear that no reactive power is absorbed when the voltage is below 1.04 p.u. With a rated power of 16.8 kVA and following the Hawaii grid code the maximum reactive power absorption should be -7.392, this is also the case as has been made visible by the dashed reference line. In figure 4.5 it is shown that the reactive power absorption is -2.651 kVAr when the voltage is at 1.047. According to section 2.5 the reactive power absorption should at this voltage level be 35 percent of the maximum reactive power absorption, or in other words -2.5872 kVAr. Figure 4.7 shows how the reactive power absorption is at -7.392 kVAr when the voltage is at 1.071 and the active power is still not near the inverter rated power. Figure 4.7 shows how the reactive power absorption reduces as the active power output of the PV-system close in on the rated power. At 11.00 the active power output is 16.52 kW, while the reactive power absorption is -3.081. These figures give an apparent power of 16.80 kVA as expected. This shows that even though there is a need to absorb more reactive power, the amount absorbed is limited by the rated apparent power of the inverter.

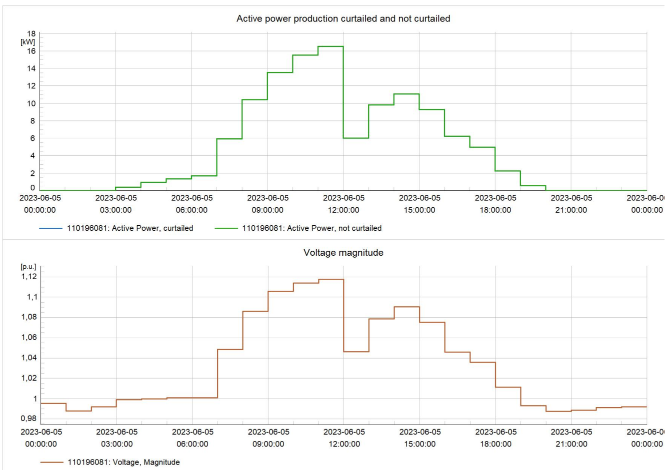


Figure 4.2 Plot of voltage and active power output with no control active. The green line in the upper figure shows the calculated active power output without control while the blue line (not visible) shows the actual active power output. As can be seen the green and blue line are identical. The lower figure shows the voltage levels for the different hours of the day.

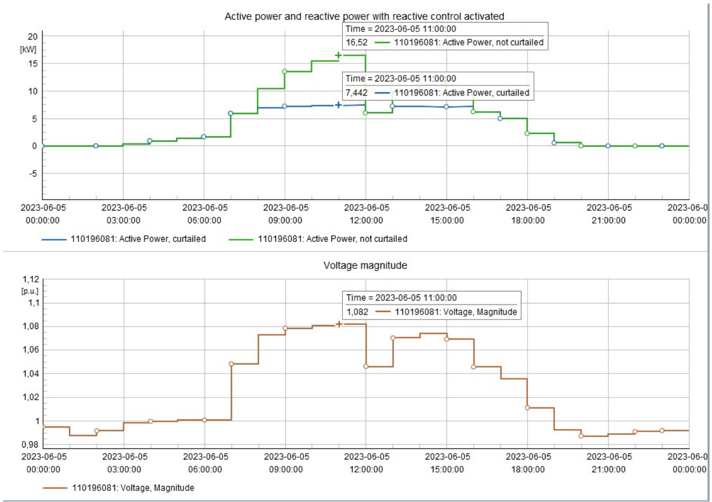


Figure 4.3 The green line in the upper figure shows the calculated active power output without VWC while the blue line shows the actual active power output with VWC activated. The lower figure shows the voltage levels for the different hours of the day. The point where the voltage is 1.082 p.u is marked.

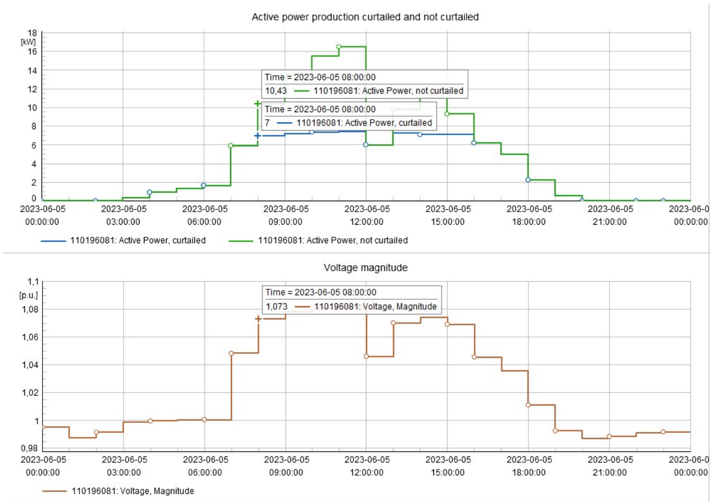


Figure 4.4 The green line in the upper figure shows the calculated active power output without VWC while the blue line shows the actual active power output with VWC activated. The lower figure shows the voltage levels for the different hours of the day. The point where the voltage is 1.073 p.u is marked.

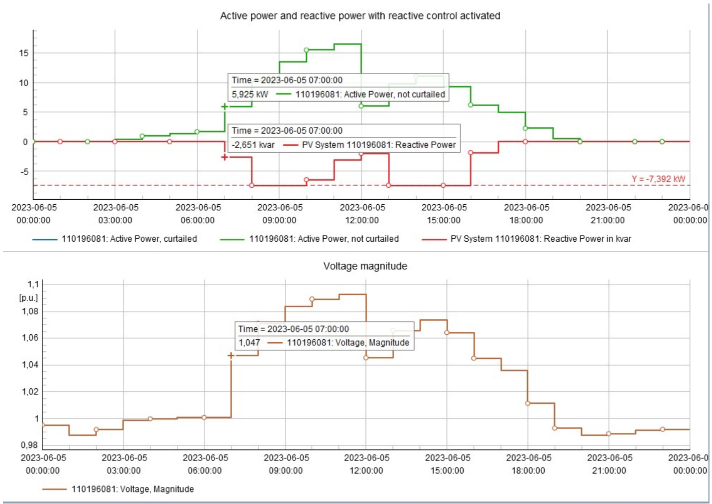


Figure 4.5 The green line in the upper figure is the calculated active power output without VVC while the blue line shows the actual active power output. The red line is the reactive power. At 07.00 the reactive power absorption is activated for the first time. The lower figure shows the voltage levels for different hours of the day, at 07.00 the voltage is 1.047 p.u.

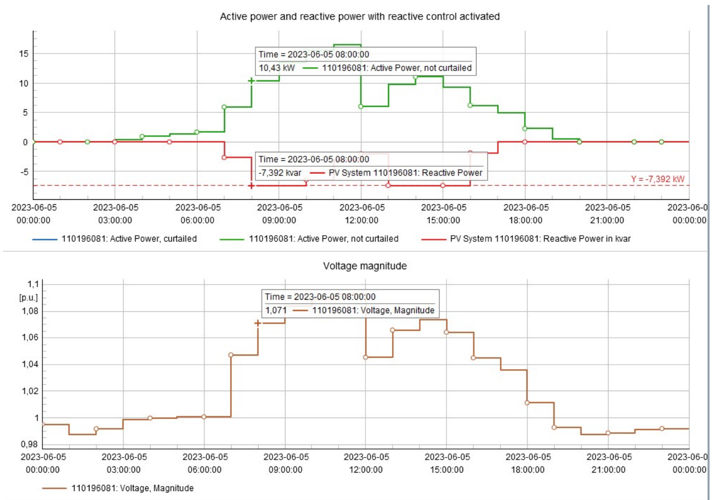


Figure 4.6 The green line is the calculated active power output without VVC while the blue line shows the actual active power output from the PV-system. The red line is the reactive power. At 08.00 the reactive power absorption is fully activated. The lower figure shows the voltage levels for different hours of the day, at 08.00 the voltage is 1.071 p.u.

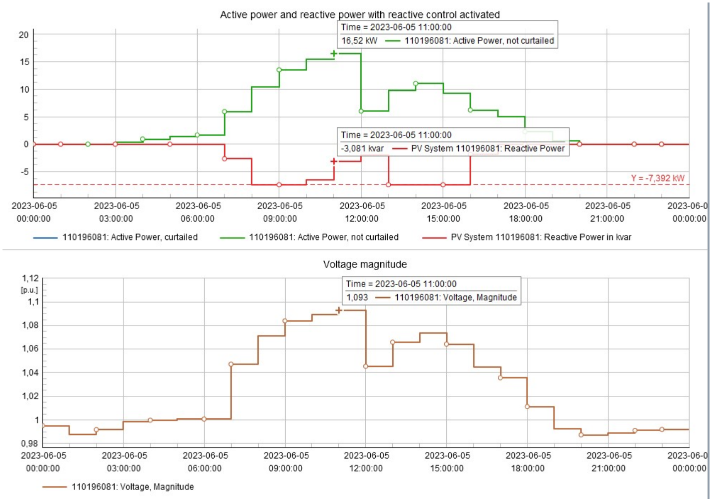


Figure 4.7 The green line is the calculated active power output without VVC while the blue line shows the actual active power output. The red line is the reactive power. At 11.00 the reactive power absorption is limited by the rated power of the inverter. The lower figure shows the voltage levels for different hours of the day, at 11.00 the voltage is 1.093 p.u.

Simulation results with 100 percent PV penetration

In the following simulations where the three different scenarios will be examined, a simulation will be deemed feasible if the transformer is not over-loaded and the voltage magnitudes stays below the limit of 1.10 p.u. The reason why the transformer is not to be over-loaded is twofolded. First and foremost the transformer can not operate at above 100 percent loading. As a second reason, the transformer voltages is only valid within the transformers operational region. This means that if the transformer is loaded above 100 percent, it is hard to say anything about the voltages acquired from the simulation, except that they are to low.

In figure 4.8 the voltage magnitude during a full year of simulation without any control is shown for two connection points, namely 110196081, that is the node with the most severe voltage issues, and connection point 110106599, that is the node with the least problems. In the upper part of the figure it is clear that the voltage exceeds the limit of 1.10 during many hours of the year for connection point 110196081, while the voltage magnitude stays below 1.10 all year for connection point 110106599. In the lower part of the figure it is clear that both PV-systems operate at, or around their respective rated value of 16.8 kW for 110196081 and 11 kW for 110106599. In figure 4.9 the transformer loading is shown to be loaded above 100 percent 442 hours of the 8760 hours in the year, reaching the maximum of 130 percent. This means that the simulation case is not feasible.

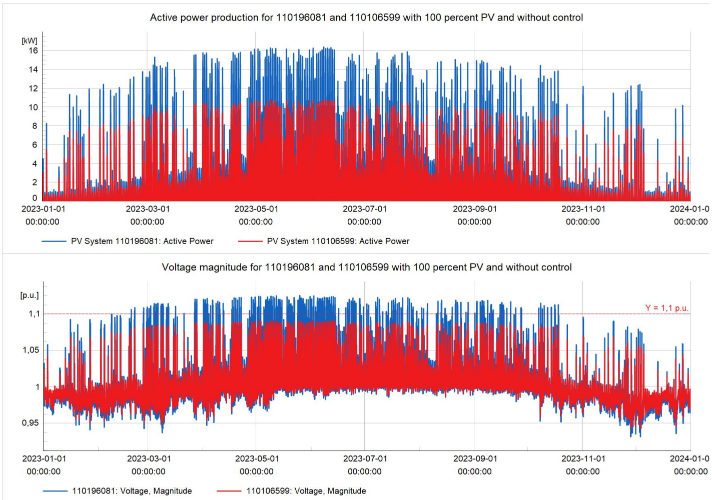


Figure 4.8 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases when no control is active. In the upper part of the figure it is clear that the voltage for connection point 110196081 reaches above the limit of 1.10 p.u for large parts of the year, while the voltage for connection point 110106599 stays below 1.10 p.u during the full year.

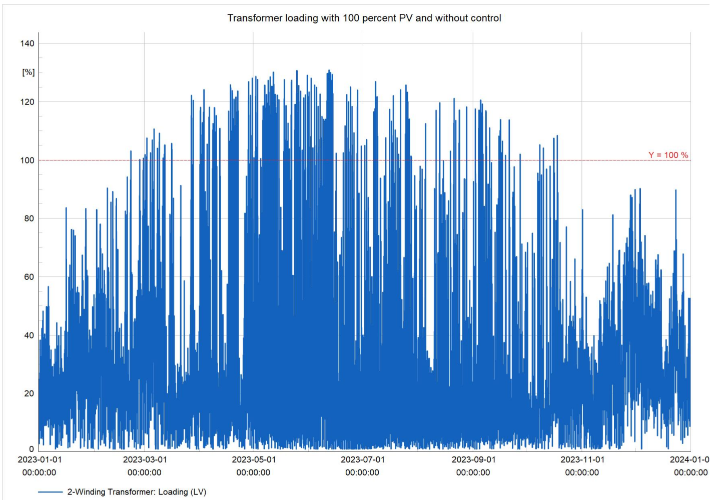


Figure 4.9 Transformer loading during a full year of simulation when no control is activated. The loading is way above 100 percent for large parts of the year.

Figure 4.10 shows the voltage magnitudes and active power production when VWC is active. Here it is clear that the voltage magnitude problems have vanished since the voltage stays well below 1.10 p.u at all times of the year. In the lower part of the figure is the active power production. In the figure, the red line is plotted above the blue, and therefor the blue is not visible when the active power output is actually larger for connection point 110106099 during many hours of the summer months, even though the PV installation of 110106599 is 5.8 kW smaller.

The reason for this is that the PV-system at connection point 110196081 has to be curtailed much more during the months when there is a lot of production and low loads due to the location in the grid. On the other hand, when for instance analysing the production outside the summer months it is clear that when the production is lower in general, the voltages are lower, resulting in less, or no curtailment for either PV-system. During these times the production is larger for 110196081 in comparison to 110106599. Another interesting observation is the production spike in the middle of November. At this point in time 110196081 experience the largest production during the year and is well above the production of 110106599. This would suggest that it was cold and sunny during these days, resulting in a lot of PV production, while the loads are large from all of the heating. This results in a large part of the produced solar electricity being used within the owners own grid without being exported to the external grid. The fact that the voltages are the lowest during the full year the same day, but when the sun has gone down, further strengthens this theory. The voltage magnitude of 110196081 peaks at 1.084 p.u while 110106599 peaks at 1.071 p.u.

In figure 4.11 the transformer loading is shown when there is 100 percent PV penetration but with VWC active. As can be seen the problem concerning overloading of the transformer that were present without any control is no longer an issue. The transformer loading peaks at about 90 percent during all year. In general, the loading stays relative constant throughout the year. Both the transformer loading and the voltage magnitudes indicate that this solution seems feasible.

Figure 4.12 shows the active power, reactive power and the voltage magnitudes for connection points 110196081 and 110106599 when VVC is active. The active power is not curtailed, just as in the case with no control.The reactive power shows large differences between the two connection points, where connection point 110196081 absorbs the maximum of -7.392 kVAr during a substantial part of the year, while 110106599 peaks at about -2.5 kVAr. Figure 4.13 shows the transformer loading when VWC is active. It is clear that the transformer is over-loaded for 489 hours of the year with a top loading of 136 percent, which is not actually doable. This means that even though it at a first glance looks like the VVC worked quite well in terms of voltage levels, the transformer would be heavily over-loaded, leading to the same situation as in the section without any control where the only conclusion that can be made is that the solution is not feasible.

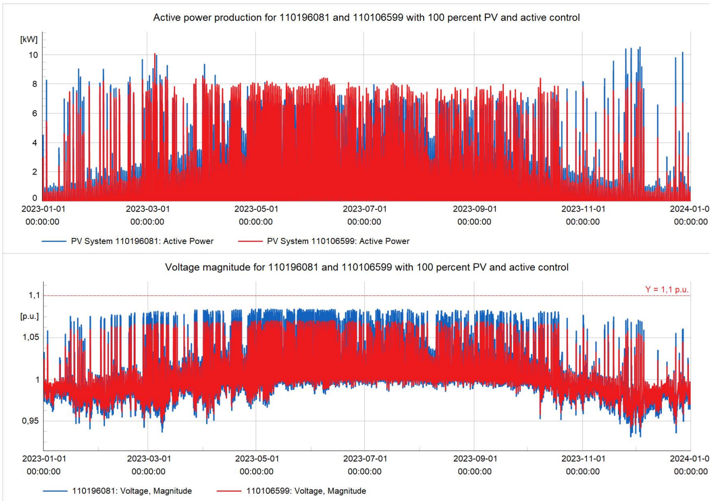


Figure 4.10 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases and curtailment when VWC active. In the upper part of the figure it is clear the the voltages never exceed the upper limit of 1.10 p.u. The lower figure shows the active power production and that the smaller installation 110106599 actually produces more active power during the summer months.

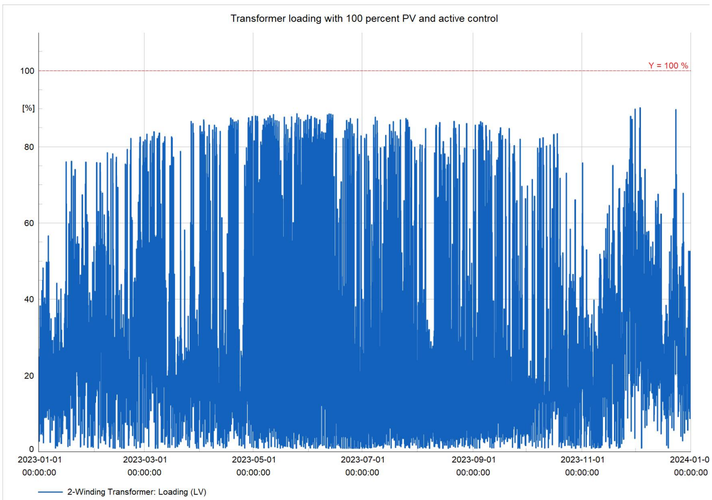


Figure 4.11 Transformer loading during a full year of simulation when VWC is activated. As shown the transformer is never loaded above 100 percent in this case.

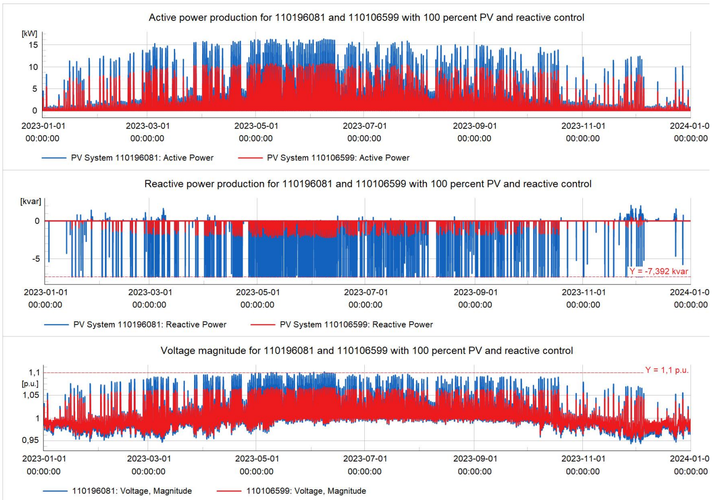


Figure 4.12 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases and curtailment. When analysing the voltages the levels are clearly below the levels when no control is active, even though the limit of 1.10 p.u is exceeded at some time instances.

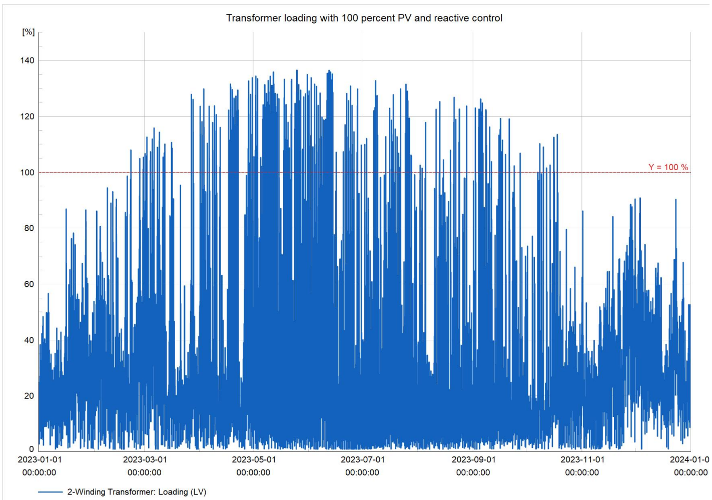


Figure 4.13 Transformer loading during a full year of simulation when reactive control is activated. it is clear the the transformer is heavily over-loaded for large parts of the year.

Simulation results with 70 percent PV penetration

Figure 4.14 shows the scenario of 70 percent PV penetration without any control. It is shown that the voltage magnitude deviates above 1.10 during many hours of the year for connection point 110196081, while the voltage stays within the limit for all hours of the year for connection point 110106599. The active power is, as expected, identical to the case with no control for 100 percent PV penetration. Figure 4.15 shows the transformer loading for this scenario. It is shown that the loading stays below 100 percent for all hours of the year, with peak values of about 95 percent. If the PV penetration would increase, the transformer would begin to close in on a situation when it would need to be replaced if no control is used.

Figure 4.16 shows the voltage magnitudes and active power production with 70 percent PV penetration and VWC active. The voltage magnitudes stays well below 1.10 p.u for both connection points and just as in the case with 100 percent PV penetration, the active power production of the smaller PV-system on connection point 110106599 actually produces more active power during most of the summer months. This behaviour is however not as prominent in this scenario as with the 100 percent scenario. As expected the transformer loading is below 100 percent during all hours of the year. This can be verified in figure 4.17. This means that this is a scenario that seems feasible according to the simulations.

Figure 4.18 shows the active power, reactive power and voltage magnitudes when VVC is active for the 70 percent PV scenario. The active power is not curtailed but output as in the case without control. As for the reactive power it is clear that the PV-system of connection point 110196081 reaches the maximum absorption of -7.392 kVAr during many hours of the year. As for 110106599 the reactive power absorption is more moderate, reaching a top value of about 2 kVAr, with Q_{min} equal to -4.84 kVAr for connection point 110106599. In this case the voltage magnitude for connection point 110196081 stays below 1.10 p.u during all hours of the year, just as the voltage magnitude for 110106599 stays well below 1.10 p.u.

Figure 4.19 shows the transformer loading with VVC active. From the figure it is clear that in this case the transformer never gets over-loaded. This means that with this setup the voltage levels stays within the limit, at the same time as the transformer stays within its operational limit. This means that VVC, according to the simulations, could decrease the voltage levels enough to stay within the legal limit in this situation. This shows how VVC can help a lot in situations where the voltages are somewhat increased and needs to be lowered a few volt to still be within the legal limit. When comparing the transformer loading to the case without control it is seen that the transformer is a bit more loaded when VVC is active.

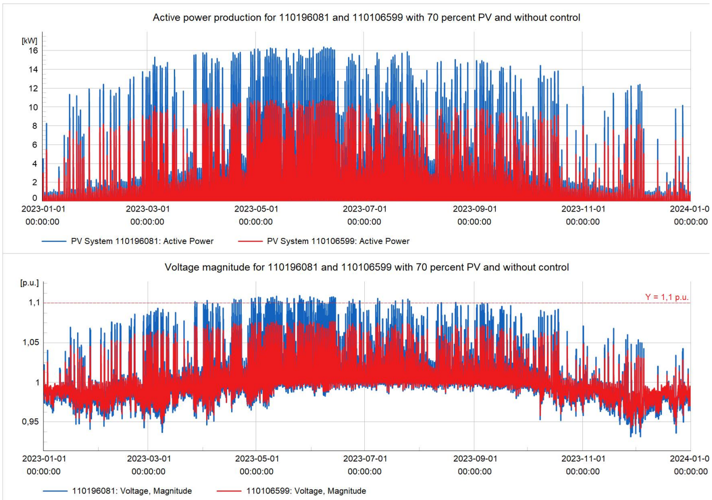


Figure 4.14 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases. In this scenario the voltage for connection point 110196081 exceeds 1.10 p.u on multiple occasions, while the voltage magnitude for 110106599 never reaches 1.10 p.u. The active power output is identical to the case with 100 percent PV-penetration

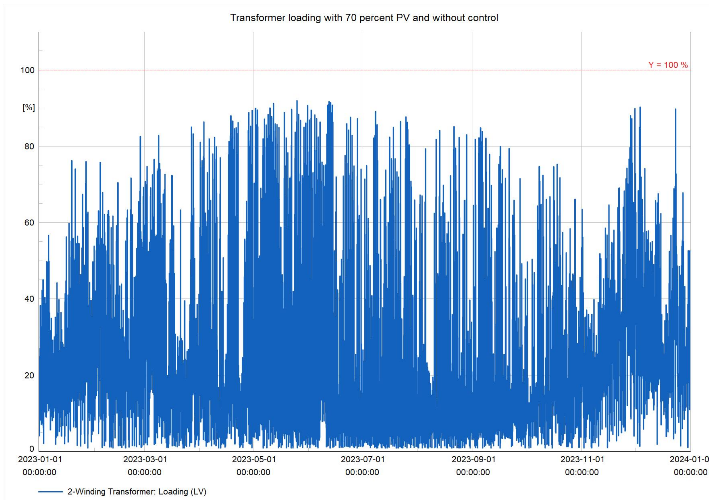


Figure 4.15 Transformer loading during a full year of simulation when no control is activated. It can be seen that the transformer is never over-loaded during the year.

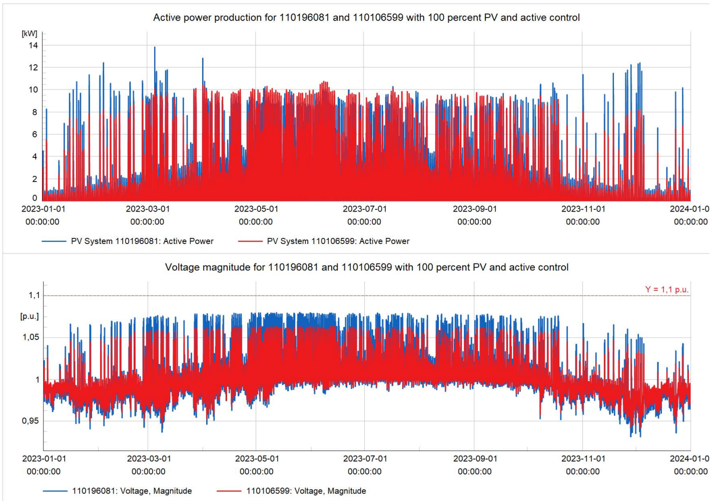


Figure 4.16 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases and curtailment. The voltage levels never exceed 1.10 p.u and just as in the case with 100 percent PV penetration the smaller installation on 110106599 actually produces more than 110196081 during much of the summer months.

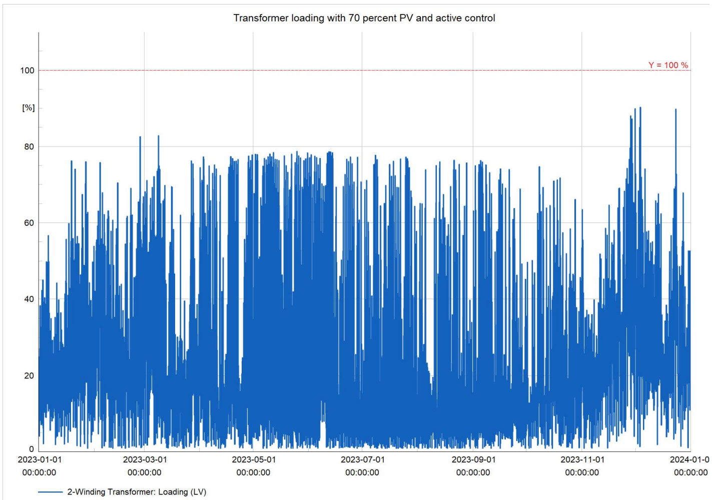


Figure 4.17 Transformer loading during a full year of simulation when active control is activated. The transformer is never over-loaded during the year.

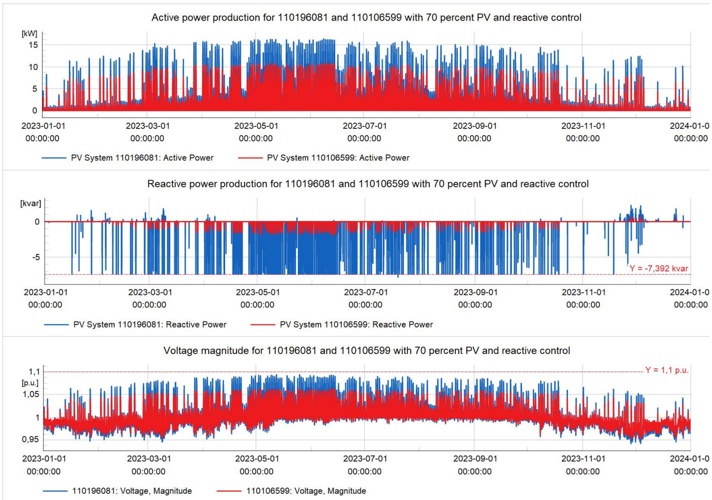


Figure 4.18 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases, curtailment and reactive power.

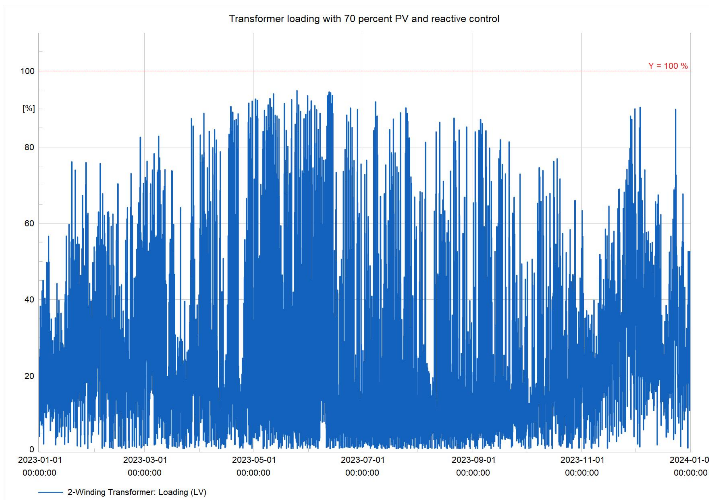


Figure 4.19 Transformer loading during a full year of simulation when reactive control is activated. As can be seen the transformer is never over-loaded during the simulation time.

Simulation results with today's percent PV penetration

In this section, the part without control was left out due to being identical to figure 4.20 and 4.21 in terms of active power production and transformer loading. The voltage levels are lower and do not cause a problem while the transformer loading is less than 100 percent at all times. These plots therefore do not provide any additional information.

In figure 4.20 the voltage and active power are shown when VWC is active. First of all, in today's scenario 110106599 does not have a PV installation, therefor only the active power of 110196081 is visible in the lower part of the figure. This figure shows the interesting result that the active power output is actually identical to the case without any control. This means that the voltage never exceeds 1.06 p.u and no active power curtailment occurs. This is interesting since an overlaying grid impact of 1.1 percent has been added to the transformer operational voltage, this should make the voltages higher than when this scenario was simulated in dpPower when only local behaviour was taken into consideration, but this is not the case. The voltages are actually a bit higher in the dpPower calculations when only local behaviour is taken into consideration. The reason for this is that with a lower operational voltage in the dpPower calculations, the no-load voltage was lower, resulting in dpPower choosing tap position 4 instead of tap position 3 since the no-load voltage in the dpPower case was still at E.ONs limit of 235 V when using tap position 4. For this reason the PowerFactory simulation starts at a lower transformer voltage as the reverse power flow begin. This gives more room to the upper voltage limit but leaves less margin to the lower limit. The transformer is never over-loaded and as seen by figure 4.21 the loading is largest during the winter months due to high loads. The impact of the transformer setting and the overlaying grid impact will be further examined in section 4.4.

In figure 4.22 the active and reactive power of connection point 110196081 is shown together with the voltage magnitudes for connection point 110196081 and 110106599. It is clear that the active power is unchanged from figure 4.20 while the reactive power is somewhat modest in comparison to the cases with 70 and 100 percent PV penetration. The voltage magnitudes is similar, but a bit lower than in the VWC scenario. The transformer is still not nearly over-loaded, even though the loading is a little bit higher during the hours when the VVC is activated.

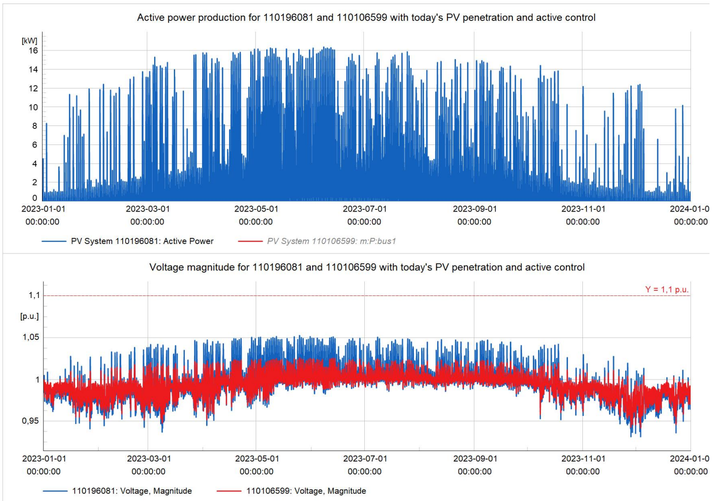


Figure 4.20 Comparison between the connection point with the most severe problem with the connection point with the least problems concerning voltage increases and curtailment.

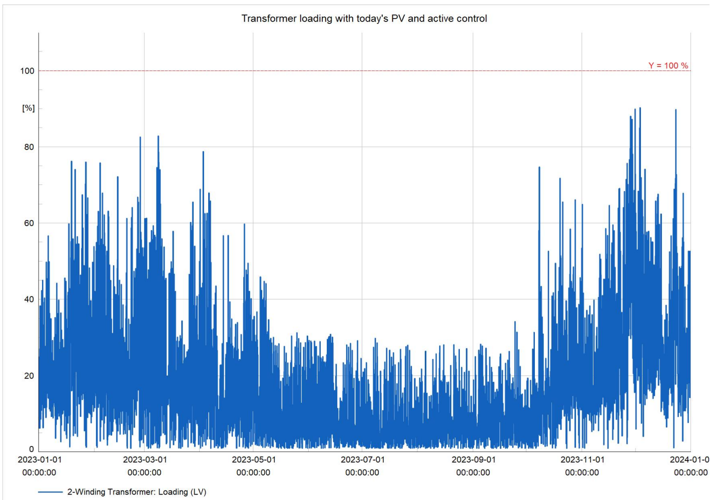


Figure 4.21 Transformer loading during a full year of simulation when active control is activated.

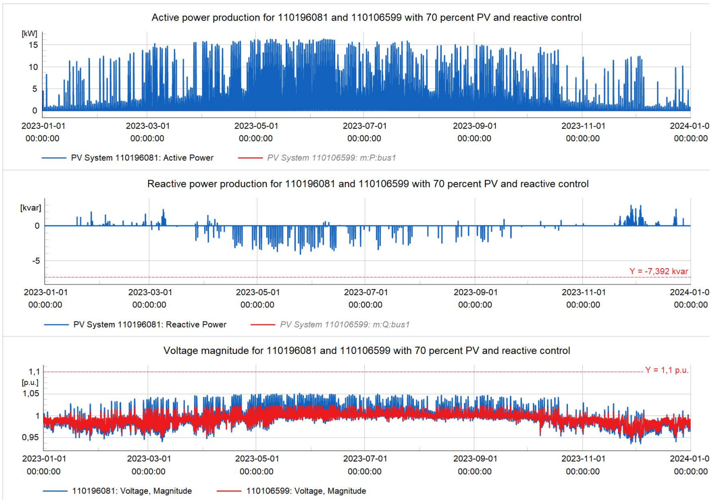


Figure 4.22 Comparison between the connection point with the most severe voltage magnitude problem with the connection point with the least problems. In this scenario there is no PV installed at 110106599, therefor only the voltage is visible for 110106599.

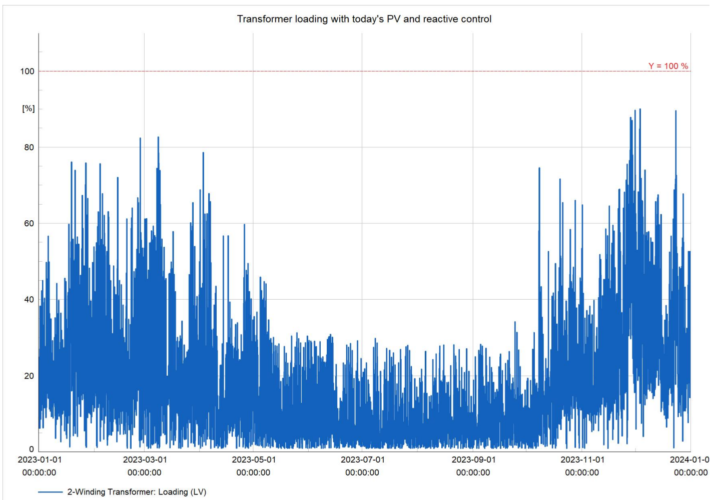


Figure 4.23 Transformer loading during a full year of simulation when reactive control is activated.

Active power curtailment during a full year

Figure 4.24 shows how much active power curtailment each connection point were subjected to during the simulations with VWC active. The scenario of today's PV penetration was left out due to the absence of active power curtailment. What is most obvious is the large dispersion between the connection points. In the scenario with 100 percent PV penetration the curtailment varied from 7.2 percent curtailment up to 36.1 percent with an average curtailment of 15.37 percent. In the scenario with 70 percent PV penetration the curtailment varied from 0.5 percent up to 18.9 percent with an average curtailment of 6.78 percent. From analysing the curtailment variation it is clear that multiple factors impact the curtailment and that these factors interact with one another. One factor is the input resistance. Another factor is at what level the connection point is situated within the local grid. On top of this there is of course a difference in the loads of the connection points. There is also the factor of the size of the PV installation that impact the curtailment.

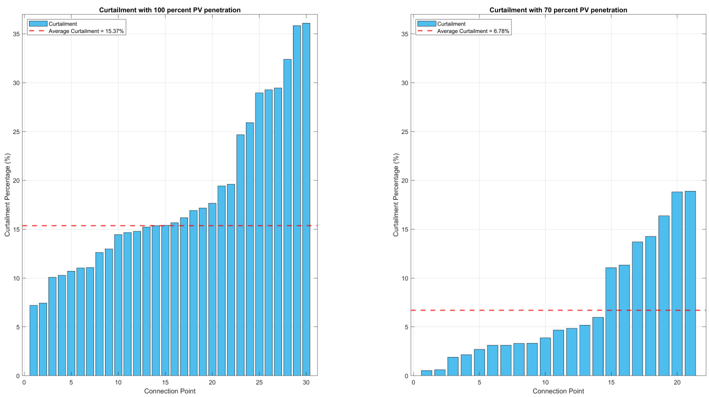


Figure 4.24 Figure of active power curtailment for each connection point in group 5, for 100 percent and 70 percent PV penetration. Each bar shows how many percent of a connection points production is curtailed during a full year, when compared to the case without any control. Due to spacing limitations the connection points are named from 1 to 30 instead of their actual numbers. The red dashed lines indicates the average curtailment for the whole group. The case of today's PV scenario is left out since no active power curtailment were needed in this case.

4.3 Active power curtailment of all groups

In the previous simulations all groups except group 5 were simplified down to one single node with one load, one PV-system and one impedance. In this section, all groups were instead modelled with multiple loads and PV-systems. All cable boxes are modelled and to each cable box is all loads, PV-systems and lines connected to it. This enhances the model in many ways and extends each group to instead being represented by more than five nodes with a distribution of the loads and PV-systems. Since group 4 was much smaller than group 5, it was actually possible to model group 4 in detail in this scenario. Figure 4.25 shows the average curtailment of all groups in this simulation. First of all it is clear that the average curtailment of group 5 is very close to the results in section 4.2 when the group were modelled in detail. This gives more weight to these results. Secondly, it is clear that group 5 is heavily curtailed in comparison to all other groups. The average is also high in relation to all the other groups curtailment since group 5 is much larger than the other groups with its 30 connection points, in comparison to the second largest with 18 connection points.

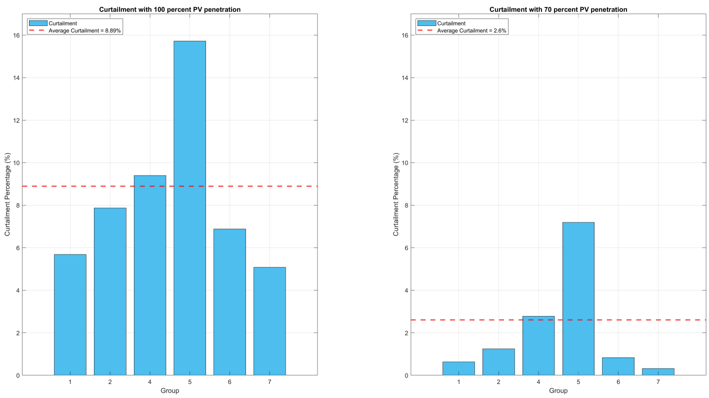


Figure 4.25 Figure that shows the active power curtailment for all six groups on VKT-003. The left figure shows the scenario with 100 percent PV penetration and the right figure with 70 percent.

4.4 Transformer settings impact

The purpose of this section is to explore how different characteristics of the grid impact the active power curtailment. In figure 4.26 the overlaying grid impact has been changed to 3 percent instead of the 1.1 percent that was the average for VKT-003. When comparing to figure 4.25, the difference is large. With this setup the curtailment is almost doubled in comparison. This shows that the curtailment behaviour between different locations of the grid can vary quite substantial. The 3 percent is quite unlikely and is at the top end of what is allowed within E.ONs own regulations.

In figure 4.27 the overlaying grid impact is back to 1.1 percent, but this time the no-load voltage of the transformer has been raised to emulate a situation where the tap position has to be higher due to for instance high loads. This gives less room up to the voltage limit. This setting is more in line with the setting used in the dpPower calculations but with the added 1.1 percent impact. Figure 4.27 clearly shows the importance of the transformer setting when analysing these issues.

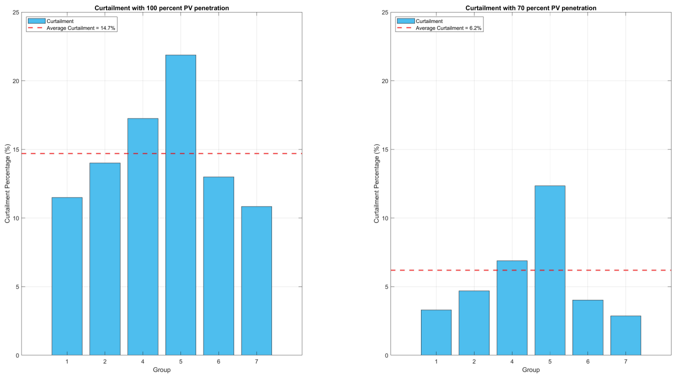


Figure 4.26 Figure that shows the active power curtailment for all six groups on VKT-003. The left figure shows the scenario with 100 percent PV penetration and the right figure with 70 percent. In this case the overlaying grid impact on the transformer voltages has been changed to 3 percent, instead of the 1.1 percent in the previous sections.

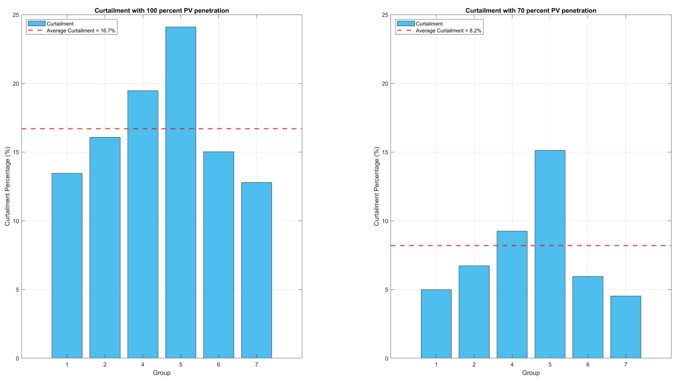


Figure 4.27 Figure that shows the active power curtailment for all six groups on VKT-003. The left figure shows the scenario with 100 percent PV penetration and the right figure with 70 percent. In this case the no-load voltage of the transformer has been raised to 235 V instead of 231 V that has been previously used.

5 Discussion

5.1 Verification of model

Not that much can be said about the verification of the model in PowerFactory except that it would be hard to get the two models to be more alike. Since dpPower only presents the voltages without any decimals, and all measurement points were within the 1 V margin, this gives as good of a validation as can be given. To get an even better validation that the model not just behaved as the dpPower model, but also behaved in accordance to reality, it would have been a significant improvement if real measurement values were available from the studied grid. Unfortunately this was not possible to get.

5.2 Simulations of group 5

From the simulation results in section 4.2 it was clear that VWC was a feasible solution in both the case with 100 percent PV installations and in the case of 70 percent PV installations. One clear takeaway from this was that the transformer were never overloaded during the simulations, which would indicate that these solutions would be possible without any grid strengthening measures. Another takeaway was how large the disparity was in terms of curtailment for the different connection points. It was clear from the theory that there would be differences, but the size of these difference was, at least for me, a surprise. There are ways to limit these differences by control measures. For instance it would be of interest to test how the system would behave with different setpoints for the VWC in different parts of the system. Nodes that experience large curtailment could start the curtailment at a higher voltage magnitude, while nodes with less curtailment could start earlier. In this way the connection points could share the effort in a more fair manner. As an alternative to this the nodes could start control at the same voltage levels but where the nodes closest to the transformers regulate more aggressive. During this project, after getting more knowledge in the subject, I am not sure that the best solution would be a technical in this case. From E.ONs point of view, this solution would input a lot more complexity into an already complex system. In practice it would be hard to uphold this type of solution from the Distribution System Operators point of view.

Regarding VVC it was not as clear that this solution would work to keep the voltage within the legal limit. It was shown that the R/X ratio of approximate 10 within each group made active power a much better tool for limiting the voltage increases. VVC did however show some promise in lowering the voltage somewhat, and in many cases this would probably be enough. There are a lot of grids where the voltages either are close to the limit, or exceeds 1.10 p.u by a small margin. In these cases VVC would be an excellent solution, with no active power losses. It has to be said though that regulations regarding VWC still need to be in place to be implemented once, or if the VVC is not enough anymore. One reason why most focus were on VWC in this thesis was that the unknowns were many more regarding VVC. There is for instance the fact that if this solution is implemented in a large scale, at many locations within the grid, there would be a need for a lot of reactive power to be absorbed. This yields another limitation that would need to be examined closer. For that reason this thesis settle on acknowledging VVC as at least a theoretical possibility, if the circumstances are correct. Regarding the loading of the transformer, the case with 70 percent PV penetration and VVC showed that the transformer were nearly fully loaded. If more PV would be installed, the transformer would not be able to handle the apparent power loading. This means that the rough approximation made in the beginning of the thesis seems to be quite accurate.

A solution that in many cases would be optimal is a control method where VWC and VVC is combined. In that case the VVC could operate up until the inverter rated apparent power is reached (or until there is no more reactive power to absorb), after this, VWC could curtail the active power, limiting the voltage even further. This curtailment would give room for even more reactive power absorption, and so on. Theoretically, this would be a solution that would function in all situations when VWC work, but with way less curtailment over time.

5.3 Simulations of all groups

One limitation of this thesis that can not be overlooked is the limited number of nodes on the PowerFactory license. This limited the results that could be extracted and forced me to think differently about the problem. Theoretically, representing each group with approximate five nodes give a much better result than modelling it with just the one node. When comparing the results from the simulations of group 5 to the simulation results of group 5 in the new model, it gave a clear indication that both models exhibited approximately the same average behaviour over time. In this model, group 4 could be modelled in an exact manner, just as group 5 were earlier. In practice, these types of models were built for all groups but excluded in the report, those simulations showed the same similarities between each other as in the case with group 5. When simulating for instance group 1 in detail, the average curtailment during a full year were very close to the simulation results for group 1 in the limited model.

The simulations showed that there was not just a large disparity between the different connection points within a group, there were also clear difference between the groups. If once again looking back at equation 2.11, the parameters that should impact the most is the amount of connection points, and the input resistance of these connection points. At a first glance, one would suggest that groups 6 and 7 would be curtailed more than group 4, but as shown the input-resistances of the connection points in group 4 were larger, leading to larger curtailment even though the group had fewer connection points.

5.4 Grid strength

In sections 4.2 and 4.3 the main focus were to emulate the real grid as much as possible and make decisions as would be made in practice. This for instance led to the no-load voltage being way lower than in the dpPower simulations, resulting in less of a problem with all scenarios, and even no voltage problems in today's scenario. In section 4.4 these decisions were challenged to see what would happen if the grid status were different. These results made it clear that the tap position of the transformer and the overall strength of the overlaying grid is a huge factor that will differ in different locations. To account for this the next step would include field tests where these type of control schemes is tested in real life, at different locations to get a fair assessment of the situation.

It is exactly for the impact of the overlaying grid that On-Load Tap Changer could be part of the solution. It is not common practice to put On-Load Tap Changer at the low voltage part of the grid, it is however a solution to put them higher up in the grid. By doing so the voltage variations due to the overlaying grid can be managed by the On-Load Tap Changer. This means that the impact from the higher levels of the grid could be handled. The voltage increases due to the local PV penetration however, still must be dealt with locally.

When it comes to the tap position of the local transformer a clear factor is how heavily loaded the transformer is during high loads. If the transformer have for instance an off-circuit tap changer, the tap position can be changed but when On-Load Tap Changer is not used, this has to be done manually, on site. To do this the transformer also has to be de-energized. This would require a lot of manual work to regularly change the tap positions on transformers all around the country and would not be a solution that would hold up in the long run. It would also come with some risks of the transformer voltage being to low if the loads would be high when not expected, for instance if a cold front would come earlier than expected, resulting in high loads and therefor low voltages.

Limitations

One limitation of this thesis was that only one year of simulations were used. In general there is a variation on the solar irradiation from year to year, and there are variations when it comes to the loads from year to year. The results from this thesis can therefor be seen as a guidance of how a future situation could look like. Another limitation regards the transformer settings and the impact from the overlaying grid. It is always hard to estimate future scenarios since it is impossible to know how such a scenario will behave. To account for this uncertainty section 4.4 included a couple of different scenarios to show the difference between different possible scenarios.

6

Conclusions

- VWC is according to the simulations in this thesis a good way to limit voltage increases due to high PV penetration, and thereby limit the need for grid strengthening measures.
- There is a large disparity between the different connection points within a group and a large difference between the groups in terms of how much active power curtailment is needed.
  - For the case with 70 percent PV installations on group 5, there is a difference between 0.5 percent in the least curtailed node to 18.9 percent in the worst node.
  - In the case of 100 percent PV the curtailment on group 5 differ between 7.2 and 36.1 percent.
- VVC is a good way to delay grid strengthening measures when the voltages are not to high. Under certain conditions it might be a permanent solution.
  - The resulting R/X ratio of the groups on VKT-003 are about 10, this makes active power 10 times more effective in limiting voltage changes.
- The grid that were examined in this thesis could have a 70 percent PV penetration without the transformer being overloaded, either when no control were active or when VVC were active.
- With VWC active there could be 100 percent PV penetration without the transformer being overloaded.
- A larger load during high PV production could reduce the need for active power curtailment and reactive power absorption by a lot.
  - This load could be in the form of for instance a charging car, heating or a battery that could charge during high production and discharge during the evening.

6.1 Future work

The most obvious continuation of this work would be to find a test grid where the controls of the inverters could be tested in reality to further verify the conclusions of this thesis. As mentioned before, most inverters on the market today already have the option to activate VWC and VVC and set the parameters for the control directly within the inverter software. At this stage different grid codes could be tested and it could be verified if enough reactive power is available. It would also be interesting to analyse the dynamic parts of the voltage control that were excluded in this thesis.

Another idea for future work would be to examine how VWC and VVC could be combined and simulate how the voltage profile would look with this approach and to analyse how the active power curtailment would be influenced by this approach.

A final idea for future work would be to model a similar grid with Battery Energy Storage Systems (BESS) connected to the PV system. It would be interesting to see how a BESS solution could limit the need for curtailment. Not considering the high cost for a BESS, this would be a good solution for PV-system owners since it would limit the need for curtailment, at the same time, the owners would store the solar energy from the day to use at the evening when they are home again. Except for the positive impact on the voltage profile of the grid this also makes sense since the PV-system owners do not have to pay any grid network charges when using electricity during the evening since the energy is stored within their own grid. In a future situation, if the prices on BESS continue to decrease, this could hopefully become an economical investment.

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A

Model of group 5

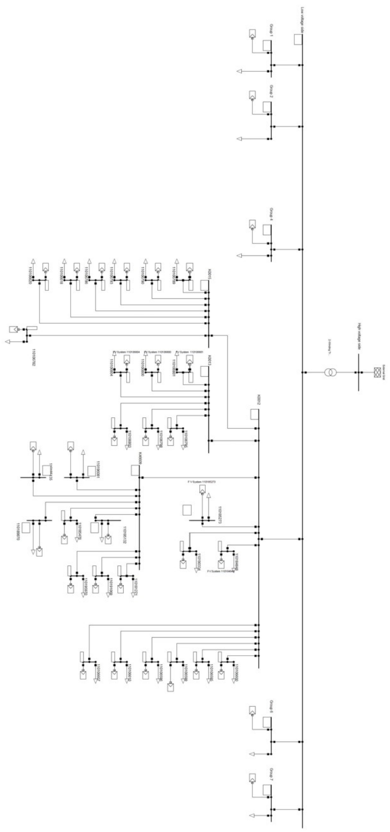

Figure A.1 Model of VKT-003 where group 5 has been modelled in detail.

B

Model of all groups

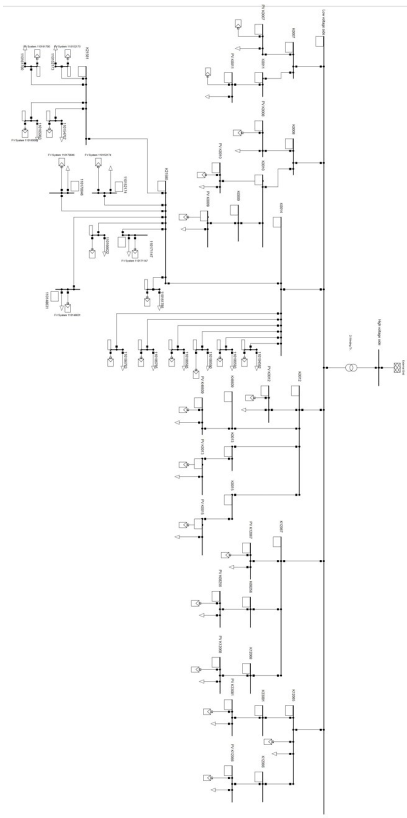

Figure B.1 Model of VKT-003 where group 4 has been modelled in detail and the other groups have been simplified.

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Local voltage control in a low voltage grid with high photovoltaic penetration

Abstract

This thesis examines how active power control (Volt-Watt control) and reactive power compensation (Volt-VAr control) can help limit voltage increases on the low voltage grid due to high photovoltaic (PV), installations. Due to the large increase in interest to install small scale PV-systems within residential areas the Distribution System Operator E.ON, has noticed problems concerning high voltage levels on the customer side as the amount of PV installations increase. To limit the voltage increases the Distribution System Operator can upgrade the grid with newer and thicker cables and a new transformer, which takes time and costs money. In some cases it might also lead to relatively new cables being excavated. Another possible solution would be to use the existing grid in an optimal way.

To test how the different control methods behave and to quantify how the overall impact would be for the PV-system owner, a model of an existing substation in the south of Sweden was built in PowerFactory. Once the model was built, local Volt-Watt and Volt-VAr controls were implemented on each PV-system. The system was then simulated for a full year using real load data from the customers and real solar irradiation values from SMHI where focus was on the aggregated behaviour over time. The simulations using Volt-Watt control found that, depending on where within the grid they were located, there was a large disparity between the different customers in terms of how much they would have to be curtailed. The figures ranged from 0 percent up to almost 20 percent of all yearly production in a scenario where 70 percent of all household had a PV-system installed. Volt-VAr was not as effective in decreasing the voltage magnitude as Volt-Watt due to the high R/X ratio but showed promise in cases when the voltage levels were not that prominent. Volt-Var could help lower the voltage magnitude by a few volts if needed, and serve as way to delay the eventual need to curtail active power.

This thesis also showed that there are many grid characteristics that influence how effective the voltage control can be. If situated in a weaker part of the overall grid, the voltage magnitudes in the local grid will become higher, leading to more active power curtailment if Volt-Watt is used, and limited chances that Volt-Var could work. Another finding was that the tap position of the transformer makes a large difference in terms of curtailment of the PV-systems.

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