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Voltage support strategies for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Networks

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Abstract

The increasing penetration of distributed photovoltaic generation in low voltage distribution networks has led to higher risk of overvoltage. This has made it necessary to utilize the capability of the inverter in the photovoltaic systems to consume reactive power as voltage support. Different strategies have been developed in accordance with the voltage support capability of the inverter.

The purpose of this thesis is to study different voltage support strategies used by photovoltaic system inverters and compare their ability to mitigate the overvoltage generated by high PV penetration in the LV distribution network. Reactive power efforts and losses in the network for the different inverter strategies are examined to find which is the most effective. How the different strategies affect the PV capacity of the network will also be emphasized during the evaluation of the effectiveness of the strategies.

The "IEEE European Low Voltage Test Feeder" network is modelled in Simulink using the program "GridBuilder", which is made by the author for this thesis. Photovoltaic generation is introduced to the loads in the network model with these voltage support strategies:

- Strategy 1: Constant power factor.
- Strategy 2: Power factor dependent on PV power production.
- Strategy 3: Reactive power consumption dependent on the voltage.
- Strategy 4: Power curtailment.

Simulations of one day steady state operation with each strategy, using load profiles from IEEE for the loads and irradiance data from Oslo on the 4.mai 2016 for the PV systems, were performed. From the results it was found that strategy 1 and 2 utilized the most of the voltage support available through the photovoltaic systems in the grid. Strategy 2 and 3 had the least losses of all the strategies. Concluding with strategy 3 as the most efficient strategy for the case presented.

Preface

This thesis represents the final work on my M.Sc. Degree at the Norwegian University of Science and Technology (NTNU). It was carried out between January and June 2016 at the faculty of Information Technology, Mathematics and Electrical Engineering, Department of Electric Power Engineering. The master thesis has been supervised by Professor Ole-Morten Midtgård and Iromi Ranaweera, and in cooperation with the Hafslund AS.

A big thank you to my supervisors and Christian Granum at Hafslund Nett AS for providing assistance and guidance when needed.

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1 Introduction

1.1 Background and Motivation

With half of the world population living in densely populated urban environment the need for an energy source that fit into this setting is essential. Solar power, which is a renewable and clean energy resource available in most cities, is a solution. Photovoltaic (PV) generators can be built in any scale and only require a connection to the grid and a well oriented support to function as distributed generators (DG). PV modules can be attached or integrated into buildings not taking up space in an already built-out urban environment [1, 2].

Already today PV has gone from a niche marked to a mainstream electricity source. Germany is in the forefront of installed PV capacity, producing 38,5 TWh of PV generated power in 2015 [3, 4]. This is largely caused by their strong incentive schemes, supported by the Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz", EEG) and the continuing decline of PV system costs. The growing trend of PV can also be seen worldwide. With the increasing penetration of distributed PV many countries have found it necessary to make new standards concerning grid connected PV in order to maintain the power quality of the grid. Permissible range of grid voltage is one of the most stringent constraints for the penetration of PV generators, especially when connected to the low voltage (LV) distribution network. To keep voltage in compliance with power quality regulations; power generation limitation, electrical storage devices, line voltage compensator and capacitor/reactor banks are widely used . However PV systems, or more accurately the PV inverters, can similarly contribute to voltage control. By over dimensioning the inverter capacity by 11% of the PV modules nominal power, the inverter is able to generate power with a power factor (PF) between 0.9 lagging and leading [5]. By using a lagging PF, the reactive power consumption this entails, the over voltage created by DG can be mitigated. Most standards regarding grid connected PV require that the inverter is able to perform this function. Using the inverters ability to vary the PF, different voltage support strategies for the inverter have been developed to aid in controlling the voltage. Regulations regarding grid connected PV, states that it is the distribution system operators (DSOs) who are responsible for deciding the requirements for grid connected PV.

The voltage support capability of the PV systems inverter is a good tool for maintain the safety and reliability of the network as well as further increasing the potential capacity of PV penetration in a network.

1.2 Goal and Objectives

The purpose of this thesis is to study different voltage support strategies used by PV inverters and compare their ability to reduce the overvoltage generated by high PV penetration in the LV distribution network. Reactive power efforts and losses in the network for the different voltage support strategies will be examined to find which is most effective.

1.3 Research Method

A LV distribution network which under normal operating condition experience voltage outside of the admissible range when high level of PV penetration is introduced, is simulated. The different voltage support strategies are implemented and modified until voltage inside the admissible voltage range is achieved. The effectiveness of the strategies will be based on the strategies ability to achieve the necessary voltage reduction with the least amount of losses in the network. How the different strategies affect the PV capacity of the network will also be emphasized during the evaluation of the effectiveness of the strategies. The following voltage support strategies are studied:

- Strategy 1: Constant PF.
- Strategy 2: PF dependent on PV power production.
- Strategy 3: Reactive power consumption dependent on the voltage.
- Strategy 4: Power curtailment.

The simulation tool used is Simulink. The simulation time spans 24 hours with a time step of 1 minute. The inverter modes ability to mitigate the overvoltage is tested in the Simulink network model by looking at the voltage at the critical point in the network. The losses caused by the different inverter modes are also compared to find the most effective one.

A quasi static power flow is performed using phasor simulation. The mode is found to be insufficient if the voltage at the critical busses goes outside of the voltage band +/- 10% of the nominal voltage.

1.4 Key Assumptions and Limitations

This thesis focuses on Steady-state voltage support, which refers to support provided by the DG on change in voltage encountered under normal operation of the grid. It does not look into dynamic voltage support, when DG sustains the network through voltage drops on higher voltage networks of the grid. The inverter modes studied are only for local voltage support that does not need a communication infrastructure.

The voltage at the transformer in the LV distribution network is set to a constant 240V. In a real network these parameters would not be constant, but fluctuates with the loading of the distribution network. This thesis only considers the dynamics of the LV distribution network and not the medium voltage (MV) distribution network.

The thesis will only look into the changes in voltage magnitude and not the voltage unbalance between phases. Therefore the loading of the phases are kept balanced and the lines in the studied LV distribution network are assumed perfectly transposed. The power generated by the PV systems is also balanced between the phases.

Using phasor simulation the frequency is assumed to be constant 50 Hz.

2 Distribution network

2.1 Introduction

The power grid can be divided into three networks:

- Main grid,
- Regional grid
- Distribution network or distribution system

The main grid can be described as the highway of the grid connecting the big generators to the rest of the grid; it also includes the transmission lines to neighboring countries. The regional grid connects the main grid and the distribution network. The regional grid and the distribution network are separated by substation transformers. Distribution network is the local network that distributes power to the supply terminal[1]. The distribution network by Norwegian standards has voltages at 22 kV (HV, high voltage) and 11 kV (MV, medium voltage), but is transformed by a distribution transformer to 230/400 V (LV, low voltage) for distribution to the consumer. The LV distribution network is the part of the grid called "Secondary" in Figure 2-1. The distribution network has long been disregarded in the development of new analysis and operational techniques compared to the main and regional grid. As a result, distribution networks were typically overdesigned. Although times have changed and it has become more common to operate distribution networks close to its maximum capacity, the LV distribution network is still in many ways marginalized compared to the rest of the grid. With increasing trend of grid connected distributed generation, like PV generators, in the LV distribution network; distribution system operators (DSO) are forced to pay more attention to the LV distribution network to maintain the voltage quality that is required from them.

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[1] Point in a public supply network designated as such and contractually fixed, at which electrical energy is exchanged between contractual partners. [6] H. S. Kjell Sand, "A Guid to Voltage Quality Planning," 2012.

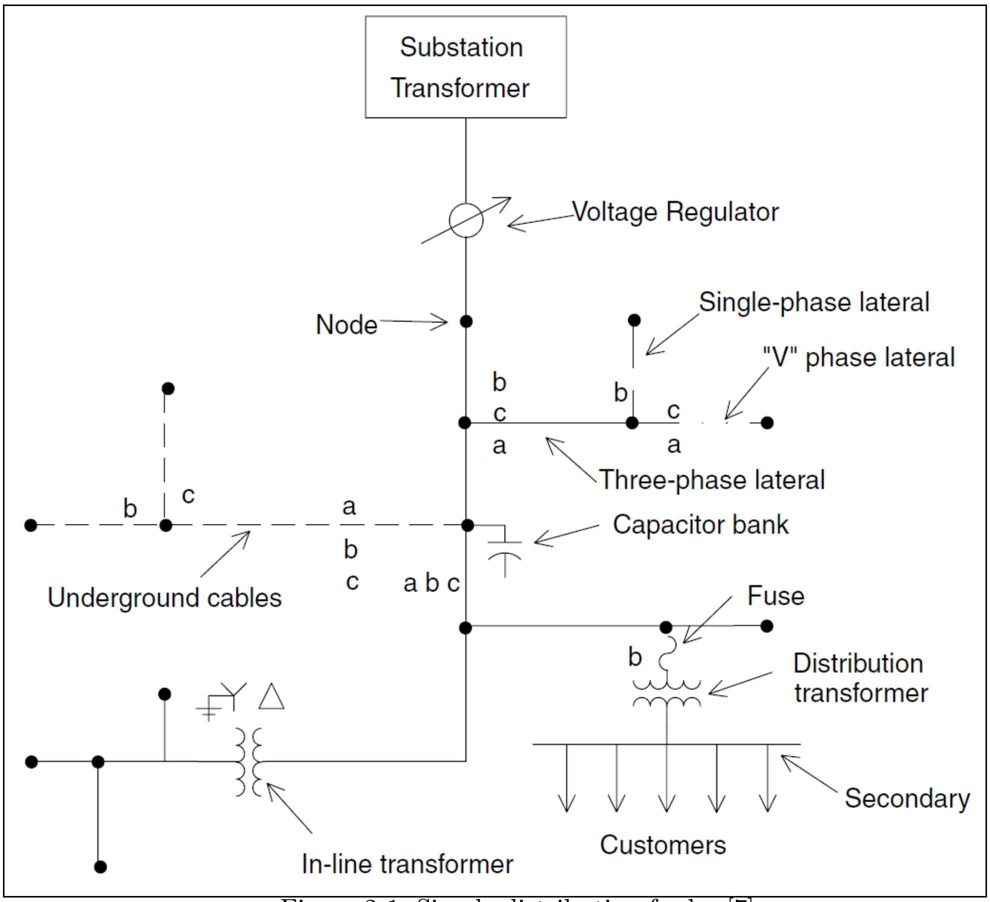

Figure 2-1: Simple distribution feeder [7]

2.2 Modelling distribution networks

To model distribution networks, data including the topology of the network and electrical characteristics of the objects in the network are needed. Topology refers to where the objects of the network are placed and how they are connected to each other. Details like distance, phasing, conductor size and ratings are also usually included in the topology. Electrical characteristics describe the impedances, turn ratios of the transformer and other parameters necessary to analyse the network.

It is often hard to collect exact network data on topology and electrical characteristic of LV distribution network. Changes are done relatively frequently to the topology and some values belonging to the electrical characteristics or used to find them, like mutual inductance and ground resistivity, are greatly approximated or do not exist.

It is often necessary to simplify the network when it is modelled. Dependent on what is studied; different simplifications can be used to make the analysis faster and easier, without jeopardizing the results.

2.3 Voltage control in the distribution network

In the HV and MV part of the distribution network the voltage is kept to the desired magnitude by capacitor banks in-line transformers, voltage regulators and the substation transformers. The substation transformers are usually on-load-tap-changer (OLTC) transformers. These components keep the voltages at the distribution transformer close to the nominal voltage. Some variation can still be expected, but this variation is quite small. According to Hafslund it is approximately 0.02 pu voltage variation with the change in load according to Hafslund.

The distribution transformer is a manual tap-changer transformer. The tap position is set so that the voltage at the LV side is 240 V. Permissible range of the supply voltage[2] is in Norway set to be ∓10% of 230 V. 230 V is the nominal r.m.s voltage in the LV distribution network with an IT configuration. The voltage is set to be above the nominal voltage in order to mitigate the voltage drop from the transformer terminal over the transmission lines to the supply terminal. This method is based on unidirectional power flow from the distribution transformer to the supply terminal. The voltage will decrease as you go further from the distribution transformer and the impedance; the current has to traverse to supply power, increases. This makes the supply terminal furthest from the transformer the critical terminal. This is where undervoltage can be expected to appear in weak or high impedance networks. With the introduction of DG into the LV distribution network, bidirectional power flow will occur when the generation is larger than the consumption or the loading of the network [8]. This is further explained in chapter 3. When the penetration of DG is so high that the power flow changes from entering to exiting the LV distribution network there is risk of overvoltage. For there to be a flow of power the starting point need to have a voltage larger than the end point voltage and the voltage

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[2] R.m.s value of the voltage at a given time at the supply terminal, measured over a given interval.

drop over the line combined. Since the voltage at the transformer is close to constant the voltage at the supply terminals will experience the voltage rise. The same supply terminals that are in danger of low voltages when the power flows into the feeder is subject to overvoltage when the flow changes direction. Due to the risk of undervoltage if the tap position of the distribution transformer is changed, different solutions are needed to ensure that the voltage is kept inside the permissible range even with bidirectional power flow. Lowering the impedance of the lines, and thereby the voltage drop, would work in most cases, but is expensive and require extensive work on the network. Limiting the DG capacity per feeder could also ensure voltages inside the permissible voltage band. However, this does not comply with current convention of facilitating for the increase of renewable and emission free power like PV. Using reactive power to regulate the voltage, at least for PV generation, seems to be the preferred way according to standards like VDE-AR-N 4105 on requirements of PV connected to the LV distribution network. The PV system can increase the consumption of reactive power acting as an inductive load. Since most networks are inductive and so are the loads representing house consumption, an increasing in the reactive load of a network will decrease the voltage. [6]

The effect of active or reactive power compensation on the voltage can be determined by a sensitivity analysis. Using the Newton-Raphson method on the two nonlinear load flow equations, Equation 2-1 and Equation 2-2, S_{UP} and S_{UQ} sensitivity matrix in Equation 2-3 can be calculated. It can also be found by manually changing the active and reactive power at the busses and divide the change in voltage over the change in reactive or active power. An important thing to take into consideration is that the sensitivity matrix will change with different loading. In a real network the loading is always changing. Therefore it is limited what one sensitivity matrix can tell us about the real time voltage change in a network.

$$P_i = |V_i| \sum_{j=1}^{n} |V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad \text{Equation 2-1}$$

$$Q_i = |V_i| \sum_{j=1}^{n} |V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad \text{Equation 2-2}$$

$$\begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{UP} & S_{UQ} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad \text{Equation 2-3}$$

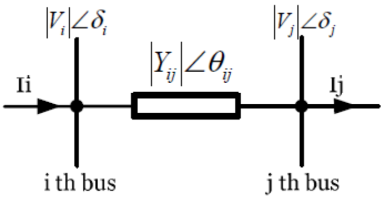

Figure 2-2: Load flow solution.

From the power flow equations one can also see that the voltage sensitivity to active vs. reactive power is heavily influenced by the X/R ratio of the network in question. A highly resistive network will be more susceptible to voltage change from active power than reactive power. For network with high reactance the opposite is true. This is important to take into consideration when planning voltage control with reactive power for a network with DG. A network with high X/R ratio will need less reactive power to mitigate the voltage increase caused by active power feed to the network by DG, and more if the X/R ratio is low. [5]

3 PV system

3.1 Introduction

Production of solar energy can be divided into three system groups:

- Centralized generation
- Distributed generation
- Generation not connected to the grid

PV systems not connected to the grid are the most common ones in Norway today. Examples are cabins, lighthouses and telecommunication systems not connected to the grid, utilizing solar panels and batteries as a simple power supply. Centralized PV systems are large solar parks that feed power to the grid. Centralized PV systems may have capacity of several megawatts.

Distributed grid connected generation is the system group with the most potential in Norway in the in the immediate future. Countries all over Europe, with Germany as the forerunner, have had large growth of distributed PV generation. This is largely caused by financial incentives for photovoltaics like feed-in tariff, investment subsidies and net metering. Distributed PV can come in many shapes and forms, from simple rooftop PV systems installed on houses to larger installations in fields. All that is needed from a prosumers, see chapter 3.2, perspective is the PV system and metering device. The metering device measures how much power the home uses and any excess power the PV system feeds to the grid, see Figure 3-1. The PV systems consist of solar panels or PV modules that convert sunlight into direct current (DC) and an inverter that converts the DC into alternating current (AC). This alternating current is ready either for direct use or to be feed to the grid. It is the excess or surplus power feed to the grid that creates bidirectional power flow in the grid. This change, from pure load to a power source, creates potential overvoltage problems, especially in the LV distribution network. The DSOs responsibility is to maintain the voltage at point of common coupling (PCC) between the grid and the household also called the supply terminal. In Figure 3-1 it is the “Digital time of use consumption meter”. The voltage must be maintained inside the admissible voltage range. As mentioned in Chapter 2.3, reactive power control is the preferred method for voltage support.

A more and more used tool for mitigating the increase in voltage caused by distributed PV is the inverter. Modern inverters, as well as inverting DC to AC, are able to generate or consume reactive power when the output current of the PV system is lower than the rated output current of the inverter.

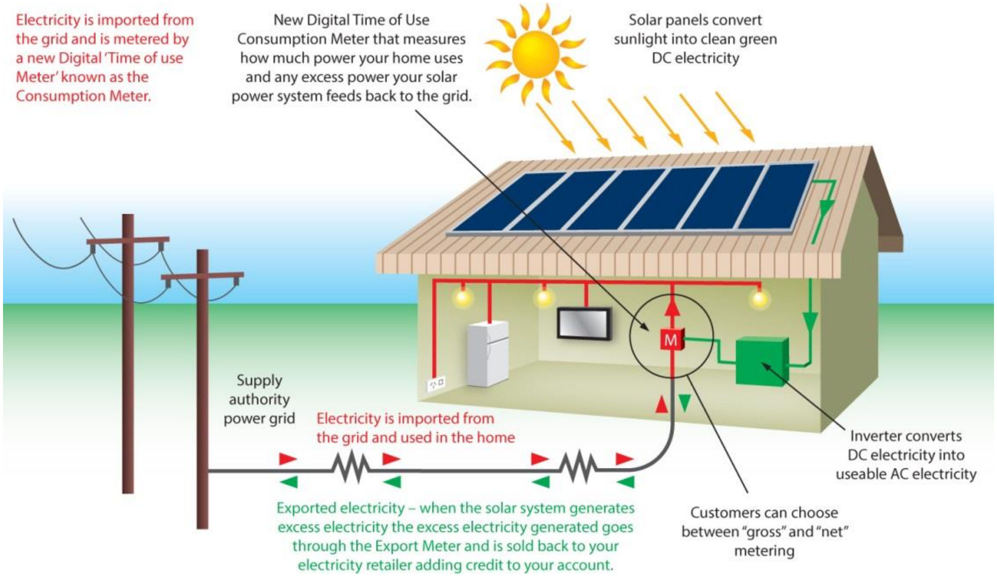

Figure 3-1: Flowchart for a typical grid connected PV system.

3.2 Prosumer

When a household generate more energy than they consume, the possibility of delivering energy to the grid opens up. When a customer choses to feed surplus energy to the grid, the customer becomes a prosumer. NVE, "Norges Vassdrags- og Energidirektorat", defines prosumers as:

> *"A prosumer is an end user of electric energy with an annual production which normally does not exceed their consumption, but in some operating hours have a surplus of power which can be fed into the distribution network."*

To facilitate for these kinds of transactions, Norwegian regulation states that grid companies with an agreement with the prosumer, which is voluntary for both parties, buy this surplus of energy fed to the grid. The prosumer is only billed a transmission fee for the amount of energy fed to the grid and not for the amount generated. Transmission fee and connection cost is decided by the grid company. As to requirements for power quality and security the system operators are responsible for setting the necessary demands to secure that their networks are in line with the requirements laid down in the governing laws and regulations. [9]

3.3 Regulations regarding grid connected PV and voltage support under steady state conditions

PV systems and its inverter were traditionally designed to produce as much active power as possible from the solar panels at a unity power factor, PF=cos($\varphi = 0°$)=1, and feed to the PCC. As the grid operators experienced higher and higher penetration of decentralized or distributed PV generation, the cumulative installed PV power started to adversely affect the grid. To maintain the stability and power quality specified by grid codes, regulations for grid connected PV systems have been added to existing standards or been developed specifically for grid connected PV systems. The distributed generation interconnection standards that target PV systems in the LV distribution network are VDE-AR-N 4105, IEEE 1547 and IEC 617272.

It has become common practice to require that grid connected PV systems are dimensioned so that the power delivered from the PV system can have a leading and lagging PF that can be used for voltage support. Generally over 95% of the time a PV inverter is running below its rated output current when converting DC solar power to AC active power, this required PF capability does not greatly affect normal operation. In other words, the PV system can deliver the necessary reactive power, decided by the PF, without having to limit the active power production most of the time. The rest of the time, limiting the power generated by the PV modules or over dimensioning the inverter will ensure that the required voltage support is satisfied. The size of the PF and how it is utilized differs based on which standard is used and the capacity of the PV system.

A PQ characteristic of a PV inverter with lagging PF is showed in Figure 3-2. P_{PV} and Q_{PV} is the active power delivered to or absorbed from the grid. Q_{PV} is negative in Figure 3-2, meaning that the reactive power is absorbed from the grid. For PV connected to the LV distribution network usually a lagging PF is requested. With a lagging PF the PV system work as an inductive load and consumes reactive power as seen in Figure 3-2.

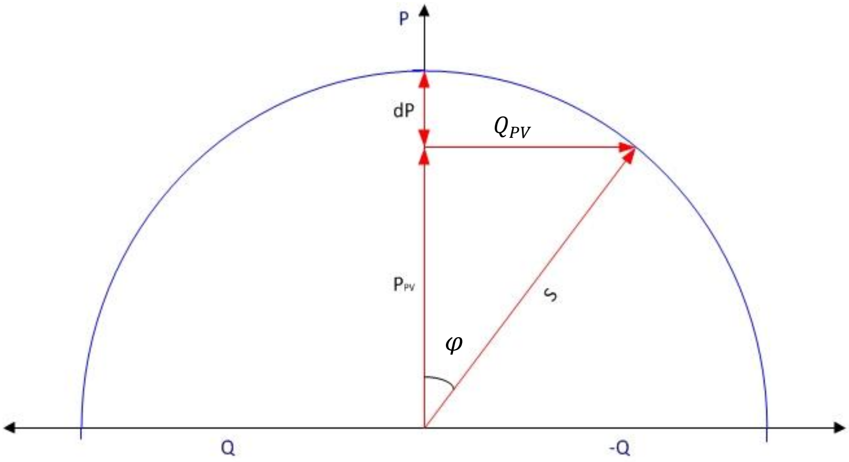

Figure 3-2: PQ characteristic of an inverter with lagging PF.

Under normal operating conditions and during steady state the standard requirements for voltage support differ to some degree. IEEE 1547 state that no active voltage regulation of any kind can be performed and the network voltage of the system should not be adversely affected. IEC 617272 require of the PV system a lagging power factor greater than 0.9 when the output is greater than 50% of the rated power [10]. VDE-AR-N 4105 require voltage support if the DSO requests it. The reactive power capabilities can be seen in Table 3-1. VDE also state that the maximum permissible voltage change, the difference in terms of voltage between the system with and without DG, is 3%. [11, 12]

Table 3-1 show the voltage support methods required based on the power rating of the PV system. Constant PF and PF characteristic or PF(P_{PV}) is two of the four voltage support strategies explained in 4 Inverter modes for voltage and tested in this thesis.

Table 3-1: VDE-AR-N 4105 reactive power capability limits. [11]

Rated power of the PV system	PF range
$S_{max} \leq 3.68\ kVA$	Constant PF 0.95 capacitive (leading) to 0.95 inductive (lagging)
$3.68\ kVA < S_{max} \leq 13.8\ kVA$	PF characteristic 0.95 capacitive to 0.95 inductive
$S_{max} > 13.8\ kVA$	PF characteristic 0.90 capacitive to 0.90 inductive

4 Inverter modes for voltage support

4.1 Introduction

There are two methods the inverter can affect the voltage in the grid and contribute with voltage support:

- Limit the active power generated by the PV system.
- Absorbing reactive power from the grid.

These methods are used in different strategy to mitigate the voltage increase from DG. The strategies used in this thesis can be defined using either a constant value or a first order piecewise equation that can be easily implemented in the inverter controllers. The strategy implemented is decided by the inverter mode. The equations are graphically presented in Figure 4-1. [5, 13-15]

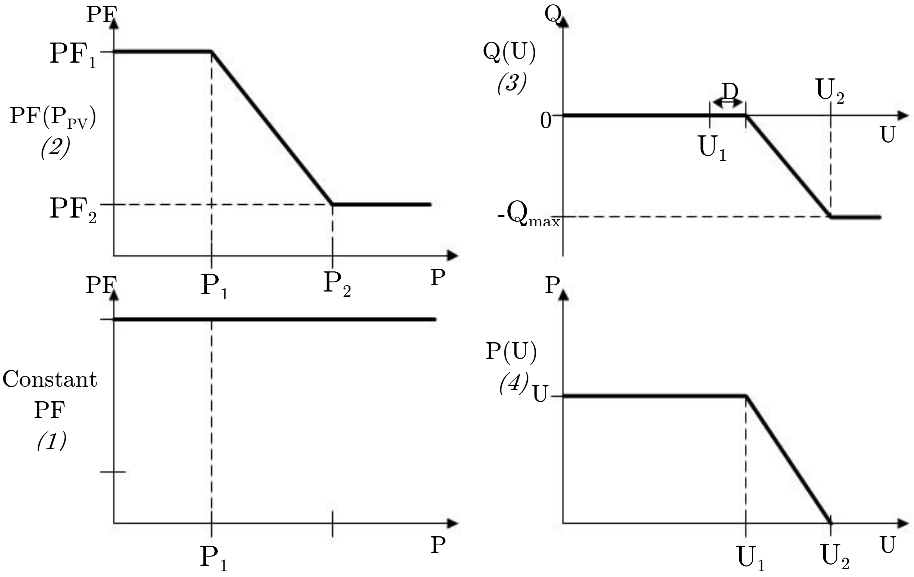

Figure 4-1: Voltage support strategy Constant PF *(1)*, PF(P_{PV}) *(2)*, Q(U) *(3)* and P(U) *(4)*.

4.2 Strategy 1: Constant PF

The constant PF or constant $\cos(\varphi)$ strategy leads to the PV inverter consuming or generating reactive power proportional to the active power generated by the PV modules (see Equation 4-3). This is inherently enabled as long as active power is produced. To mitigate the voltage increase from DG a lagging PF is used in order for the PV inverter to consume reactive power. A smaller PF means a larger part of the apparent power is reactive power, see Figure 4-2. In Figure 4-2, the blue line represent the rated apparent of the inverter, S_i. P_m is the power produced by PV modules or solar cells. The PF that the inverter can operate with is P_m dividing by S_i, Equation 4-1. By dimensioning the PV system so that the rated power of the inverter S_i is larger than the rated power of the solar modules, the constant PF strategy will not inhibit the PV systems active power production capability.

$$\mathrm{PF} = \cos(\varphi) = \frac{P}{S} \qquad \text{Equation 4-1}$$

$$\tan(\varphi) = \frac{Q}{P} \qquad \text{Equation 4-2}$$

$$Q = \tan(\cos^{-1}(PF)) * P_{PV} \qquad \text{Equation 4-3}$$

This strategy is a passive control strategy. It does not react to changes in the network and is only dependent on the power production of the PV system. The risk of overvoltage is smaller when the production is low, as a bigger portion of the power is consumed locally and less is transferred to the MV network. Even if the reactive power consumed by the inverter reduces with the decrease in active power production, it might not be need at all if the voltage is not in danger of exceeding the limit.

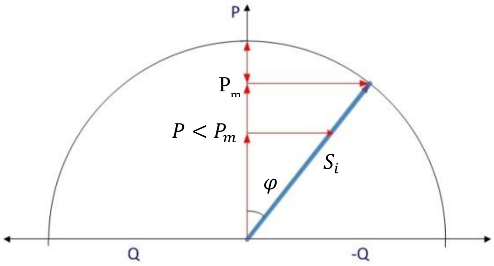

Figure 4-2: PQ graph of inverter using constant PF strategy.

4.3 Strategy 2: PF dependent on PV power production, PF(P_{PV})

PF dependent on PV power production is still a passive control strategy, but have more flexibility than the constant PF strategy.

The PF characteristic, PF(P_{PV}) in Figure 4-1 *(2)* given by Equation 4-4, is used to decide the PF for strategy 2 and can be modified specifically for a network. The goal is still to keep the voltage inside the permissible range, with the minimum additional losses occurring in the process. The key parameters in achieving this are:

- PF_1 and PF_2, which decide the PF band in which the inverter operates.
- P_1 and P_2, that decides at which active power band the PF droop initiate and ends.

PF_1 is the highest PF and is used when there is no risk of overvoltage. It is usually set to unity power factor[3]. PF_2 is the lowest PF the PV system is designed to operate with. Standards on grid connected PV indicate that the common consensus for LV distribution networks is a PF_2=0.9. This value can also be varied based on the sensitivity matrix to ensure less unnecessary reactive power consumption. P_1 is the active power produced by the PV system at the point where the PF droop initiates. When the PV system produces less than P_1 there should not be risk of overvoltage and the power produced will have PF_1. P_2 is the nominal power of the PV system. P_{PV} is the active power produced by the PV system.

$$PF(P_{PV}) = \begin{cases} PF_1, & P_{PV} < P_1 \\ \dfrac{PF_1 - PF_2}{P_1 - P_2}(P_{PV} - P_1) + PF_1, & P_1 \leq P_{PV} \leq P_2 \\ PF_2, & P_{PV} > P_2 \end{cases} \qquad \text{Equation 4-4}$$

4.4 Strategy 3: Reactive power consumption dependent on the voltage, Q(U)

Strategy 3 is an active voltage support strategy. The strategies given so fare support the grid voltage indirectly or passively and they work by assuming that the grid voltage increases with the PV systems real power production. This is proven not to be correct as it is the power fed into the grid that causes the voltage increase. The power fed to the grid is equal the power consumed by the house subtracted from the PV production. Consequently, if the consumption is high, very little or no power is fed to the grid, but the voltage support is still unchanged. If high irradiance levels coincide

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[3] Unity power factor means that all the apparent power is active power, PF=1.

with high power demand, the reactive consumption of the PV inverter will be high without a real need to regulate the voltages. Using strategy 3, the reactive power consumption is directly controlled by the local voltage at the PCC and the total reactive power consumption by the inverter can be considerably reduced. This strategy however does provide weaker voltage support compared with the strategies above. Weaker as in the reactive power contribution from the PV inverters close to the transformer will be negligible since the measured voltage at these inverters will be lower. The critical houses at the end of the network could experience voltages over the limit without any reactive power consumption from the inverters closer to the transformer.

Equation 4-5 describes the reactive power consumed by the PV inverter based on U, which is the voltage at the PCC. U_n is the nominal voltage and U_2 is the voltage at which maximum reactive power compensation is performed. D is the dead band around nominal voltage where no voltage support is performed.

$$Q(U) = \begin{cases} 0, & U < U_n + D \\ \dfrac{Q_{max}}{U_2 - U_n - D}(U - U_n - D), & U_n + D \leq U \leq U_2 \\ Q_{max}, & U > U_2 \end{cases} \quad \text{Equation 4-5}$$

Q_{max} is the maximum reactive power the PV inverter can compensate. It is a function, see Equation 4-6, of the instantaneous PV power production (P_{PV}) and the inverters PF limit (PF_{lim}).

$$Q_{max} = P_{PV} * \tan(\cos^{-1}(PF_{lim})) \quad \text{Equation 4-6}$$

To increase the reactive power consumed by a PV inverter using strategy 3, one has to reduce the dead band and/or reduce the PF limit. Reducing the dead band will make voltage support start at lower voltages levels. Making the PF limit more lagging will increase the maximum reactive power that the inverter can consume and make the droop steeper between $U_n + D \leq U \leq U_2$. P_2 is the rated power of the PV system.

4.5 Strategy 4: Droop based power curtailment, P(U)

Overvoltage caused by the PV systems can be avoided by limiting the maximum installed capacity PV in the LV distribution feeder. This strategy is counterproductive to the goal of increasing the penetration of PV. The same can be said for limiting the power generated from the PV system based on the voltage at the PCC, P(U). This strategy does not directly limit the PV capacity of a network, but limiting the PV systems production reduces the revenue. This makes the investment less profitable and will inhibit the growth of PV penetration. Power curtailment is usually used for frequency support rather than voltage support. [16]

P(U) is droop based active power curtailment. The droop can be described with Equation 4-7.

$$P = \begin{cases} P_{PV}, & U < U_{lp} \\ P_{PV} - P_{PV} * \dfrac{U - U_{hp}}{U_{hp} - U_{lp}}, & U \geq U_{lp} \end{cases} \qquad \text{Equation 4-7}$$

P: The active power delivered to PCC.
P_{PV}: The power generated by the PV system.
V: Phase to phase voltage at the load terminal.
V_{hp}: Voltage at disconnection point.
V_{lp}: Voltage at power reduction poin

This strategy has the same strength and weaknesses as strategy 3 in that the inverter uses the voltage at PCC which has little change close to the transformer despite overvoltage in the end of the network.

5 Method

5.1 Introduction

All simulations are done with the use of Simulink, a simulation tool running in Matlab. The network is modeled using three-phase PI section lines, three-phase busses, a three-phase source block and three-phase IT loads. All the blocks are found in the Simulink library, except the three-phase loads. The loads are designed by the author and simulate a house with grid connected PV using the different inverter modes or strategies listed in chapter 4. Phasor simulation method in Simulink is used to compute the complex bus voltages and currents.

5.2 Simulation Tool – GridBuilder

LV distribution networks are usually quite complex with many different line segments, branches and loads. To manually design them in Simulink is both time consuming and prone to human error. Manually changing the network, like changing the line parameters or the loads, is also inconvenient when the number of lines and loads are high. “GridBuilder” is a Matlab function developed by the author, which models LV networks in Simulink. The input data is an excel document with different worksheets describing the bus coordinates, lines and loads (see appendix A.1). This function makes it possible to quickly design and test a number of different LV distribution networks and find one that meet the criteria’s listed in 1.3 Research Method. Changes in the network are also easily implemented by altering the Excel documents.

The program consists of a main function called “GridBuilder.m” and six other sub functions. Figure 5-1 shows order in which the sub functions run by the main function and how they interact with the Excel documents containing the network data. The sub functions do what their names indicate. “Bus placement.m” places the three-phase busses in Simulink according to the bus coordinates provided by the Excel file “Bus coordinates.xlsx”. It also gives unique name to the signal label for the voltage and current at the bus, making these values available with the “From” block found in the Simulink library. “Line placement.m” places the three-phase PI section lines between the busses in Simulink using the Excel file “Lines.xlsx” that describe which buses are connected and what type of line it is. “Connect Bus Line.m” connects the three-phase PI section lines and three-phase busses also using “Lines.xlsx”. “Load placement.m” and “Connect Bus Load.m” places the loads in Simulink and connect them to the rightiec bus given by “Loads.xlsx”.. “ParamAss.m” assigns the parameters to the three-phase PI section lines in the Simulink model using “Line Codes.xlsx”.

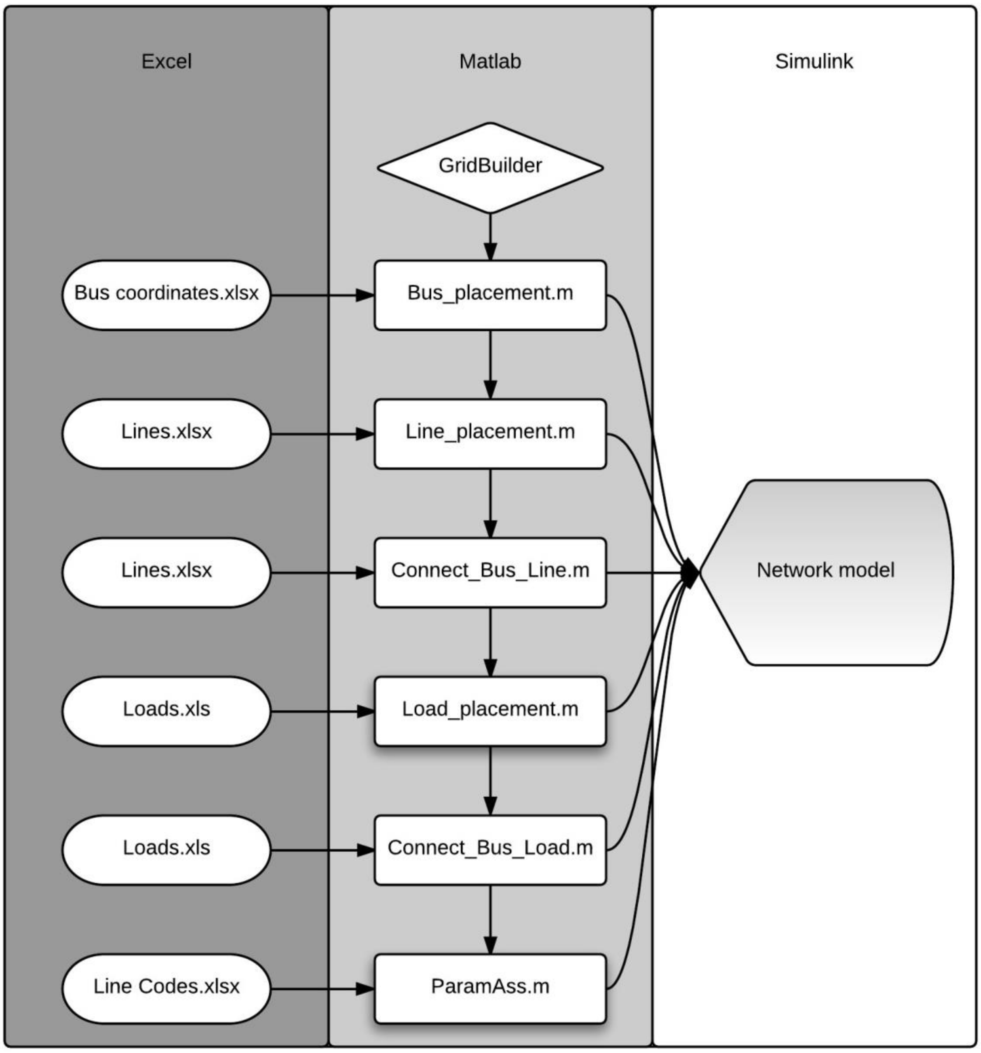

Figure 5-1: Flow chart for the Matlab function GridBuilder.m.

Modeling networks in Simulink is also beneficial in other ways. Many other programs used to simulate and study networks, like RTDS and opal RT.dspace, can use the Simulink model to model the network in their software.

5.3 Simulink model of the load

There is no object in the Simulink library that can use a load profiles from workspace to emulate a residence in a LV distribution network. Therefor it was necessary to make the three-phase IT load shown in Figure 5-2. It calculates the phase current peak value, I_{pk}, from the peak value of the voltage, U_{pk}, and the phase load, S_{phase}, provided by the load profiles using Equation 5-2, which is derived from Equation 5-1. The active power contribution from the PV system is subtracted from P, which represent the active power of the load. The reactive power consumption of the PV inverter is added to Q, the reactive power part of the load. This makes it so that the inverter is 3-phase delta connected.

$$S_{phase} = \frac{1}{2} * U_{pk} * I_{pk}{}^{*} \qquad \text{Equation 5-1}$$

$$I_{pk} = \left(2 * \frac{S_{phase}}{U_{pk}}\right)^{*} \qquad \text{Equation 5-2}$$

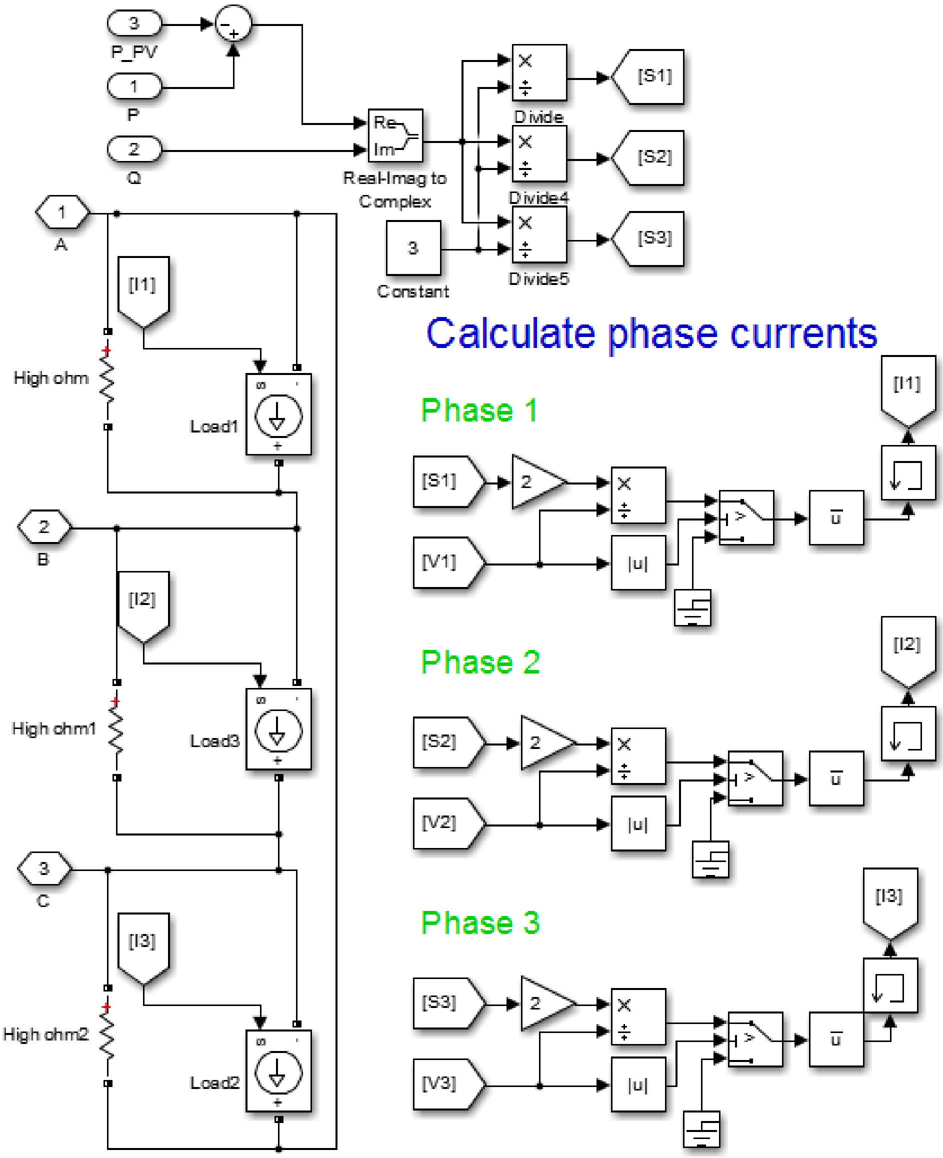

Figure 5-2: Simulink model of three-phase IT load.

5.4 Measurements

The measurements used in this thesis are taken by Three-Phase VI measurement blocks, found in the Simulink library, that are inserted as the busses in the models created by GridBuilder. All the loads and the transformer will have busses between them and the network and it is from these measurements are collected. Measurements from the “Three-Phase VI measurement” block or the busses are complex value matrix of the peak currents in the 3-phases,

$\left[\hat{I}_a, \hat{I}_b\ ,\hat{I}_c\right]$, and peak phase-to-phase complex value matrix of the 3-phase voltages, $\left[\hat{V}_{ab}, V_{bc}\ ,\hat{V}_{ca}\right]$, at each time step of the simulation. It is also possible to get the peak phase-to-ground complex value, but as the IT network was chosen for this thesis there is no neutral line the phase-to-phase measurement was chosen.

With the delta configuration of the loading Figure 5-2, the current measurement from the Three-Phase VI measurement block does not equal the current going through the loads. With the assumptions of balanced loading and perfectly transposed network the current through the load can be calculated from the measured current divided by the square root of three and multiplying with a 30 degree angle phasor, see Figure 5-3.

Measurements from busses that connect the loads and the transformer to the LV distribution network are used to display the voltage change with the different strategies mentioned in chapter 4 Inverter modes for voltage . Power flow through the transformer will also be calculated using Equation 5-2. The base voltage is set to 230 V and the voltage is represented in per unit (pu) values in the graphs. Reactive power efforts and power loss is also studied. Signe convention for the power flow used in this thesis is that a positive power flow indicates power flowing into the LV distribution and a negative power flow is the power flowing out of the LV distribution system.

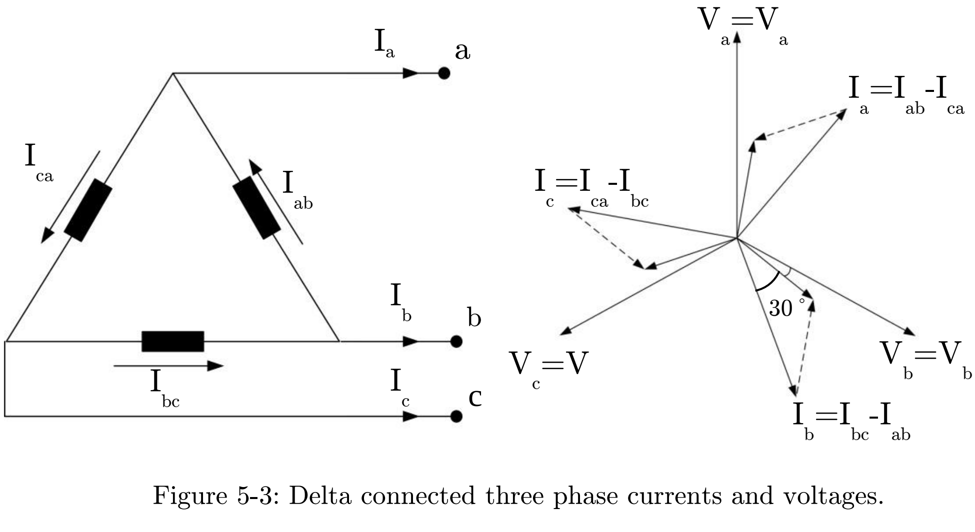

Figure 5-3: Delta connected three phase currents and voltages.

6 Case study

6.1 Introduction

This chapter describes the case in which the different strategies are to be implemented and studied. The case includes a LV distribution network, load profiles and irradiance data. As mentioned in chapter 1.3, the LV distribution network should operate inside the admissible voltage band of 1.1 to 0.9 pu without PV, and outside the band when high level of PV is introduced.

6.2 LV distribution network

The LV distribution network used in this thesis is the "IEEE European Low Voltage Test Feeder" [17]. The described purpose of "IEEE European Low Voltage Test Feeder" is to provide a benchmark for researchers who want to study low voltage feeders common in Europe, and their mid- to long-term dynamic behaviours. This complies well with the goal of this thesis.

To have the network complying with the assumptions and limitations of this thesis as well as simulations running without problems in Simulink, some changes and simplifications where done to the network:

- The transformer was changed from 11kV/400V to 11kV/240V, and the transformer and overlaying MV distribution network was simulated using a source block with parameters found in Appendix A.4.
- The 55 loads where changed from single phase to 3-phase IT loads, see Figure 5-2.
- Number of line segments where reduced where possible without effecting the topology of the network. Number of line segments where brought from 905 to 152[18].

The layout of "IEEE European Low Voltage Test Feeder" is shown in Figure 6-1. "N.1" is the critical load with the highest short-circuits impedance and therefor also the load in the greatest risk of experiencing voltages outside of the permissible voltage band. "N.2" is the load closest to the transformer.

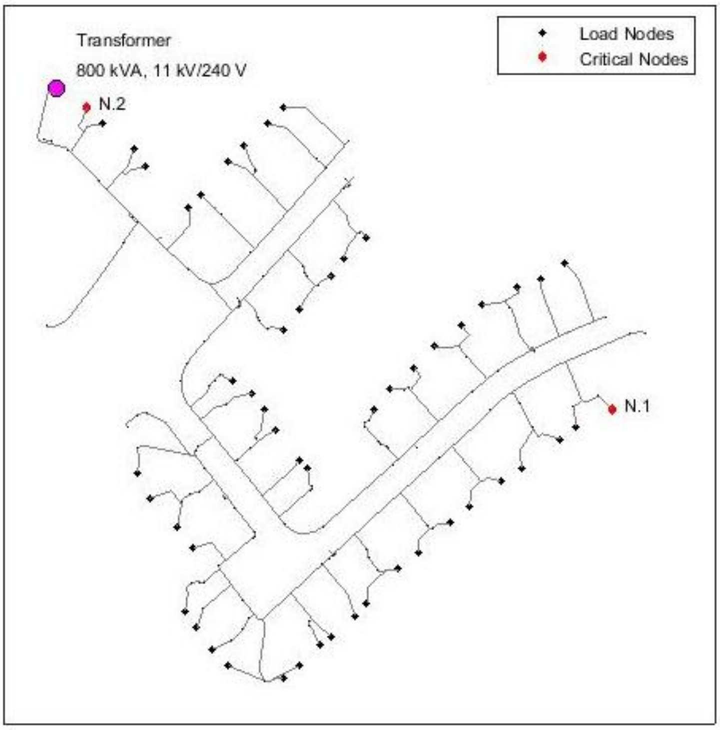

Figure 6-1: The layout of "IEEE European Low Voltage Test Feeder".

6.3 Load profiles

The load profiles are also from IEEE and belong to the Distribution network "IEEE European Low Voltage Test Feeder" [17]. They describe the active load each minute for 24 hours. The reactive load is calculated by using a PF=0.95 on the active load profiles. Even if this is not the case in a real network, it will not have a big impact on the study of the different inverter modes. Also the main contributors to reactive load in houses usually contribute to the active load as well, and some resemblance of proportionality is true for a real network. Figure 6-2 show the sum of the reactive power and the active power of the 55 load profiles chosen for this thesis.

It is mentioned in the description of the load profiles that a multiplier value can be used to dimension the loads. To create a scenario where the network experience overvoltage when PV is introduced, the multiplier value 1 was chosen.

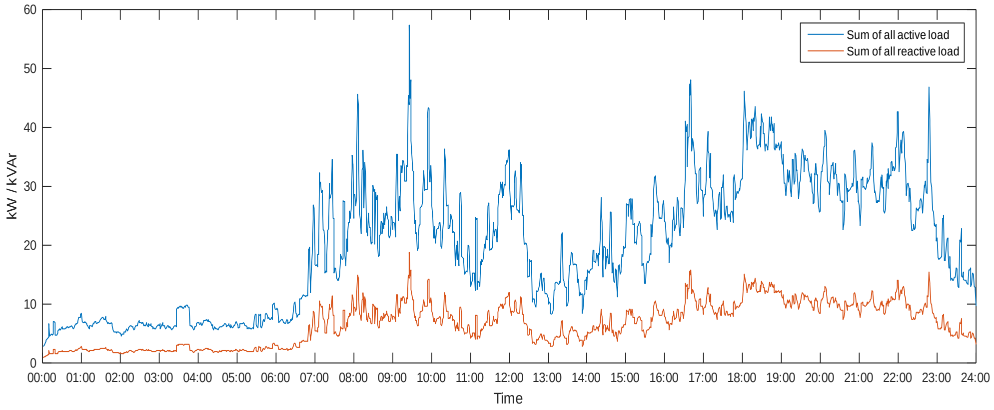

Figure 6-2: The sum of all active and reactive loads in "IEEE European Low Voltage Test Feeder"

6.4 Irradiance data

The irradiance data used was collected using a SMA Sensorbox and found at SunnyPortal [18]. The irradiance was measured 4.mai 2016 in Oslo and the 15-minute measurements where interpolated to coincide with the load profiles 1-minute data.

Figure 6-3 show the active power delivered to the network by the PV system, with a PV cell area of 15 m^2, PV cell efficiency of 0.15 and inverter efficiency of 0.9, experiencing the irradiance measured by the SMA Sensorbox on 4.mai 2016. The PV system is assumed to be dimensioned in such a way that it can operate with a PF=0.9 leading and lagging without decreasing the active power shown in Figure 6-3. Maximum generation is 1.4742 kW at 13:00. The sun rises is at 06:00 and set at 22:15.

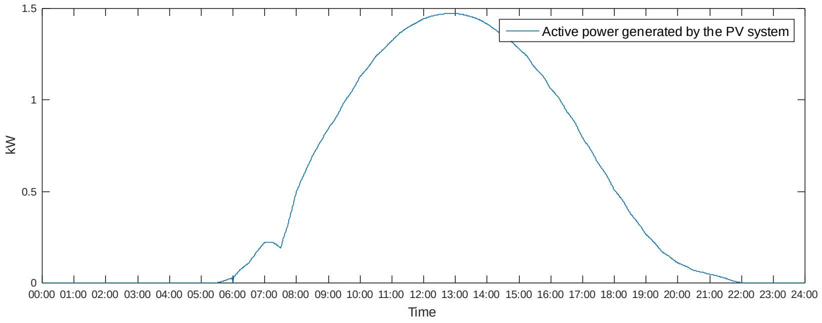

Figure 6-3: Active power from PV system.

6.5 Network simulation without PV

The voltages at the critical busses N.1 and N.2 keep inside the admissible range of 1.1-0.9 pu. The power flow through the transformer is unidirectional, in that the power only flows into the LV distribution network. The voltage is seen to fluctuate with the loading of the network, but is never higher than 1.04 pu, the voltage at the transformer. This is expected as there is no generation of power constituting for bi directional power flow in the network. All the loads are supplied with power from the transformer and the overlying grid. There is no risk of over voltage and loading of the network would have to be much higher for under voltage to occur. Minimum voltage is in N.1 at 09:28 and is 0.9602 pu or 220.8 V. The network is easily able to handle the loading presented by the load profiles. Losses are 8.14 kVAh for the time period simulated.

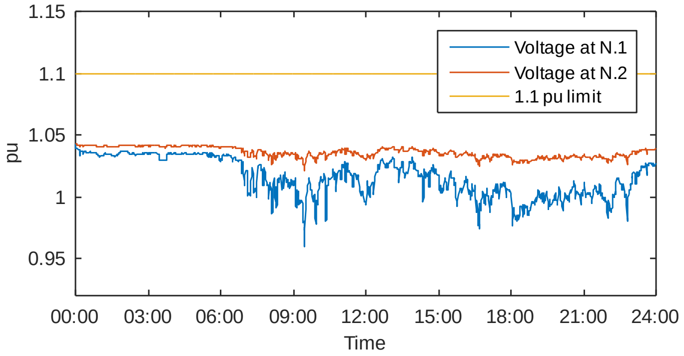

Figure 6-4: Voltage in N.1 and N.2, without PV.

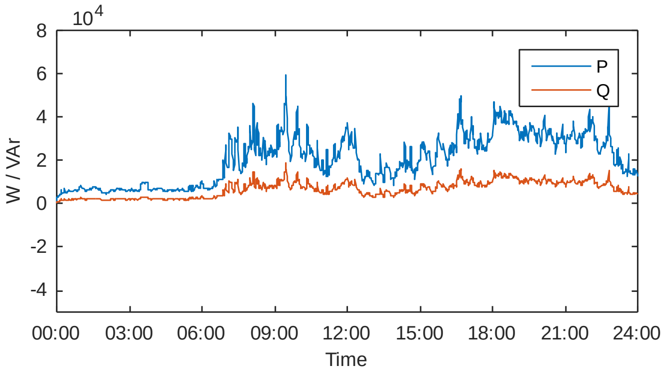

Figure 6-5: Power flow through transformer, without PV.

6.6 Network simulation with PV and no voltage support

When PV is introduced to every load without any form of voltage support the network no longer operates in the admissible voltage band set by Fol and VDE 0.9 to 1.1 pu. 06:00 is when the PV systems start generating power and the voltage starts rising compared with the network without PV. For the given loading conditions, 10:57 is the earliest that the network experience over voltage and the latest is 14:51 making this the critical time interval. The voltage at N.1 exceeds 1.1 pu 72 % of the time in this interval or 171 minutes. The time of first overvoltage, the active power flow at the transformer is -55.139 kW where the negative sign imply power flow out of the LV distribution system. The highest voltage, 1.118 pu, occurring at 13:07 the same time as the maximum power is transferred out of the network.

The voltage is seen to be affected by the load profile of the different houses, but not much. The ratio of load and PV power generation lean heavily toward PV in the critical time interval. The PV power generation does not change with the location in the network as the load profiles does.

As the voltage at the critical busses are outside of the admissible range. The network is in need of voltage support. The reactive power flow through the transformer is seen to be positive, meaning that the network is consuming reactive power. To lower the voltage in the network through reactive power compensation, it is necessary to further increase the reactive consumption of the network. The PF chosen for the constant PF and $PV(P_{PV})$ need to be lagging.

Loss of the network is 12.44 kVAh for the time period simulated, a 4.30 kVAh increase from the simulation without PV. This increase is caused by the peak PV production hours is situated in the time interval of low loading of the network. The surplus power is substantial compared to the loading and the losses occur when the surplus power is transferred to the transformer.

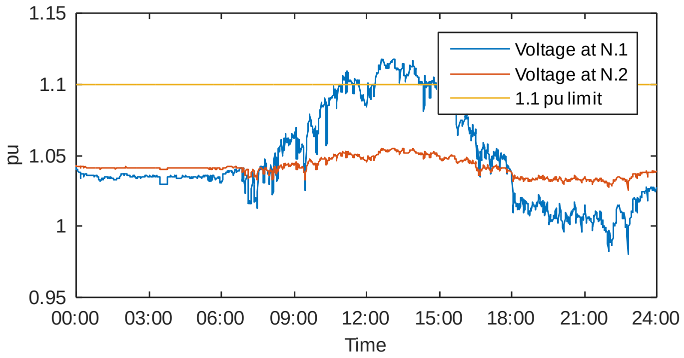

Figure 6-6: Voltage magnitude at N.1 and N.2, no voltage support.

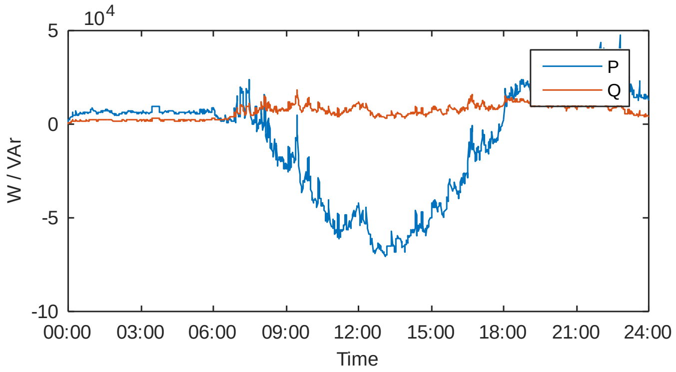

Figure 6-7: Power flow through transformer, no voltage support.

7 Results and Discussion

7.1 Results: Strategy 1

7.1.1 PF=0.95

Using the strategy 1 with a PF=0.95 solve the overvoltage problem seen from Network simulation with PV and no voltage . In N.1 the voltage is over 1.1 pu four times with the highest voltage being 1.1007 pu at 13:07. This is less than 0.1 % over the upper bound of the admissible voltage band and the voltage support is deemed a success. The reactive power consumption of the network is clearly increased compared with Network simulation with PV and no voltage . The PF used by the inverter is lagging 0.95, which equals a reactive power consumption of approximately 33 % of the active power produced by the PV system. The active and reactive power load of the network is shown in Figure 7-2. The increase in reactive power consumption starts at 06:00 and ends at 22:15, which is the time of sunrise and sunset. This is long before and after the critical time interval for overvoltage that was identified in Network simulation with PV and no voltage .

Total loss in the network is 16.72 kVAh, 4.28 kVAh more than Network simulation with PV and no voltage support. This increased loss stems from the additional reactive power flow forced by PV inverters voltage support effort.

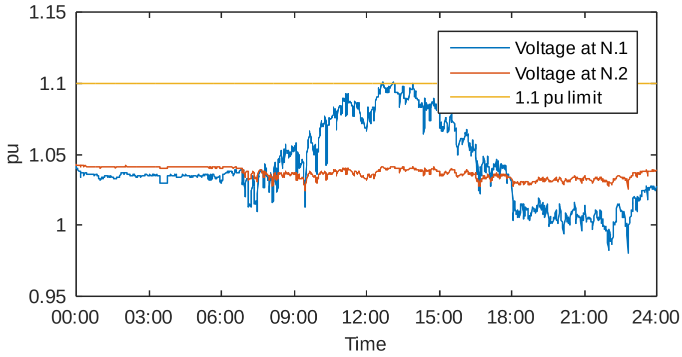

Figure 7-1: Voltage magnitude at N.1 and N.2, constant PF.

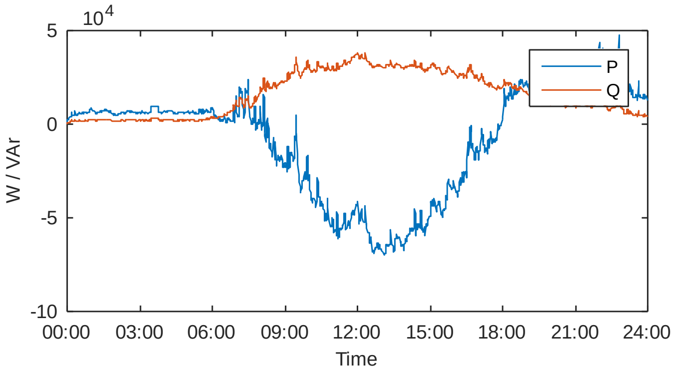

Figure 7-2: Power flow through transformer, constant PF.

7.2 Results: Strategy 2

7.2.1 $P(P_{PV})$, P_1=1kW, P2=1.5kW and PF_{lim}=0.95

The constant PF simulation showed that a PF of 0.95 is enough to prevent overvoltage in this network. With this knowledge the P_1, P_2 and PF_{lim} of the PF characteristic for the PV systems was chosen so that PF is close to 0.95 in the critical time interval for overvoltage. Using this PF characteristic resulted in the voltage seen in Figure 7-3 and the power flow through the transformer seen in Figure 7-4.

The voltage in N.1 exceeds 1.1 pu a total of 9 times with the largest voltage being 1.1009 in N.1. This is less than 0.1 % over the upper bound of the admissible voltage band and the voltage support is deemed a success.

Total loss is 14.71 kVAh, 2.01 kVAh less than with constant power factor. This is mainly contributed by less reactive power compensation when it is not needed for voltage control. Using this strategy reactive power consumption by the PV inverter does not happen if the PV production is less than 1 kW. In this simulation this means that unity power factor is used until 09:30 and is used again at 16:77, when generation by the PV systems is less than 1 kW. The PF is also gradually goes towards 0.95 as the PV production passes the 1 kW mark and close in on 1.5 kW. This can be seen by the less steep climb and droop in reactive power consumption by the network in Figure 7-4 compared with Figure 7-1.

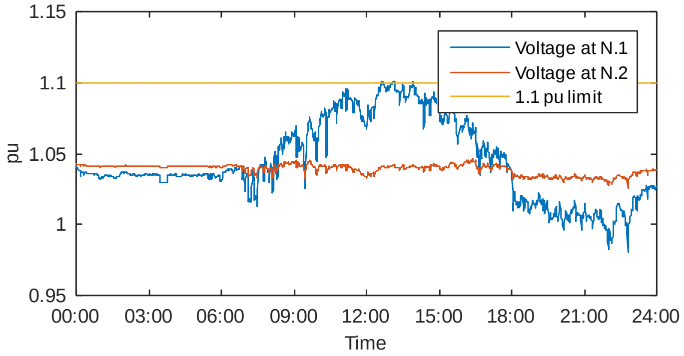

Figure 7-3: Voltage magnitude at N.1 and N.2, PF(P_{PV}).

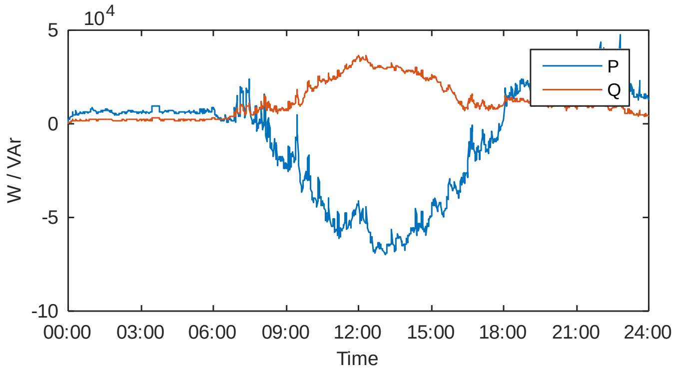

Figure 7-4: Power flow through transformer, PF(P_{PV}).

7.3 Results: Strategy 2

Since the voltage at the transformer is 240 V or 1.044 pu, the dead band (D) have a minimum value of 10 V or 0.044 pu for the PV inverters close to the transformer not to consume reactive power at all times. The voltage variations at the PV inverters close to the transformer are also very small, further complicating the problem. The only other parameter in strategy 3 that increase the mitigation of overvoltage, other than lowering the dead band, is the PF_{lim}.

7.3.1 Q(U): PF_{lim}=0,95 and D=0.044 pu

Highest voltage 1.1043 pu, number of times over 1.1 pu is 29 N.1. With voltage in N.1 exceeding the upper bound of the admissible voltage band, the voltage support is deemed unsuccessful. In Figure 7-5, the voltage at the house closest to the transformer is shown to not go above 1.0462 pu. The lowest PF used the PV inverter in this house is therefore 0.996, which means very little reactive power consumed compared to N.1 that around 13:00 has several minutes where the PF=PF$_{\text{lim}}$. To keep the voltage under 1.1 pu with the Q(U) method it is necessary to either have the PV inverters close to transformer contribute more, or the PF$_{\text{lim}}$ must be dropped to allow higher maximum reactive power consumption by the inverters in the end of the network. For reasons explained above and seen in Figure 7-5, it is difficult to increase the voltage support provided by the PV inverters close to the transformer with this strategy when it uses the voltage at PCC as reference.

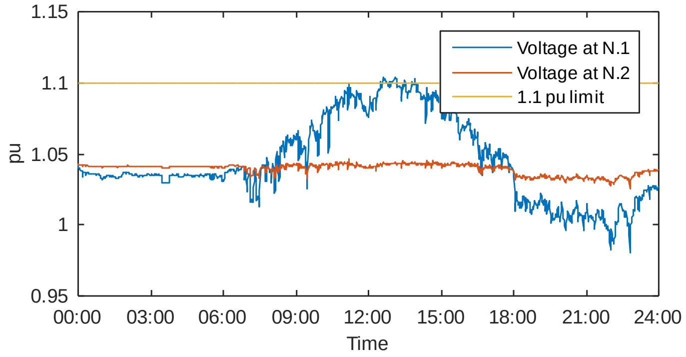

Figure 7-5: Voltage magnitude at N.1 and N.2, Q(U) with PF$_{\text{lim}}$=0,95 and D=0.043 pu.

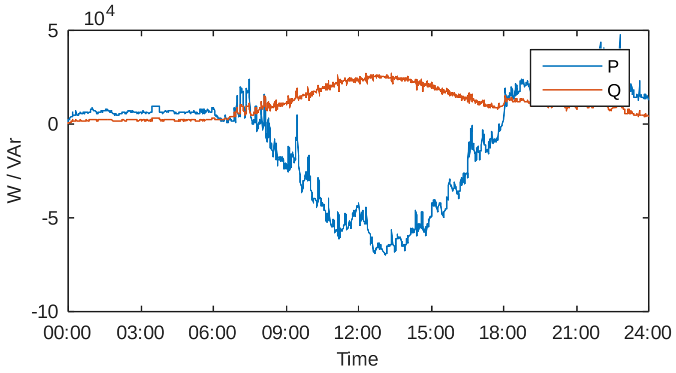

Figure 7-6: Power flow through transformer, Q(U) with PF$_{\text{lim}}$=0,95 and D=0.043 pu.

7.3.1 Q(U): PF$_{\text{lim}}$=0,9 and D=10 V

Setting the PF limit to 0.9 enable all the PV inverters in the network to potentially contribute more to the voltage support. The lowest PF used by N.1 is 0.9002 at 12:37 barely over the PF limit. That the PF in N.1 never go below the PF limit indicates that the voltage at N.1 does not go over U$_2$. The inverter closest to the transformers lowest PF is 0.995 at 11:12, which is almost no change from the simulation done in 7.3.1. The inverters close to the transformer do still not contribute much voltage support in the network. However the increased capability provided by the decrease of the PF limit is enough for the inverters closer to the end of the network to prevent overvoltage. The highest voltage in N.1 is 1.0998 pu at 12:37. The active power through the transformer has not changed much from the other strategies, but that is not true the reactive power. Figure 7-8 and Figure 7-7 show that the reactive power is a lot smoother with Q(U) voltage support. For the other strategies the fluctuation is caused by the change in the load. Since the Q(U) strategy reacts to the voltage and the active and reactive load provided by the load profiles are proportional, the reactive power consumption of the inverters will fluctuate close to opposite of the fluctuation in reactive load. The voltage is also somewhat smoother with this strategy for the same reason.

The losses are 14.17 kVAh. This is 2.55 kVAh less than when constant PF is used. This is caused by the inverter only consuming reactive power when the voltage goes over nominal voltage plus the dead band.

Compared to the PF(P_{PF}) strategy, Q(U) have 0.54 kVAh more loss in the network. Since Q(U) reacts to the voltage there is less reactive power consumption with this strategy which should result in less losses. However since most of the power consumption when the Q(U) strategy is used happens further away from the transformer than when the PF(P_{PV}) strategy is used, the reactive power traverse more line or more impedance. This results in more loss.

Max apparent power going through the transformer is 77.054 kVA.

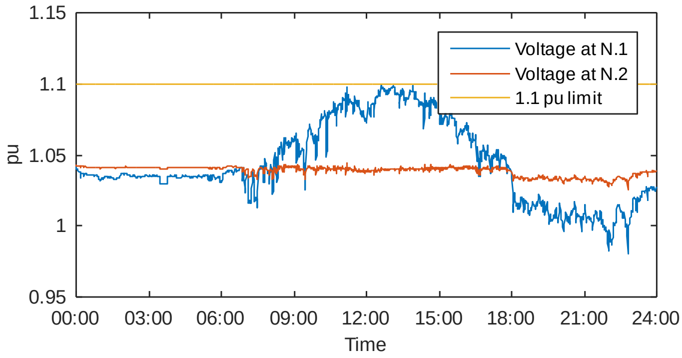

Figure 7-7: Voltage magnitude at N.1 and N.2, Q(U) with PF_{lim}=0,9 and D=0.043 pu.

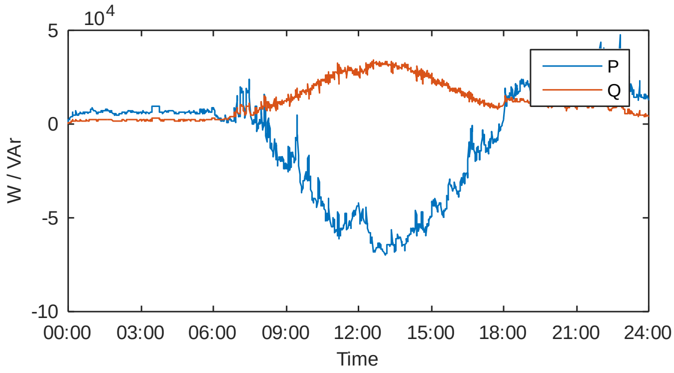

Figure 7-8: Power flow through transformer, Q(U) with PF_{lim}=0,9 and D=0.043 pu.

7.4 Results: Strategy 4

7.4.1 $P_{PV}(U)$: U_{hp}=1.174 pu and U_{lp}=1.057 pu

Using the $P_{PV}(U)$ strategy, with U_{hp}=1.174 pu and U_{lp}=1.057 pu, the maximum voltage at N.1 was 1.0991 pu, se Figure 7-9. This strategy exhibits the same weakness as the Q(U) strategy, in that the voltage close to the transformer experience very little change.

Losses in the network during the simulation were 8.49 kVAh. The loss of potential PV power or the total curtailed power during the simulation was 7.87 kVAh. In Figure 7-9 one can see how the active power through the transformer is much smaller than for the other strategies. This is caused by the power curtailment. The maximum curtailed power was 528 W in N.1 and 72 W in N.2. This happened at 12:48, when the potential production for each PV system is 1470 W.

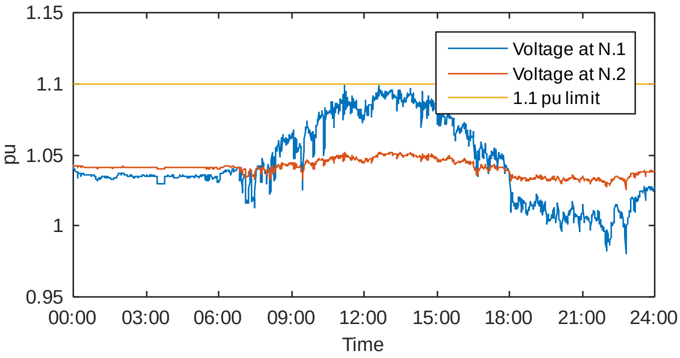

Figure 7-9: Voltage magnitude at N.1 and N.2, $P_{PV}(U)$ with U_{hp}=1.174 pu and U_{lp}=1.057 pu.

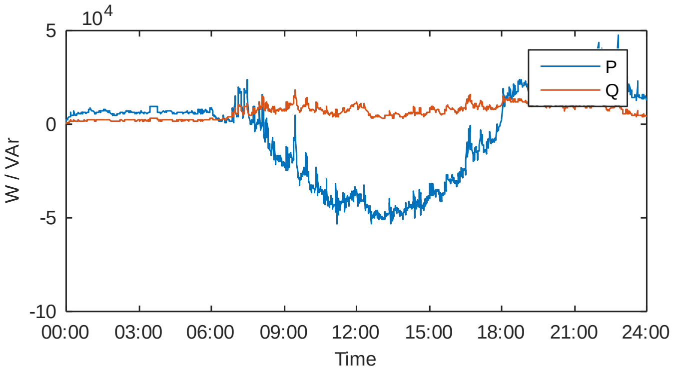

Figure 7-10: Power flow through transformer, $P_{PV}(U)$: U_{hp}=1.174 pu and U_{lp}=1.057 pu.

7.5 Comparison of the voltage support strategies

Table 7-1: Voltage strategies and important measurements.

Strategies	PF_{lim}	Other parameters	Max Voltage[pu]		Losses [kVAh]	
			N.1	N.2	Network	Curtailed
No voltage support	-	-	1.1180	1.0549	12.44	-
1: Constant PF	0.95	PF=0.95	1.1007	1.0435	16.72	-
2: $PF(P_{PV})$	0.95	P_1=1 kW P_2=1.5 kW	1.1009	1.0460	14.71	-
3: Q(U)	0.9	U_2=1.1 pu D=0.043 pu	1.0998	1.0441	14.17	-
4: $P_{PV}(U)$	-	U_{hp}=1.174 pu U_{lp}=1.057 pu	1.0991	1.0440	8.49	7.87

By choosing the right values for the parameters belonging to the different voltage support strategies, the voltage increase caused by the PV systems, seen in Figure 6-6, is mitigated sufficiently. The voltages are kept inside the admissible voltage band of 0.9 to 1.1 pu, see Table 7-1.

Total losses in the network during the simulation vary for each voltage support strategy. The $P_{PV}(U)$ strategy, has the least network losses of all the strategies. However if the curtailed power is included in the losses, the total losses in the network are 16.36 kVAh. This is 0.36 kVAh less than the total losses in the network when the strategy with the highest losses, constant PF, is used. From the DSOs perspective the power curtailed does not represent an economic loss as that loss is financed by the prosumer. This will make it more expensive to invest in PV for potential prosumers and therefore inhibit the growth of PV. When including curtailed power as losses, the Q(U) strategy resulted in the least amount loss, but only differ from the $PF(P_{PV})$ strategy with 0.54 kVAh.

A weakness of the Q(U) strategy, compared with the other strategies that uses reactive power control for voltage support, is that it requires a higher PF limit of the PV systems. The PV systems at the end of the transformer needed a PF limit of 0.9, while for the other reactive power control strategies 0.95 was sufficient to keep the voltage inside the admissible band. The burden of the voltage support is mainly shouldered by the prosumers at the end of the network when using the Q(U) strategy. The prosumers at the end of the network therefor need larger inverters, resulting in greater cost. These PV systems have higher voltage sensitivity to change in reactive power, because of the inherent properties of the network. Still it will inhibit the PV capacity of the network, as there was effective way to make use of the voltage support capability of the PV systems close to transformer. The impedance of the transformer and MV distribution grid, and its high X/R ratio, makes the PV systems close to the transformer a good potential source for voltage control.

The prosumers at the end of the network bears most of the voltage support burden when the $P_{PV}(U)$ strategy is used as well. The curtailed power of the prosumer at the end of the network represent the biggest share of the potential power lost too curtailment.

8 Conclusion

The results show that all voltage support strategies are able to keep the voltage inside the admissible voltage band of 0.9 to 1.1 pu for the case presented in this thesis.

In terms of losses in the network, it is not much difference between strategy 2 and 3. Strategy 1 and 4, when curtailed power is included in losses, causes considerably higher loss compared to strategy 2 and 3.

In terms of the PV capacity of the "IEEE European Low Voltage Test Feeder" was clearly in favour of strategy 1 and 2. These strategies utilize more of the voltage support ability than strategy 3 and 4.

The most effective voltage support strategy for the case presented in this thesis is strategy 2.

9 Further work

The strategies where only simulated in one case. It would be interesting to see if different networks would yield different results to which the most effective strategy is. Especially the impact of the X/R ratio of the network on the strategies efficiency would be interesting to further explore.

A study into new strategies would also be interesting. For example a modified version of strategy 2, where the PF characteristic is decided by the power fed to the grid instead of the power produced by the PV modules.

The impact of communication between the different inverters would also open up a broad specter of possibilities for further study.

10 References

[1] IEA, "Overcoming PV grid issues in the urban areas," 2009.
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11 Appendix

A.1. Excel setup of Network data used by GridBuilder

A.1.1. Loads

PV type decides which strategy is used in the model. Strategy 1 is PV type=1, Strategy 2 is PV type=2, etc.

Name	PV type	Bus	phases	kV	Model	Connection	kW	PF
LOAD1	1	34	A	0,23	1	wye	1	0,95
LOAD2	1	47	B	0,23	1	wye	1	0,95
LOAD3	1	70	A	0,23	1	wye	1	0,95

A.1.2. Lines

Bus 1	Bus 2	Phases	Length [m]	Line Code Nr.
1	15	3	19	1
15	25	3	5,2165	9
25	27	3	5,9049	3

A.1.3. Line Codes

CodeNr	Name	Phases	R1	X1	R0	X0	C1	C0
1	2c_.007	3	3,97	0,099	3,97	0,099	1,4E-07	1,4E-07
2	2c_.0225	3	1,257	0,085	1,257	0,085	1,4E-07	1,4E-07
3	2c_16	3	1,15	0,088	1,2	0,088	1,4E-07	1,4E-07
4	35_SAC_XSC	3	0,868	0,092	0,76	0,092	1,6E-07	1,6E-07
5	4c_.06	3	0,469	0,075	1,581	0,091	1,6E-07	1,6E-07
6	4c_.1	3	0,274	0,073	0,959	0,079	2E-07	2E-07
7	4c_.35	3	0,089	0,0675	0,319	0,076	4,3E-07	4,3E-07
8	4c_185	3	0,166	0,068	0,58	0,078	2,8E-07	2,8E-07
9	4c_70	3	0,446	0,071	1,505	0,083	1,6E-07	1,6E-07
10	4c_95_SAC_XC	3	0,322	0,074	0,804	0,093	2E-07	2E-07

A.1.4. Bus coordinates

Buss	X	Y
1	-37,1	-1217,1
15	434	-1403,8
25	770,1	-918,3

A.2. GridBuiler.m

Main function and all sub functions can be found in the digital attachment to the master thesis. The zip file includes the library with the different three-phase IT load with strategies and the excel file used to construct the Simulink model of the "IEEE European Low Voltage Test Feeder".

A.3. How the different inverter modes are modeled in Simulink

A.1.1. Power curtailment

Out1 is the active power that is curtailed. Umag is measured from over the load, see Figure 5-2. Uhp and Ulp is provided from the workspace in Matlab.

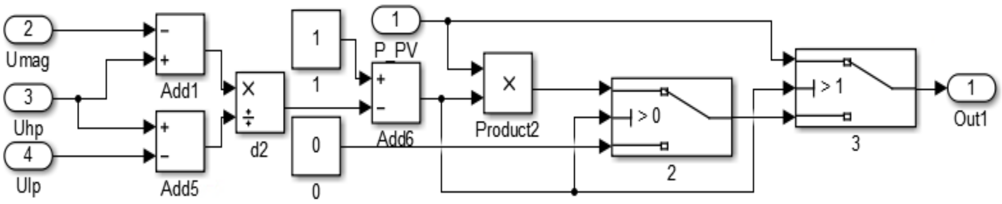

Figure 11-1: Simulink model of power curtailment.

A.1.2. Constant PF

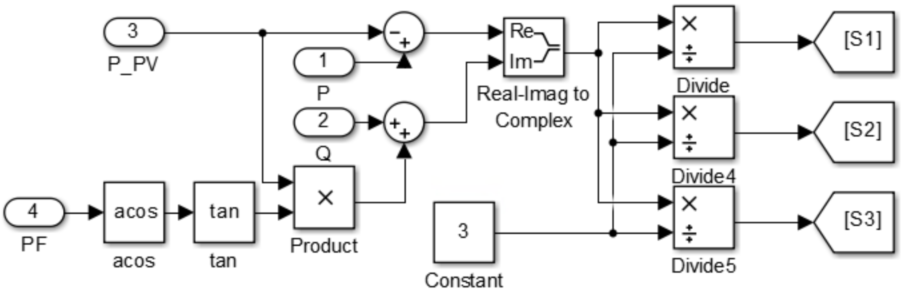

Figure 11-2: Simulink model of inverter mode constant PF.

A.1.3. PF dependent on PV power production

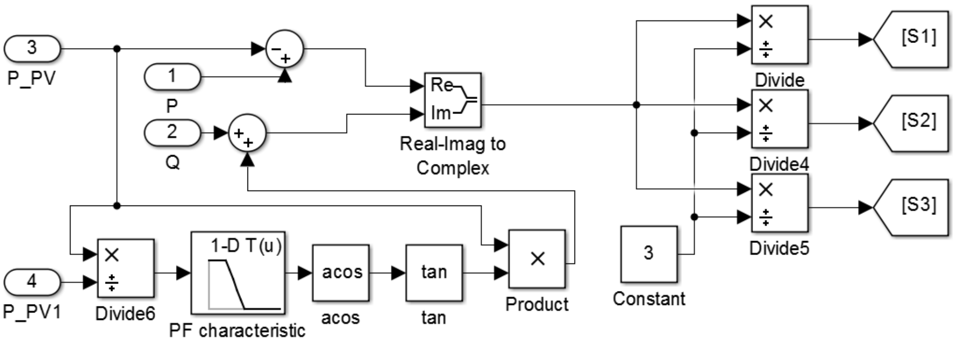

Figure 11-3: Simulink model of inverter mode PF(P_{PV}).

A.1.4. Reactive power consumption dependent on the voltage

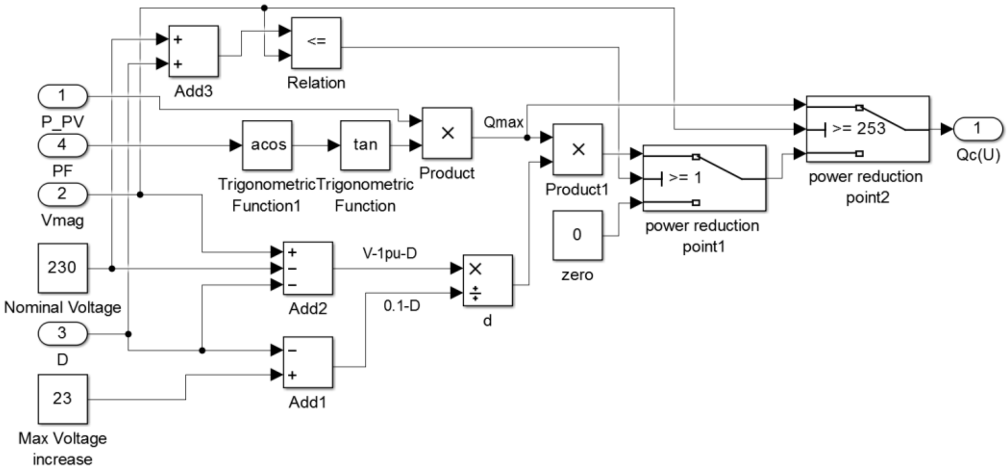

Figure 11-4: Simulink model of inverter mode Q_{PV}(U).

A.4. Transformer and overlaying MV distribution network parameters for Simulink three-phase source

Table 11-1: Transformer and overlaying MV distribution network parameters from [15].

Phase-to-phase rms voltage (V)	240
Frequency (Hz)	50
3-phase short-circuit level at base voltage (VA)	1945400
Base voltage	230
X/R ratio	2.478