Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

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Abstract

The main focus of this thesis project is to study the impact on the voltage rise of PV penetration in one urban area of a Swedish city with high residential PV population when assuming the LV distribution grid has a constant frequency of its voltage.

The study is done by modeling the system, i.e. the targeted LV distribution grid in Västerås, Sweden. The aspects of the model include network design of the LV distribution grid, everyday load/demand within the LV distribution grid, PV penetrations at different levels and Swedish DSOs’ codes in regard to purchase of PV power from residential PV systems.

The thesis aims to find the tolerable maximum installed capacity of a residential PV system according to the result of possible over-voltage rise in the LV distribution grid and then give suggestions to Swedish DSOs about their current regulations in regard to the purchase of electricity from residential PV systems. To facilitate the possible maximization of the use of PV and renewable power is the ultimate concern of the thesis.
Acknowledgement

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List of Abbreviations

PV: Photovoltaic
IEA-PVP: International energy agency - photovoltaic power program
DG: Distributed Generation
LV: Low Voltage
MV: Medium Voltage
RMS: Root Mean Square
CCP: Common Coupling Point
DSO: Distribution System Operator
LL: Line to Line
MW: Megawatt
KWh: Kilowatt-hour
PSCAD: Power System Computer Aided Design
P.U.: Per Unit
OLTC: On-load tap changer
kWp: Kilowatt-peak
SEK: Svensk krona, the Swedish currency, 1 SEK = 100 öre
Chapter 1 Introduction

1.1 Background

1.1.1 Huge market of PV power

As the climate change associated with burning of fossil fuel becomes more pronounced and the long-term supply of oil and gas as well as other fossil fuels are dwindling, renewable energy sources as electricity generation are gaining increasing importance in the countries all over the world.

Particularly, solar energy source has its incomparable advantage. It is both abundant and even 'democratic'. ‘Solar is the most democratic of energy sources, falling fairly evenly on all the world’s surfaces. A full midday sun averages about 1,000 watts per square meter. The amount of sunlight falling on the earth contains far more energy than we can use- 10,000 times more than the whole of humanity's current consumption.’ [1]

To convert solar irradiation into electricity, a new technology-photovoltaics is needed. It realizes the conversion of the energy of light to electricity by using solar cells. Solar energy conversion into electricity via PV systems or PV in short has tremendously expanded in the first decade of 21st century in the world. In the IEA-PVPS countries, the installed PV power increased from below 1000 MW to almost 8000 MW between years 2000 and 2007[3]. Figure 1 shows the installed PV capacities in leading countries in the year of 2008.

Figure 1: Installed PV capacities in leading countries in the year of 2008[4]

PV is now a commercially available and reliable technology with a significant potential for long-term growth in nearly all the regions in the world. Figure 2 shows the global cumulative installed PV capacities between the year of 1992 and 2008 with an annual growth rate of global PV markets of 40%.
IEA estimates that by 2050, PV will provide around 11% of global electricity production and avoid 2.3% gigatonnes (Gt) of CO2 emissions per year [4].

1.1.2 PV application in residences

In the markets of PV power, right now there are two categories of PV systems: grid-tied systems which are connected to the public electricity grid, and stand-alone systems which are not. To be more specific, there are now four primary applications for PV power systems nowadays [5].

- Off-grid domestic.
- Off-grid non-domestic.
- Grid-connected distributed.
- Grid-connected centralized.

Right now, off-grid applications only constitute less than 10% of global total PV market. It can be seen also in Figure 2. Grid-connected distributed application for PV power can be further divided into residential systems and commercial systems. Grid-connected centralized application for PV power can be also called utility-scale system [6].

Now there are four end-use sectors with distinct markets for PV. Figure 3 shows the relative market share of the four market segments. It states the possible development path worldwide while different countries have varying paths corresponding to the particular market framework [4].
Figure 3: Evolution of PV electricity generation by end-use sectors [4]

According to Figure 3, by the year 2050 the cumulative installed capacity of residential PV systems is expected to decrease from 60% to 40% of the total installed PV capacity, it still takes the prominence in the whole worldwide PV markets. Figure 4 shows an example of residential PV system.

Figure 4: Example of residential PV systems [7]

The solar energy is converted into electricity via a PV system (including PV array, cell, inverter and etc.), then consumed locally by the installer (residents in this case) and/or fed into the LV (Low-voltage) distribution grid and MV (Medium-voltage) distribution grid via transformer substations.
1.1.3 Concerns in residential PV systems

With fast growing penetration of PV as well as other distributed power generation, the impact of PV on the grid and vice versa is under discussion. In 2007 the investment in pilot and demonstration projects and programs constituted 30% of the worldwide PV public research and development expenditures [4]. The main concerns are the maximum tolerable level and the quality of the supply voltage as well as the acceptable penetration limits [8]. In particular, the concerning issues include:

- Power quality related to standard EN 50160
- Voltage rise effects
- Harmonic current injections from PV
- Maximum permissible capacity of PV
- Network design

The voltage rise is a result from solar irradiation, subsidies, demand levels, and installed capacity of residential PV systems and network design of the LV distribution grids. The voltage rise in the LV distribution grid is one most frequent concern in the leading countries of residential PV market. It is mainly because in some cases, excess PV penetration from residential PV systems into the LV distribution grid can increase the mismatch between consumption and generation. Unlike the loads in an LV distribution grid that have statistical variations and thus smoothen the peak load of the system, the PV production occurs almost simultaneously in all PV systems connected in the same area.

Sweden has a small number of installed residential PV systems compared to the leading countries of residential PV market, e.g. Germany. That’s why Sweden has not met the problem of voltage rise in its LV distributed grid yet. However, in the future, with the development of residential PV market in Sweden, how to avoid voltage rise and maximizes the utilization of PV power is the motivation of this thesis.

1.2 Project goal and objective

This thesis is concerned with the study the voltage rise effects in a typical Swedish LV distribution grid due to the applications of residential PV systems.

The thesis has several goals:

1. The first goal is to analyze the solar energy included in solar irradiation in a typical Swedish city in one year.
2. The second goal is to analyze the Swedish DSOs’ codes related to PV power generation in a LV distribution grid and how the residential customers in a typical Swedish LV distribution grid, e.g. residents in an apartment, make their choices of the capacity for a residential PV system when they are going to install a PV system in their residence.
3. The third goal is to simulate such a typical Swedish LV distribution grid with everyday demand and PV power generation in PSCAD and find out the voltage rise effects.

After the thesis work, the following questions should be answered:
• How is the Swedish market of PV residential systems now?
• What are the DSOs’ subsidies and regulations related to installations of PV residential systems and PV power generation?
• What is the characteristic of Swedish solar irradiation?
• When the residential customers are going to install PV residential systems in their residences, how will they make their choice of the capacity?
• How will their choice impact the voltage rise effects in the LV distribution grid finally?
• What suggestions can we give to the Swedish DSOs based on the work of the thesis?

1.3 Project outlines

In chapter 2, the studied system, research approach and scope of this master thesis are defined.

In chapter 3, the model of the studied system is built.

In chapter 4, the simulation platform of the model in chapter 3 is described.

In chapter 5, the results of the simulation in chapter 4 are presented and analyzed.

In chapter 6, the conclusions of the thesis work are summarized.

In chapter 7, the limitations of this thesis work are claimed and future work is suggested.
Chapter 2 Scope

Chapter 2 defines the studied system and research approach, as well as the research scope.

2.1 Undeveloped Swedish market of residential PV systems

There are only less than 2000 residential PV systems installed in Sweden due to the current market framework in Sweden for PV power [5]. In Sweden in 2011 the annual installed PV power reached 4.3 MW– up from 2.7 MW installed the previous year. ‘A direct capital subsidy for installation of PV systems has been in operation in Sweden since 2009. The subsidy lasted from 2009 to 2012 and applied to any type of grid-connected PV systems including private individuals. The budget for 2012 is 60 MSEK’ [5]. However, if the subsidy continues in 2013 is not known yet. Such incentives are still very few if compared to Germany and other leading countries in residential PV markets and are only temporary subsidies.

- Expected subsidies

Measures directed to domestic end-users including residences are few. Nonetheless, legislative changes, investment support, and subsidies can be expected. Together with prospects of decreasing prices for residential PV systems and increasing efficiency of PV systems in future facilitate a possible extensive integration of residential PV systems in Sweden [7].

- DSOs regulations to the purchase of PV solar power

Sweden has few regulations in regard to DSOs’ purchase of PV solar power from residential PV systems. The main DSOs in Sweden now are Fortum, E.on and Vattenfall. E.on now sets the limit of purchasing PV solar power from a residential PV system at 43.5 kW [13], which is much higher, compared to 9.8 kW [9], the typical maximum power demand from one household in Sweden.

2.2 Studied system of the thesis work

The studied system of the thesis is a typical Swedish LV distribution grid with no installations of residential PV systems yet. The study is carried out based on the assumption that in the future, each residential household installs a residential PV system.

The simplification of the studied system can be well illustrated in Figure 4. Figure 4 has only 1 household, though a typical LV distribution grid usually has many more households, and/or offices and etc. The simplified studied system can be divided into 3 parts.

1. PV generation: Incident solar irradiation is converted into AC power output via photovoltaic systems and the associated system components first.
2. PV local consumption: AC power output is consumed locally to compensate the residential demand of power.
3. PV transmission to the grid: If the AC power output is at excess, then the excess part, which cannot be consumed locally by the residence where the AC power output is
produced, is delivered to the LV distribution grid to which the residence is connected.

2.3 Study approach and scope of the thesis work

The study approach is to model a typical LV distribution grid, with focus on PV generation, local consumption and transmission. The study scope is accordingly defined as follows.

The study scope of PV-generation is focused on weather and customers in the location of the LV distribution grid. ‘Weather’ refers to ‘solar irradiation’—how much solar energy can be utilized for electricity in the area. ‘Customer’ refers to ‘how the customers decide the capacity of a residential PV system if they are going to install one in their residence’. The study on the customers’ choice is particularly important because their choice decides how much electricity can be generated from PV.

The study scope of ‘PV-consumption’ is focused on the study of everyday electricity demand/consumption of the LV distribution grid before and after PV-generation is penetrated into the grid.

The study scope of ‘PV-transmission’ is focused on the study of network design and grid connections of the studied system because they limit the transmission of PV generation into the grid. Besides, the network design and grid connections of an LV distribution grid have always direct influence on the voltage within the grid.

All the generation, consumption and transmission of energy are calculated in kWh/h. The operation frequency of the LV distribution grid is assumed to be constant at 50 Hz, which means only the static analysis of the grid is the focus of this thesis work.
Chapter 3 Model

The studied system is an urban area in Västerås, Sweden. Västerås is a city in central Sweden, located about 100 km west of Stockholm and had a city population of 110,887 in 2010[10].

3. 1 The grid

3.1.1 The voltage requirement

The LV distribution grid is a secondary distribution grid and the nominal line-to-line voltage level is 400 V. (Note: all the voltages mentioned in the thesis are line-to-line voltages. Explicit notification will be made if the voltage types are different.) The voltage range at operation is 400V ±10%. Once the voltage level is out of the above range, then the voltage level is not qualified. The requirement of the voltage range applies to every household and every point of the targeted LV distribution grid.

The targeted LV distribution grid is connected into a primary distribution grid, which has a nominal voltage level of 10 kV. The primary distribution grid then is connected into the sub transmission network of nominal voltage level at 130 kV.

3.1.2 Network design and configurations
The primary distribution grid

Figure 5 is the single-line diagram of the primary distribution grid. It illustrates the network design of the primary distribution grid and grid configurations. The primary distribution grid was built in 1980s [11] and has a total load capacity of 80 MVA, though relevant records show that the peak total load ever in the primary distribution grid is only 30 MVA. It shows that the primary distribution grid is in the status of light load. The primary distribution grid has a short-circuit capacity of 3080 MVA. The primary distribution grid is composed of one 80 MVA primary substation, 19 sections of power cables and 19 aggregated, balanced loads and the targeted LV distribution grid. The load factor is assumed to be 0.9 lagging for all loads in the primary distribution grid. The targeted LV distribution grid is connected via its own secondary substation to the primary distribution grid.

In the primary substation in the primary distribution grid, there are two 40 MVA, wye/wye, 145 kV/11.6 kV transformers installed with on-load tap changers. Other requirements of the transformers are stated in Figure 5 and Appendix B.1. The length of each section of power cables between is stated in Figure 5. The configurations of power cables are included in Appendix B.2. In the primary distribution grid, 19 loads are assumed to have the same power factor of 0.9. Only peak values of the loads are known, which are listed in Appendix B.3.

The targeted LV distribution grid

Figure 6 is the single-line diagram of the targeted LV distribution grid [11]. It shows the network design and grid configurations of the targeted LV distribution grid. It is composed of a 1.6 MVA secondary substation, 9 sections of power cables, 12 buses, and 11 aggregated loads. Each load resembles an accumulation of a number of flats, supermarket, school, day-
care center of kids and/or offices. The loads are assumed as balanced loads (residential-, commercial-, or mixed-type) operating at the power factors of 0.9 lagging. The residential part of 11 aggregated loads consists of 450 flats. Each bus connects different sections of power cables, loads and/or the secondary substation. The 12 buses serve as the CCPs in the targeted LV distribution grid.

The secondary substation in the targeted LV distribution grid has two 800 kVA, delta-wye, 11 kV/420 V distribution transformers. The distribution transformers are installed with off-load tap changers which can only be operated manually. The configurations of the distribution transformers and 9 sections of power cables are included in Appendix C.1 and C.2.

3.2 The load

For the primary and targeted LV distribution grid, the original load data is limited to annual energy consumption in kWh and peak load. The load factor is assumed to be 0.9 for all loads. The load data in the targeted LV distribution grid is attached in Appendix C.3.

A probabilistic calculation method based on RTS-96 (IEEE Reliability Test System) can be used to produce hourly load profile of each load at CCPs in the targeted LV distribution grid [12]. A complete list of hourly load profile of each load for a whole year is already produced in [12] by application of the same probabilistic calculation method. With the 19 loads in the primary distribution grid, the same probabilistic method has been applied too. However, the method can only produce the average demand/consumption in the interval as long as one hour (e.g. kWh/h).

Electricity demand/consumption on the winter day, summer day and autumn day

In this thesis it is of particular interest to find out the worst scenario of voltage rise effect. As well, a day with the least voltage impact from PV generation is of interest. The mismatch between PV generation and electricity consumption decides directly the voltage rise. The higher the mismatch is, the more voltage rise can be caused. Thus, a day with lowest demand and highest irradiation for PV generation and in the studied system would be ideal for the worst scenario of voltage rise. On Sep. 23rd, the targeted LV distribution grid has the lowest load profile throughout a year. However, the solar irradiation in September is usually not as high as in summer. In summer (week 18-30) on July 8th the targeted LV distribution grid has the lowest load profile of the summer season. On Dec.20th, the targeted LV distribution grid reaches the peak load level in a year[11][12]. In the following text, Dec. 20th, July 8th and Sep. 23rd are called ‘the winter day, the summer day and the autumn day’.

Figure 7-9 and 10-12 are the plots of the hourly load profile in the targeted LV distribution grid and the primary distribution grid on the winter, summer and autumn day in the figures). Each marked point in each curve corresponds to the average load within a particular hour. The horizontal axis represents 24 hours in the day, e.g. hour1 means 00:00-01:00, hour 2 01:00-02:00, and so on. In Figure 7-12 the vertical axes show the apparent
power demanded in MVA. The load profile of the Load 19 in the primary distribution grid is not plotted in Figure 10-12 since it is much bigger than other loads and thus impacting the visibility of other load plots if included in the same figure.

*Figure 7: Hourly loads on the winter day in the targeted LV distribution grid*

*Figure 8: Hourly loads on the summer day in the targeted LV distribution grid*
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**Figure 9:** Hourly loads on the autumn day in the targeted LV distribution grid

**Figure 10:** Hourly loads on the winter day in the primary distribution grid
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Figure 11: Hourly loads on the summer day in the primary distribution grid

Figure 12: Hourly loads on the autumn day in the primary distribution grid
3.3 Swedish PV-generation

3.3.1 Swedish Solar irradiation and energy in Västerås

In Västerås, there is a house already installed with a residential PV system. The PV system has a 3.36 kWp, which means the nominal and potentially maximum output power of the PV system is 3.36 kW. The hourly PV production (included in Appendix D) and electricity consumption of the house for the year of 2011 have been recorded in kWh [11]. The records of the house are named ‘G case’ in short in the following part of the thesis. By analysis of the ‘G case’, the characteristics of solar irradiation in Västerås can be found out.

Then the question comes which hours/days to choose for the study of voltage rise effects? An ideal day would be one with highest irradiation and lowest demand in the studied system.

PV generation on the winter day and summer day

However, such a day doesn’t exist here. The peak PV generation in kWh appears at 10:00-11:00 on May 26, peaking to 2.91 kWh, but the day with lowest demand is on ‘the autumn day (Sep. 23rd). Finally, a compromise is reached and two particular days have been chosen: the summer day (July 8th) and the winter day (Dec. 20th). On the summer day, solar irradiation is still comparably high (the peak PV production is 2.66 kWh) and the targeted LV distribution grid has the lowest load profile in summer. On the winter day the targeted LV distribution grid has the lowest PV generation and the highest load profile in the year. The hourly PV generation on the summer and winter day is plotted in Figure 13. The horizontal axis represents hours in a day. Vertical axis shows the PV generation in kWh.

![Hourly PV production on the winter and summer day](image)

*Figure 13: Hourly PV production on the winter and summer day in G case*

In Figure 13 on the winter day the PV production keeps at zero level due to the irradiation characteristics in high latitudes.
3.3.2 Customers’ choice

Assume that the customers in the 450 flats in the LV distribution grid are going to install residential PV systems in their apartments. The customers in each apartment are provided with ‘G case’ for reference. Besides, they know about Swedish DSOs’ regulations and their electricity bills. Then, what capacity of a residential PV system will they choose? Before analyzing the customers’ choice, relevant Swedish DSOs’ regulations and the form of a typical Swedish electricity bill of a household are introduced as follows.

Swedish DSOs’ regulations

- **Grid tariff**
  In Sweden, DSOs offer grid connections to consumers. If the annual consumption of the consumers is larger than the annual production of electricity, then the grid tariff for them to sell PV solar power to DSOs in Sweden is 0 SEK. Otherwise the customers of the DSOs need to pay 1875 SEK as the grid tariff [14] because they are considered producers of electrical energy rather than consumers.

- **Limit on the installed capacity of a residential PV system in one household**
  One of the three main Swedish DSOs, E.ON, offers to buy as huge as 43.5 kW PV production from one individual household since the distributed PV generation is consumed locally and the grid loss is then decreased. 43.5 kW is set based on the limit current of a fuse in one Swedish household [13] and can be calculated as follows.

  \[
  43.5 \text{ kW} = 3 \times 230 \text{ V} \times 63 \text{ A}
  \]

  63 A is the highest current limit and 230 V is the nominal single-phase voltage level in a Swedish household.

- **The price of PV generation when Swedish DSOs purchase it from households**
  The price for purchase of PV production usually includes two parts, i.e. compensation of reduced grid loss and electricity price. An example is that in Stockholm, E.ON pays 5.6 öre per kWh PV production as the compensation of reduced grid loss and the spot price on Nord Pool minus 4 öre as the electricity price [14].

Electricity bills of the flats

The annual consumption of electricity per flat in the targeted LV distribution grid is 3502 kWh [11]. The peak hourly load per flat is 0.8 kWh/h [11].

Choice of installed capacity of residential PV systems

How will the customers in the flats make a choice of installed capacity of residential PV systems? It is assumed that the irradiation conditions are similar as the year 2011.

- **First choice - Zero emission houses**
The most common choice is made in the following way.

Assume $A=$ annual electricity consumption of a flat in the targeted LV distribution grid in kWh (3502 kWh per flat); $B=$ annual electricity production of the residential PV system in ‘G case’ in the year of 2011 in kWh (2900 kWh). $X=$ the capacity of a residential PV system to be installed in the targeted LV distribution grid, which is to be decided.

Having known $A$ and $B$, a family in a flat of the targeted LV distribution grid might do the simple following calculation to find out the capacity of a PV system they need to compensate the annual energy consumption of the family.

$$\frac{A}{B} = \frac{X}{3.36}$$

(1)

Then $X=4$ kWp.

In order to let the grid tariff for a family to sell extra PV production be zero, it is assumed that the annual PV production of a family is very close to and slightly smaller than the annual energy consumption.

- **Second choice - Peak production equals peak load**

The family in one flat might just want the installed capacity of a residential PV system as big as the peak load (0.8 kWh/h [11]). In this case, the annual PV generation per flat is only 20% of the annual electricity consumption per flat. Then the grid tariff for the customers to sell the extra PV production for DSOs is zero.

By linear amplification of the PV production from a 3.36 kWp PV system, the PV production from a 4 kWp (first choice) and 0.8 kWp (second choice) PV system can be obtained. The PV production of two choices on the summer day is plotted in Figure 19. The red and blue columns represent PV production of the first and second choice. The horizontal axis represents hours in a day. Vertical axis shows PV production in kWh.
Both choices will lead to PV penetration into the LV distribution grid and selling PV production from flats to the DSOs in the hours when PV generation is higher than the electricity consumption.
Chapter 4 Simulation model

In Chapter 4, the simulation model of the studied system is built on the platform of software PSCAD (Power System Computer-aided Design).

4.1 The targeted LV distribution grid

4.1.1 The grid

- Network topology

*Figure 15: Network topology of the targeted LV distribution grid in PSCAD*
• Secondary substation topology

The secondary substation consists of two 800 kVA, delta-wye, 11 kV/420V transformers with star point solidly grounded on the LV side. Each of the two transformers is equipped with an off-load tap changer on the secondary winding, of which the default tap position is step 2 and the effective transformer ratio for this step is 11.275 kV to 420 V. The tap changers can be operated only manually. Figure 16 illustrates the basic topology of the secondary substation. Though only one transformer is shown in Figure 16, two transformers are included in the substation as shown in Figure 15.

![Figure 16: Substation topology](image)

• Power cables

The targeted LV distribution grid under study has 11 aggregated loads located at 11 CCPs. Along different sections of power cables, the distance between the 11 aggregated loads and secondary substation vary from 0 m to 360 m.

![Figure 17: Model of power cables](image)

As shown in Figure 17, a coupled PI section from the main library of PSCAD has been used to model the power cable sections. The input into coupled PI sections of PSCAD and original power cable data is listed in Appendix E.1.
• **Multi-meters**

As shown in figure 15, multi-meters are set at each of 12 buses to measure the voltage and power flow.

4.1.2 The loads

• **Topology of the load model**

![Diagram of aggregated loads at CCPs](image)

*Figure 18: Model of aggregated loads at CCPs*

Figure 18 shows the topology of the aggregated loads in the targeted LV distribution grid on the platform of PSCAD. The content of loads in detail is shown in Appendix C.3. In Figure 18, Load 1 at Bus 4 is taken as an example. Load 1 is split into a combination of three single phases, i.e. phase a, b and c. Load 1 is a balanced, symmetrical 3-phase load and voltage at phase a, b and c are the same only except that voltage angle in phase a, b and c have a difference of 120 degrees. Phase b lags phase a 120 degrees and phase c lags phase b 120 degrees. The reason to split the originally 3-phase load into the combination of 3 single-phase loads is that in PSCAD main library, variable load models only includes single-phase load components.

In Figure 18 each single-phase load consists of one variable resistor and inductor in parallel, as well as a variable current source. When there is no current injected from the variable current source into the paralleled resistor and inductor, the load at each phase is purely consuming power; while there is current injected from the variable current source into the paralleled resistor and inductor, the load is compensated by the PV production in each flat, i.e. the current source is used for modeling the PV production. The reason why a variable current source is used to model the PV production is that there is no variable power source yet in the main library of PSCAD.

• **Control of loads**
In Figure 19 the control of each single-phase of Load 1 is taken as an example. The four parts in Figure 24: (1) resistor & inductor building by CSM function, (2) S (apparent power) input building, (3) load control panel, (4) Vnom (nominal voltage setting) are illustrated as follows.

**Part (1): resistor & inductor building by CSM function**

The single-phase resistor and inductor are modeled as voltage dependent and built by CSM functions in PSCAD main library. The following basic theory has been used.

- **Theory**

  \[ R = \frac{U^2}{P} \]  

  \[ P = S \cos \Phi \]  

  \[ L = \frac{U^2}{Q \times (2\pi f)} \]  

  \[ Q = S \sin \Phi = S \sqrt{1 - \cos^2 \Phi} \]
L is the single-phase inductance at each phase; Q the reactive power consumed by the corresponding inductor and f the operation frequency. In this thesis project, we are only interested in the steady-state frequency in Sweden, which is \( f = 50 \text{ Hz} \). \( \cos fi=0.9 \), since each aggregated load in the targeted LV distribution grid is assumed to have the same power factor of 0.9.

When U is fixed, by changing the value of S and \( \cos fi \), the values of R and L become variable. Thus, the variable load can be modeled according to Equation (6) and (7).

- **Expression of variable loads**

\[
R_{\text{load1}} = \frac{V_{\text{nom}}^2}{S_{\text{1 single}} \cdot \cos fi_1} \text{[Ohm], single-phase} \quad (6)
\]

\[
L_{\text{load1}} = \frac{V_{\text{nom}}^2}{(S_{\text{1 single}} \cdot \sqrt{1-\cos fi_1^2} + \sqrt{x}) \cdot 2\pi f} \text{[Henry], single-phase} \quad (7)
\]

There is a special part in Equation (7) i.e. ‘\( + \sqrt{x} \)’. It corresponds to the red circle in part (3) of Figure 19, named as ‘coefficient’. The coefficient varies between 0 and around 0.02 and controlled via a control panel. The reason to introduce it is to remove the unwanted reactive power production when PV production is not zero. The unwanted reactive production is caused by the slight calculation error in PSCAD itself due to the delay in phase shift. More about the slight calculation error will be mentioned in Section ‘current source into power source’ on Page 31.

\( S_{\text{1 single}} \) is illustrated in ‘Part (2): S (apparent power) input building’ in Figure 19.

\( \cos fi_1 \) is controlled in ‘Part (3): load control panel’.

\( V_{\text{nom}} \) is illustrated in ‘Part (4): V_{\text{nom}} (nominal voltage setting)’.

**Part (2): S (apparent power) input building**

\( S_{\text{1 single}} \) represents the single-phase load corresponding to the single-phase resistor \( R_{\text{load1}} \) and inductor \( L_{\text{load1}} \) in VA. \( S_{\text{1 single}} \) is calculated from the value of 3-phase load in MVA as follows.

\[
S_{\text{1 single}} = \frac{(S_{\text{load1,3p}})}{3 \times 10^6} \text{[VA]} \quad (8)
\]

\( S_{\text{load1,3p}} \) is the value of 3-phase, aggregated Load 1 in MVA and controlled in ‘Part(3): load control panel’ in Figure 19.

**Part (3): load control panel**

\( S_{\text{load1,3p}} \) and \( \cos fi_1 \) can be controlled via two control panels in Figure 19. The varying values of the active-power part in \( S_{\text{load1,3p}} \) are already plotted in Figure 7 and 8 in Chapter 3.2. As assumed, \( \cos fi_1 = 0.9 \).
Part (4): Vnom (nominal voltage setting)

In equation (6) and (7), \( V_{\text{nom}} = 400/\sqrt{3} = 230 \text{ [V]} \). It corresponds to ‘Part (4)’ in Figure 19. Vnom is the nominal value of phase voltage in a LV distribution grid in Sweden. Since the study of voltage impact by PV production is made within (0.90-1.10)*230 V (phase voltage), the voltage across the resistor and inductor can be set as Vnom when modeling the resistor and inductor as voltage-dependent loads.

The correctness of the above setting has later been validated in the simulation result. The multi-meters at buses in the targeted LV distribution grid show the measured values of the aggregated loads at different voltage levels (within (0.90-1.10)*230 V (phase voltage)) are the same as the input of load. It shows that the model of load control on the platform of PSCAD can correctly simulate the loads in the studied system.

• Different models of load control for Load 5 and 6

Loads 5 and 6 don’t include any flats. Then, PV production at Load 5 and 6 is always zero. There is no need to remove the unwanted reactive power production. Equation (9) takes Load 5 as an example.

\[
L_{\text{load5}} = \frac{V_{\text{nom}}^2}{S_{\text{single}}\cdot\sqrt{1-\cos^2\phi} \cdot 2\pi f} \text{ [henry], single-phase (9)}
\]

There is no ‘+\sqrt{x}’ in Equation (9) compared to Equation (7). Correspondingly, there is no ‘coefficient’ part in Figure 20.

Figure 20: Load control of Load 5 in the targeted LV grid by PSCAD
4.1.3 PV generation

In Figure 18, at each single phase of Load 1, a single-phase current source is added in parallel with the resistor and inductor to introduce the PV production at Load 1. Figure 21 shows the simulation model of PV-production control. All the aggregated loads except Load 5 and 6 all have the same simulation models of PV-production control. Load 5 and 6 don’t include flats and thus don’t have any PV production. In Figure 21, Load 1 at Bus 4 is taken as an example.

Figure 21: PV-production control

Figure 21 contains three parts: part (1) current source building of phase a, b, c (by CSM Functions in the main library of PSCAD); part (2) current source into power source; part (3) PV control panel.

Part (1): Current source building of phase a, b and c
In Figure 22, Phase a in Load 1 at Bus 4 is taken as an example. The same method has been applied to Phase b and c.

![Diagram of current source building of phase a]

Figure 22: Current source building of phase a

Unit current source

First in Figure 22, a ‘unit current source’ is built based by Equation (10).

\[
\text{unit}_i = \frac{u_{1a}}{\sqrt{2} (U_{RMS_{1a}})}
\]  

(10)

\(u_{1a}\) is the instantaneous voltage of phase a of load 1 and \(U_{RMS_{1a}}\) is the RMS value of phase-a voltage of Load 1. Both \(u_{1a}\) and \(U_{RMS_{1a}}\) are the measured values by multimeters located at phase a in Load 1.

In Chapter 3.3, PV generation includes only active power which means the power factor of PV production is set to 1. There is no particular grid code in Sweden about if reactive power can also be penetrated into the grid from a residential PV system or not now. In this thesis, the focus is on the active power produced by a residential PV system.
Current source at phase a

Then $i_{production\_1a}$, the current source at phase a of Load 1 is built by Equation (11).

$$i_{production\_1a} = Flat\_load1 \times (\sqrt{2} \times Ipv\_1p) \times unit\_i \times cosf1$$  \hspace{1cm} (11)

$Flat\_load1$ represents the number of flats within the aggregated Load 1.

$Ipv\_1p$ is the single-phase current injected from one individual residential PV system corresponding to the instantaneous PV production. $Ipv\_1p$ is an RMS value. But PSCAD requires an instantaneous value of the variable current source instead of RMS values. So $\sqrt{2}$ is multiplied with $Ipv\_1p$ to form a peak value. The calculation of $Ipv\_1p$ is included in ‘Part (2): current source into power source’.

The power factor of PV production is equal to 1, as mentioned on page 30. However, instead of 1, $cosf1 = 0.9$, which is the power factor of the loads, has been put here. It means that the PV production is lowered by 10%.

Unwanted reactive power production

$unit\_i$ is built with corresponding CSM functions in PSCAD main library, based on Equation (10). $unit\_i$ is supposed to be in phase with $u\_1a$. However, the simulation result in this part shows PSCAD introduces a slight angle shift between $unit\_i$ and $u\_1a$. An unwanted lagging angle, though very small, is produced for the phase angle of $unit\_i$. Thus, the power factor of PV production is 0.99 instead of 1 and reactive power is then produced from residential PV systems. In order to remove the unwanted reactive power production, a coefficient is introduced into the reactive load model in Figure 19. It is already stated in Equation (7). Then, the unwanted reactive power production can always be consumed by the extra reactive load.

Part (2): Current source into power source

First in Figure 23, $Ipv\_1p$ is set.

$$Ipv\_1p = \frac{Spv\_3p}{(3*Vnom\_1p)} [kA]$$  \hspace{1cm} (12)

$Spv\_3p$ is the variable PV production in MVA from each flat and controlled in ‘Part(3): control panel of PV production’.
$V_{nom\_1p} = 0.23$ kV is the nominal phase voltage in the LV distribution grid (Note: Both $V_{nom}$ in Figure 19 and $V_{nom\_1p}$ in Figure 23 represent the nominal phase voltage in the LV distribution grid. The only difference is that $V_{nom\_1p}$ uses ‘kV’ in Figure 23 and $V_{nom}$ in Figure 19 uses ‘V’.)

Then in Figure 23 Flat_load 1 is set. Flat_load 1 is the number of flats at the aggregated Load 1.

![Figure 23: Part (2) current source into power source](image)

**Part (3): control panel of PV production**

In Figure 24, the input to $Spv\_3p$ (the variable PV production in MVA from each flat) can be controlled. PV production in Figure 14, Chapter 3.3.2 is introduced as the input.
Figure 24: Part (3) PV control panel: Spv_3p
4.2 The Primary Distribution Grid

- Network topology

Figure 25: Network topology of the primary distribution grid in PSCAD

- Primary substation topology (with on-load tap changers)

Figure 26 shows the topology of the primary substation in the primary distribution grid. The primary substation consists of two 40 MVA, wye/wye 145 kV/11.6 kV transformers with star point grounded through a reactance on the LV side. The transformers are equipped with an on-load tap changer on the secondary winding. The control strategy of tap changing is to maintain an acceptable voltage at the primary substation. The step size is
1.67% of 11.6 kV and number of steps is +/-9 about 11.6 kV. The reference voltage is 10.98 kV. The regulator dead-band is 100 V. Figure 27 shows the logic model of on-load tap changers. Both CSM and logic functions in the main library of PSCAD are used.

Figure 26: Primary substation topology in the primary distribution grid by PSCAD

Figure 27: Logic model of on-load tap changer in the primary substation by PSCAD
• **Load in the primary distribution grid**

![Diagram of load model in the primary distribution grid by PSCAD](image)

*Figure 28: Load model in the primary distribution grid by PSCAD*

Different from the LV distribution grid, the loads in the primary distribution grid can be directly modeled as a 3-phase load by using the 3-phase load model from the main library of PSCAD. However, the 3-phase load model in PSCAD’s main library is a fixed load, which means no variable load control similar to Figure 19 can be done in the primary distribution grid and every time one has to manually change the input of active and reactive power for the 3-phase load models.

• **Others**

The power cables in the primary distribution grid use the same simulation model in Figure 17. The input data of power cables can be found in Appendix E.2.

Multi-meters are located at each bus in the primary distribution grid in Figure 25.
Chapter 5 Results and analysis

5.1 The winter day

By running simulations in PSCAD, the operation of the LV and primary distribution grid is obtained. The voltage and active power profiles have been produced from the simulations. They are plotted in Figure 29-35. By checking the voltage profile, whether the model is reasonable or not can be proved.
In the LV distribution grid

Figure 29: Hourly Voltage in the LV distribution grid on the winter day

Figure 30: Voltage distribution in the LV distribution grid on the winter day
Figure 29 is an example showing voltage change at each bus in the LV distribution grid over time. For better observation of the voltage ranges, Figure 30 has been produced. The blue and the red line show the minimum and maximum values on the winter day at each bus. The vertical black lines between each couple of minimum and maximum points is the drop line symbolizing the range between the above two extreme points. A data table of minimum and maximum values is attached below the plots. The voltages all keep within limits at peak load of the grid and stay at a low level (most hours below 1.0 p.u. and lowest bus voltage is smaller than 0.92 p.u.).

In Figure 29 and 30, the vertical axis shows the voltage in p.u. The nominal value of the voltage is 400 V for most buses and 10 kV for BusAll, since BusAll connects the primary side of the two distribution transformers in the LV distribution grid. In Figure 29, the horizontal axis shows the time in hours in one day. Hour 1 stands for 00:00-01:00, hour 2 stands for 01:00-02:00, and so on.

Figure 31: Active power consumption at 12 buses of the LV distribution grid on the winter day
Figure 32: Active power consumption in the LV distribution grid on the winter day

The profile of active power flow at 12 buses is shown in Figure 31 and 32. Figure 31 shows the active power change over time. The active power change follows the opposite trend of voltage change in Figure 29. Figure 32 shows the range of active power. In Figure 32, the peak active power flow at BusAll (the bus connected to the primary side of the distribution transformers in the LV distribution grid) is below 0.9 MW. It means the total load of the LV distribution grid is far below 1.6 MVA, the load capacity even on the day with the highest load of the year.

In the primary distribution grid

Figure 33-35 show the voltages at buses in the primary distribution grid on the winter day, as well as the positions of the taps in the two on-load tap changers installed in the two transformers in the primary substation. The vertical axes show the voltage in per-unit value. The nominal value of the voltage is 10 kV in Figure 33 while 132 kV in Figure 35.
Figure 33: Voltage at 19 buses of primary distribution grid on the winter day
In Figure 34, the right figure shows that on the winter day, the tap positions of the two on-load tap changers in the transformers of the primary substation have not moved since the tap positions stay at 1 all day long. Besides, the vertical axis in Figure 34 (left figure) ‘Voltage at BusL19’ shows the voltage in kV, while the voltages of other buses are plotted in p.u. It is because of the format requirement in the PSCAD model of the OLTC.
Conclusion of the winter day

All the voltages keep within the limits at peak load of the grid. The voltages at buses are close to the lower voltage limit which is 0.9 p.u. Such a result is reasonable considering the peak load on the winter day. The result also partially shows that the model is reasonable.
5.2 The summer day

5.2.1 The base case

The summer day with no PV production is set as the base case. The profiles of voltage and active power flow in the LV and primary distribution grids have been produced from simulations and are plotted in Figure 36-40.

In the LV distribution grid

![Figure 36: Voltages in the LV distribution grid on the summer day [base case]](image)

In Figure 36, the voltages of the buses except BusAll in the LV distribution grid in the base case are between around 0.97-1.02 p.u.
In Figure 37, the peak load of the LV distribution grid is only around 0.5 MW, that is much lower than 0.9 MW on the winter day.

**In the primary distribution grid**

Figure 38-39 show the bus voltages and tap positions in the primary grid on the summer day [base case].
Figure 38: Voltage at 19 buses of primary distribution grid on the summer day [base case]
Figure 39: Voltage at BusL19 (left) and positions of taps in the OLTCs (right) of the primary distribution grid on the summer day [base case]

In Figure 38-39(left), from 1 am till 8 am, the voltage curves are influenced by the movement of tap positions of the transformers. The OLTCs compare the voltage at BusL19 (shown in Figure 39(left)) with 10.98 kV, the regulator voltage level to decide if the taps should be changed or not. From 1 am till 8 am, due to the light load status, the bus voltage tends to get higher than 10.98+0.1 kV. Then, the OLTCs change the positions of taps by $+1$ step and the effective transformer ratio of taps is $(1+1.67\%)*145\text{ kV}/11.6\text{ kV}$. 
5.2.2 First choice and second choice
If the customers in the flats make the first or second choice of PV capacity in Chapter 3.3, then the hourly PV production on the summer day is as the red or blue columns in Figure 14. Simulations have been run and profiles of voltages and active power flow in the LV and primary distribution grids have been produced from simulations and plotted in Figure 40-43. Since the voltage profiles in the primary distribution grid are almost the same as in the base case, they are not shown here again.

First choice - zero house emissions

![Figure 40: Voltage at 12 buses of the LV distribution grid on the summer day [first choice]](image)

In Figure 40, the bus voltages have a larger range compared to base case. The bus voltages are between 0.97-1.094 p.u., excluding BusAll. The voltage at Bus 11 reaches 1.094 p.u., very close to the upper limit of 1.1 p.u.
Figure 41: Active power at 12 buses of the LV distribution grid on the summer day [first choice]

In Figure 41, the power flow at most buses has a wider range compared to the base case. The mismatch between PV production and load results in the negative active power flow at buses. The peak of total active power flow of the LV distribution grid reaches -0.6 MW. Such an active power flow is larger than the base case, but it means the total apparent power is still far lower than 1.6 MVA, the load capacity of the LV distribution grid.
Second choice – peak production equals peak load

Figure 42: Voltage at 12 buses of the LV distribution grid on July 8th [second choice]

In Figure 42, the bus voltages stay between 0.97-1.02 p.u., excluding BusAll. Certain buses, e.g. Bus 10-12, have wider voltage ranges compared to the base case. But the voltages have at most increased by 1%.
Figure 43: Active power at 12 buses of the LV distribution grid on July 8th [second choice]

In Figure 43, the ranges of power flow at buses are close to the base case.
5.3 Analysis

- Impact on voltage rise

![Diagram showing voltage ranges at Bus 11 in four cases.]

*Figure 44: Voltage ranges at Bus 11 in four cases*

*Table 5-1: Summary of voltage at Bus 11*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter-day</td>
<td>0.9919</td>
<td>4am-5am</td>
<td>0.9298</td>
<td>7pm-8pm</td>
</tr>
<tr>
<td>Base-case</td>
<td>0.9989</td>
<td>12pm-1am</td>
<td>0.9735</td>
<td>8pm-9pm</td>
</tr>
<tr>
<td>Choice 1</td>
<td>1.0942</td>
<td>10am-11am</td>
<td>0.9735</td>
<td>8pm-9pm</td>
</tr>
<tr>
<td>Choice 2</td>
<td>1.0159</td>
<td>9am-10am</td>
<td>0.9735</td>
<td>8pm-9pm</td>
</tr>
</tbody>
</table>
Figure 45: Hourly voltage profiles at Bus 11 in four cases

The largest voltage fluctuations happen at Bus 11 according to the results presented in Chapter 5.1 and 5.2. The fluctuations of voltage range and hourly voltage at Bus 11 in four cases are summarized in Figure 44, 45 and Table 5-1. As a result of the first choice, voltage at Bus 11 reaches 1.0942 p.u. during 10-11 am. It is close to the upper limit of 1.1 p.u. It means that a 4 kWp PV system is the peak capacity that customers can choose. Furthermore, the maximum, minimum and median voltage values at Bus 11 day are stated in Table 5-1.
Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

- **Risk of active power flow over the system limit**

![Range of active power flow at Bus 11 in four cases](image)

**Figure 46: Range of active power flow at Bus 11 in four cases**

**Table 5-2 summary of active power flow at Bus 11**

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum of active power flow [MW]</th>
<th>Time[Hour]</th>
<th>Total active power flow [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter-day</td>
<td>0.0737</td>
<td>8pm-9pm</td>
<td>1.1494</td>
</tr>
<tr>
<td>Base-case</td>
<td>0.0498</td>
<td>8pm-9pm</td>
<td>0.7048</td>
</tr>
<tr>
<td>Choice 1</td>
<td>-0.2915</td>
<td>12am-1pm</td>
<td>-1.3278</td>
</tr>
<tr>
<td>Choice 2</td>
<td>0.0498</td>
<td>8pm-9pm</td>
<td>0.2916</td>
</tr>
</tbody>
</table>
Figure 47: Hourly active power flow at Bus 11 in four cases

Figure 46, Table 5-2 and 47 compare the range of active power flow and hourly active power flow at Bus 11. They show another impact caused by PV production of the first choice. In Figure 47, on the winter day, the peak load at Bus 11 is 0.0737 MW. However, on the summer day, the negative active power flow at Bus 11 keeps between 0.08-0.3MW from 8 am to 4 pm for the first choice. The active power flow at Bus 11 might already go beyond the system limit, i.e. the power cable ampacity. These are the risky scenarios for Bus 11 and clearly stated in Table 5-3.

Table 5-3 Risky scenarios of active power flow at Bus 11

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.1217</td>
<td>8am-9am</td>
</tr>
<tr>
<td></td>
<td>-0.2336</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.2735</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.2892</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.2915</td>
<td>12am-1pm</td>
</tr>
<tr>
<td></td>
<td>-0.1428</td>
<td>1pm-2pm</td>
</tr>
<tr>
<td></td>
<td>-0.1912</td>
<td>2pm-3pm</td>
</tr>
<tr>
<td></td>
<td>-0.0800</td>
<td>3pm-4pm</td>
</tr>
</tbody>
</table>
At the phase of designing an LV distribution grid composed of residences, the system limit usually depends on the hourly peak load per flat. In Chapter 3.2, the hourly peak load per flat is 0.8 kWh/h, but the customers have chosen a 4 kWp PV system for the first choice. This is the reason of such a huge negative active power flow at Bus 11. At Bus 4, 7-10 and 12, similar risky scenarios exist and the detailed tables are attached in Appendix F.

This impact can be even worse. If considering a moment of zero-load but maximum PV production, the negative power flow could be even much higher. Though such a case doesn’t exist in this thesis, it could happen in reality.

- **Lower load at the transformers in certain hours**

![Active power flow at Transformer 1 in four cases](image)

*Figure 48: Active power flow at Transformer 1 in four cases*
Figure 49: Active power flow at Transformer 2 in four cases

Figure 48-49 compare hourly active power flow at the two distribution transformers in the LV distribution grid in four cases. As a result of the first choice, two transformers need to handle negative active power flow. The maximum absolute values of negative power flow at the transformers of the first choice are still lower than the peak load on the winter day. However, as a result of the second choice, from 3 am to 8 pm on the summer day, the loads on the two transformers are lower than the base case. It means fewer burdens on the transformers during these hours. This is good for the transformers, since less heating is produced. Table 5-4 is an example. It shows the hourly load profiles of Base case and Choice 2 of Transformer T1 between 3 am and 8 pm.

Table 5-4 Lowered hourly load at Transformer T1

<table>
<thead>
<tr>
<th>Time [Hour]</th>
<th>Base case [MW]</th>
<th>Choice 2 [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3am-4am</td>
<td>0.0783</td>
<td>0.0779</td>
</tr>
<tr>
<td>4am-5am</td>
<td>0.0726</td>
<td>0.0693</td>
</tr>
<tr>
<td>5am-6am</td>
<td>0.0705</td>
<td>0.0653</td>
</tr>
<tr>
<td>6am-7am</td>
<td>0.0769</td>
<td>0.0695</td>
</tr>
<tr>
<td>7am-8am</td>
<td>0.0933</td>
<td>0.0807</td>
</tr>
<tr>
<td>8am-9am</td>
<td>0.1418</td>
<td>0.0983</td>
</tr>
<tr>
<td>Time</td>
<td>T1</td>
<td>T2</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>9am-10am</td>
<td>0.1694</td>
<td>0.0832</td>
</tr>
<tr>
<td>10am-11am</td>
<td>0.1957</td>
<td>0.1053</td>
</tr>
<tr>
<td>11am-12am</td>
<td>0.2091</td>
<td>0.1128</td>
</tr>
<tr>
<td>12am-1pm</td>
<td>0.2091</td>
<td>0.1124</td>
</tr>
<tr>
<td>1pm-2pm</td>
<td>0.2071</td>
<td>0.1573</td>
</tr>
<tr>
<td>2pm-3pm</td>
<td>0.2021</td>
<td>0.1369</td>
</tr>
<tr>
<td>3pm-4pm</td>
<td>0.2019</td>
<td>0.1630</td>
</tr>
<tr>
<td>4pm-5pm</td>
<td>0.2071</td>
<td>0.1951</td>
</tr>
<tr>
<td>5pm-6pm</td>
<td>0.2046</td>
<td>0.1985</td>
</tr>
<tr>
<td>6pm-7pm</td>
<td>0.1935</td>
<td>0.1899</td>
</tr>
<tr>
<td>7pm-8pm</td>
<td>0.2056</td>
<td>0.2038</td>
</tr>
</tbody>
</table>

Furthermore, Table 5-5 summarizes the different load profiles at the two transformers on the winter and summer day. It shows that on the summer day, without considering the direction of active power flow at transformers (whether load or generation mode), the total active flow at both transformers from 3 am to 8 pm (when PV generation is not zero) have been lowered by Choice 1 and 2, compared to Base case.

Table 5-5: Summary of transformer loads

<table>
<thead>
<tr>
<th>Cases</th>
<th>Time [Hour]</th>
<th>Total Load [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T1</td>
</tr>
<tr>
<td>Winter-day</td>
<td>3 am-8 pm</td>
<td>4.7937</td>
</tr>
<tr>
<td>Base case</td>
<td>3 am-8 pm</td>
<td>2.7386</td>
</tr>
<tr>
<td>Choice 1</td>
<td>3 am-8 pm</td>
<td>-0.3141</td>
</tr>
<tr>
<td>Choice 2</td>
<td>3 am-8 pm</td>
<td>2.1191</td>
</tr>
</tbody>
</table>
Chapter 6 Conclusion

Simulations of a real low and medium voltage network in the city of Västerås in Sweden have been performed. The simulations show different scenarios of PV penetration and none of the cases show problems with over-voltages above the limit of 10% above the system voltage. However, during summer days with high PV production and low loads in the system, the currents might reach levels above the capacity of the installed cables.

For the simulations, two typical days have been chosen. The winter case is a day in December where the solar irradiation is low and the load is shown to be the highest in the year. This case was used to simulate the voltage levels along the feeders at full load to verify the model. The other case is a summer day in July where the production is very high and the loads are low. This is considered as the worst case in the year with PV production. All loads and PV production are assumed three phase and balanced since no transient analysis are performed.

The simulations of the winter day shows the customers in the end of the feeder will experience a voltage below the system voltage due to the voltage drop along the feeder. This voltage drop is seen to be about 8%, i.e. within the margins of ±10%. This partially shows that the used model is reasonable and can be used for the investigation.

For the simulations in the summer day two cases have been studied. In both cases a PV penetration of 100% has been assumed, i.e. all household are equipped with the PV system investigated.

The first case is a zero emission household that has an annual PV production equal to the annual electricity consumption. According to Swedish DSOs regulations, this is the limit where the household is still considered to be a consumer. With a higher PV production, the household will be classified as a producer and additional fees for the household will apply. Due to the mismatch between produced power and need of electricity, the utilization of the produced PV power is low. This means that during summer most of the produced electricity will be exported and will increase the loading of the grid. Such as result is demanding for the LV distribution grid, since the peak load in Sweden occurs during winter when there is almost no PV production and the peak production occurs during summer when the loading is very low.

The second case is based on the peak load. If a PV system is installed with a peak production equal to the peak load in the household, there should be no problems in the electrical grid. Even with a PV penetration of 100%, the loading of the grid at maximum production should not exceed the loading at peak load and no PV penetration.

The PV production used in the model is based on recorded real PV production data from 2011. From the production data and the rated power of the PV system, the production of the modelled PV systems has been calculated with a linear scaling. The time resolution of the production is 1 hour which is used also in the simulations.
A simulation model has been built in PSCAD and steady state simulations have been performed for each of the 24 hours in the proposed days. The simulations of the summer day with no PV production show that all voltages are within the system voltage±2% since the loading of the system is low.

When all houses in the network are considered as zero emission households, the voltage gradient along the feeder increases dramatically. The lowest voltage levels stay constant since the solar irradiation in the evening is not enough to significantly affect the power flows. During midday, the voltage in the outermost parts of the feeders, where also the biggest group of flats is directly connected (115 flat), reaches more than 9% above the rated voltage.

Even though the voltage levels of all buses stay within the specified limits, some limitations of the system can be seen. The power flow is reversed in the whole LV network and even though the reversed power flow in both distribution transformers exceeds the peak load during the evening, the levels are still only 65-70% of the winter loading. In one of the buses, the reverse power flow reaches more than 3 times the peak power flow in the winter. Depending on the capacity of the installed power cables, this might be above the system limit.

When a PV system with a rated power equal to the peak load is applied, the voltage profile of the feeders changes. In the case of a summer day with low load and high production, the production exceeds the load and the direction of the power flow is reversed. In the end of the feeder, the voltage reaches 2% above the rated voltage around lunchtime. The lowest voltage is still observed at 2% below the rated voltage during the load peak in the evening when the solar irradiation is lower. Due to some commercial loads in the network, all produced power is consumed within the LV network and the power flow through the distribution transformers is never reversed.

Based on the simulation results, the Swedish DSOs need to have more regulations on the PV generation and penetration from residences before the massive PV penetration from residences becomes reality. Otherwise, once more incentives are applied and prices of residential PV systems lowered, the impacts on grid components will soon show up and in some cases voltage rise in the LV distribution grids could go even higher over the limit.

Besides, all production is lowered by 10 %, as mentioned on page 31, but it only affects the numerical results and probably the results are qualitatively correct in general.
Chapter 7 limitation and future work

Due to the limited scope of the thesis, the study of the impact on voltage rise by PV generation in Swedish urban areas with high PV population can be improved with some future work.

7.1 Shorter intervals of load

In the thesis, the average load/consumption in the interval of an hour is used in the modeling and simulation of the targeted LV distribution grid, due to the limited original load data. The result can be more precise if the interval can be reduced to 15 minutes [15].

7.2 Feeder lines instead of Buses/CCPs

In the thesis, buses or CCPs are used due to the limited data of grid configurations and simulations stop at CCPs’ level. However, if simulations can further go to the feeder lines into each household, then the result of voltage at each household can be simulated instead of the voltage at each CCP or bus.

7.3 Harmonics influence from the inverter inside PV systems.

In some pilot projects of PV generation in urban areas in Europe with high PV population, the harmonics impact on current injected from residential PV systems into households or grids has been observed already [8]. A more complete study on the power quality in Swedish urban areas with high PV population can be achieved with harmonics analysis included.
Appendixes

Appendix A: References


[8] Sief Cobben (Continuon), Bruno Gaiddon (Hespul), Hermann Laukapm (Fraunhofer ISE), Impact of photovoltaic generation on power quality in urban areas with high PV population, Version date: 2008-07-14, Europe, 2008


[10] Västerås Official website


Appendix B: Configurations of the primary distribution grid

B.1 Configurations of transformers in the primary substation
The two transformers in the primary substation have identical configurations as follows.
40MVA, OFAF;
X=13.804%, R= 0.851;
YY connection; Star Pt. grounded through reactance on LV side

B.2 Configurations of power cables in the primary distribution grid

Table Appendix B.1: Configurations of power cables in the primary distribution grid

<table>
<thead>
<tr>
<th>Size</th>
<th>R- ohms/km</th>
<th>X- mH/km</th>
<th>C - uF/km</th>
<th>A65 - Ground</th>
<th>A90 - Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 AX</td>
<td>0.125</td>
<td>0.27</td>
<td>0.43</td>
<td>350</td>
<td>415</td>
</tr>
<tr>
<td>150 AX</td>
<td>0.206</td>
<td>0.29</td>
<td>0.36</td>
<td>270</td>
<td>315</td>
</tr>
</tbody>
</table>

Ground Temp = 15 deg.

B.3 Original load data of 19 loads in the primary distribution grid

Table Appendix B.2: Original load data in the primary distribution grid

<table>
<thead>
<tr>
<th>Load No</th>
<th>Amps/phase at 400V side of transformer</th>
<th>transformer rating in MVA</th>
<th>Peak Load in MVA</th>
<th>pf(assumption)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>650</td>
<td>0.8</td>
<td>0.45032</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>0.8</td>
<td>0.6928</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>750</td>
<td>0.8</td>
<td>0.5196</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>0.5</td>
<td>0.3464</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>0.5</td>
<td>0.3819</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>800</td>
<td>0.8</td>
<td>0.56424</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>450</td>
<td>0.5</td>
<td>0.31176</td>
<td>0.9</td>
</tr>
<tr>
<td>8</td>
<td>800</td>
<td>0.8</td>
<td>0.53424</td>
<td>0.9</td>
</tr>
<tr>
<td>9</td>
<td>1200</td>
<td>2.4=0.800+0.800+0.800</td>
<td>0.83316</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>1200</td>
<td>1.6=0.800+0.800</td>
<td>0.83316</td>
<td>0.9</td>
</tr>
<tr>
<td>11</td>
<td>900</td>
<td>0.8</td>
<td>0.62252</td>
<td>0.9</td>
</tr>
<tr>
<td>12</td>
<td>400</td>
<td>1.6=0.800+0.800</td>
<td>0.27712</td>
<td>0.9</td>
</tr>
<tr>
<td>13</td>
<td>900</td>
<td>0.315</td>
<td>0.03464</td>
<td>0.9</td>
</tr>
<tr>
<td>14</td>
<td>900</td>
<td>0.32852</td>
<td>0.03464</td>
<td>0.9</td>
</tr>
<tr>
<td>15</td>
<td>950</td>
<td>0.8</td>
<td>0.00810</td>
<td>0.9</td>
</tr>
<tr>
<td>16</td>
<td>1200</td>
<td>1.6=0.800+0.800</td>
<td>0.83136</td>
<td>0.9</td>
</tr>
<tr>
<td>17</td>
<td>500</td>
<td>0.5</td>
<td>0.3464</td>
<td>0.9</td>
</tr>
<tr>
<td>Load No</td>
<td>Amps/phase at 11kV side of transformer</td>
<td>transformer rating in MVA</td>
<td>Peak Load in MVA</td>
<td>pf(assumption)</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------</td>
<td>---------------------------</td>
<td>-------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>19</td>
<td>801 unknown</td>
<td>31.507408</td>
<td>11.507408</td>
<td>0.9</td>
</tr>
</tbody>
</table>

In Table Appendix B.2, the second column shows peak currents recorded at each load in the primary distribution grid. The fourth column shows the peak loads in MVA. The fifth column shows the assumed power factor.
Appendix C: Configurations of the targeted LV distribution grid

C.1 Configurations of the distribution transformers in the LV distribution grid

The two distribution transformers in the secondary substation in the targeted LV distribution grid are named T1-1311 and T2-1310 respectively and have identical configurations as follows.

800 kVA, ONAN;
X=4.829%, R=0.829%;
Delta-Y connection; Star Pt. solidly grounded on LV side

C.2 Configurations of 9 sections of power cables in the LV distribution grid

Table Appendix C.1: Configurations of power cables in the LV distribution grid

<table>
<thead>
<tr>
<th>Size</th>
<th>R- ohms/km</th>
<th>L- mH/km</th>
<th>C - uF/km</th>
<th>A65 - Ground</th>
<th>A90 - Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 AX</td>
<td>0.32</td>
<td>0.31</td>
<td>0.3</td>
<td>220</td>
<td>260</td>
</tr>
<tr>
<td>150 AX</td>
<td>0.206</td>
<td>0.29</td>
<td>0.36</td>
<td>285</td>
<td>335</td>
</tr>
<tr>
<td>50 FKKJ</td>
<td>0.641</td>
<td>0.24</td>
<td>0.5</td>
<td>150</td>
<td>175</td>
</tr>
<tr>
<td>120 FKKJ</td>
<td>0.253</td>
<td>0.23</td>
<td>0.57</td>
<td>255</td>
<td>300</td>
</tr>
<tr>
<td>240 AKKJ</td>
<td>0.125</td>
<td>0.22</td>
<td>0.6</td>
<td>370</td>
<td>440</td>
</tr>
<tr>
<td>240 N1XV</td>
<td>0.125</td>
<td>0.21</td>
<td>0.61</td>
<td>370</td>
<td>440</td>
</tr>
</tbody>
</table>

C.3 Original load data in the LV distribution grid

Table Appendix C.2: Load composition and flat numbers

<table>
<thead>
<tr>
<th>Name of Load</th>
<th>Flat number or other consumption</th>
<th>Content of other consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Load 2</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Load 3</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Load 4</td>
<td>63[12.5% residential, the rest commercial]</td>
<td>offices, school</td>
</tr>
<tr>
<td>Load 5</td>
<td>0[12.5% residential, the rest commercial]</td>
<td>Offices</td>
</tr>
<tr>
<td>Load 6</td>
<td>0[commercial]</td>
<td>School, offices</td>
</tr>
<tr>
<td>Load 7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Load 8</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Load 9</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Load 10</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Load 11</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>
Table Appendix C.3 Load compositions in the LV distribution grid

<table>
<thead>
<tr>
<th>Load</th>
<th>Annual Energy Consumption (kwh)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1</td>
<td>63045</td>
<td></td>
</tr>
<tr>
<td>Load 2</td>
<td>67141</td>
<td></td>
</tr>
<tr>
<td>Load 3</td>
<td>255704</td>
<td></td>
</tr>
<tr>
<td>Load 4</td>
<td>441155</td>
<td>Offices, flats, childcare center</td>
</tr>
<tr>
<td>Load 5</td>
<td>1108982</td>
<td>Offices, some commercial</td>
</tr>
<tr>
<td>Load 6</td>
<td>1824326</td>
<td>School and some offices</td>
</tr>
<tr>
<td>Load 7</td>
<td>33341</td>
<td></td>
</tr>
<tr>
<td>Load 8</td>
<td>312330</td>
<td></td>
</tr>
<tr>
<td>Load 9</td>
<td>402580</td>
<td></td>
</tr>
<tr>
<td>Load 10</td>
<td>148149</td>
<td></td>
</tr>
<tr>
<td>Load 11</td>
<td>75201</td>
<td></td>
</tr>
</tbody>
</table>

Maximum kVA Recorded at the secondary substation of the targeted LV distribution grid = 1201 kVA
**Appendix D: Hourly PV generation in 'G case' in 2011**

In Figure 51-55 four traditional seasons are further divided into 8 sub seasons (shown in *Table Appendix D.1*). It is for better observation of solar irradiation change with days in a year, since Sweden is located in high latitudes [10]. The horizontal axes represent hours in the sub-seasons. Hour 1 resembles 00:00-01:00 on the first day of the corresponding sub-season and so on. Vertical axes show the generated electricity from the residential PV system in kWh. The trend-lines are plotted in black.

*Table Appendix D.1 Seasons for irradiation change*

<table>
<thead>
<tr>
<th>Season</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-spring1</td>
<td>Sub-spring2</td>
<td>Sub-summer1</td>
<td>Sub-summer2</td>
<td>Sub-autumn1</td>
</tr>
<tr>
<td>Week 9-11</td>
<td>Week 12-17</td>
<td>Week 18-24</td>
<td>Week 25-30</td>
<td>Week 31-38</td>
</tr>
</tbody>
</table>

**Spring**

![sub-spring 1](image)

![sub-spring 2](image)

*Figure 50: Hourly PV production in two sub seasons of spring*
Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

Figure 51: Hourly PV production in two sub seasons of summer

Figure 52: Hourly PV production in two sub seasons of autumn
Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

**Winter**

**Figure 53: Hourly PV production in two sub-winter 1**

**Figure 54: Hourly PV production in two sub-winter 2**

Appendix D: Hourly PV generation in ‘G case’ in 2011
Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

Appendix E: Input Data of power cables by PSCAD

### E.1 Input Data of power cables in the LV distribution grid

Table Appendix E.1: Input Data of power cables in the LV distribution grid by PSCAD

<table>
<thead>
<tr>
<th>Section</th>
<th>Content</th>
<th>positive sequence resistance (ohm/m)</th>
<th>positive sequence inductive reactance (ohm/m)</th>
<th>positive sequence capacitive reactance (MOhm*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Use ideal branch 150AX</td>
<td>0.000206</td>
<td>9.11061E-05</td>
<td>8.841948751</td>
</tr>
<tr>
<td>2</td>
<td>120FKKJ 100m</td>
<td>0.000253</td>
<td>7.22566E-05</td>
<td>5.584388685</td>
</tr>
<tr>
<td>3</td>
<td>240AKKJ 200m</td>
<td>0.000125</td>
<td>6.9115E-05</td>
<td>5.305169251</td>
</tr>
<tr>
<td>4</td>
<td>2*240N1XV 130m</td>
<td>0.0000625</td>
<td>3.29867E-05</td>
<td>2.609099632</td>
</tr>
<tr>
<td>5</td>
<td>240N1XV 130m</td>
<td>0.000125</td>
<td>6.59734E-05</td>
<td>5.218199263</td>
</tr>
<tr>
<td>6</td>
<td>240N1XV 200m</td>
<td>0.000125</td>
<td>6.59734E-05</td>
<td>5.218199263</td>
</tr>
<tr>
<td>7</td>
<td>120FKKJ 70m</td>
<td>0.000253</td>
<td>7.22566E-05</td>
<td>5.584388685</td>
</tr>
<tr>
<td>8</td>
<td>240N1XV 190m</td>
<td>0.000125</td>
<td>6.59734E-05</td>
<td>5.218199263</td>
</tr>
<tr>
<td>9</td>
<td>50FKKJ 100m</td>
<td>0.000641</td>
<td>7.53982E-05</td>
<td>6.366203101</td>
</tr>
</tbody>
</table>

### E.2 Input data of power cables in the primary distribution grid by PSCAD

Table Appendix E.2: Input Data of power cables in the primary distribution grid by PSCAD

<table>
<thead>
<tr>
<th>Section</th>
<th>R, ohm/m</th>
<th>Xl, ohm/m</th>
<th>Xc, Mohm*m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>2</td>
<td>0.00159714</td>
<td>8.75158E-05</td>
<td>7.957753876</td>
</tr>
<tr>
<td>3</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>4</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>5</td>
<td>0.000206</td>
<td>9.11061E-05</td>
<td>8.841948751</td>
</tr>
<tr>
<td>6</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>7</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>8</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>9</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>10</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>11</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>12</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>13</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>14</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>15</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>16</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
</tbody>
</table>
Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>18</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
<tr>
<td>19</td>
<td>0.000125</td>
<td>8.48229E-05</td>
<td>7.402561745</td>
</tr>
</tbody>
</table>
Appendix F: Risky scenarios of active power flow at Bus 4, 7-10 and 12

F.1: Bus 4

At Bus 4, the peak load \textbf{0.1479} MW appears at 7pm-8pm on the winter day.

\textit{Table Appendix F.1: Risky scenarios of active power flow at Bus 4}

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.1602</td>
<td>8am-9am</td>
</tr>
<tr>
<td></td>
<td>-0.3757</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.3883</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.4164</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.4183</td>
<td>12am-1pm</td>
</tr>
<tr>
<td></td>
<td>-0.1724</td>
<td>1pm-2pm</td>
</tr>
<tr>
<td></td>
<td>-0.2560</td>
<td>2pm-3pm</td>
</tr>
</tbody>
</table>

F.2: Bus 7

At Bus 7, the peak load \textbf{0.1329} MW appears at 8pm-9pm on the winter day.

\textit{Table Appendix F.2: Risky scenarios of active power flow at Bus 7}

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.2148</td>
<td>8am-9am</td>
</tr>
<tr>
<td></td>
<td>-0.4023</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.4703</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.4920</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.4952</td>
<td>12am-1pm</td>
</tr>
<tr>
<td></td>
<td>-0.2516</td>
<td>1pm-2pm</td>
</tr>
<tr>
<td></td>
<td>-0.3365</td>
<td>2pm-3pm</td>
</tr>
<tr>
<td></td>
<td>-0.1419</td>
<td>3pm-4pm</td>
</tr>
</tbody>
</table>

F.3: Bus 8

At Bus 8, the peak load \textbf{0.0434} MW appears at 8pm-9pm on the winter day.

\textit{Table Appendix F.3: Risky scenarios of active power flow at Bus 8}

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.0648</td>
<td>8am-9am</td>
</tr>
<tr>
<td></td>
<td>-0.1382</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.1498</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.1571</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.1576</td>
<td>12am-1pm</td>
</tr>
<tr>
<td></td>
<td>-0.0757</td>
<td>1pm-2pm</td>
</tr>
<tr>
<td></td>
<td>-0.1057</td>
<td>2pm-3pm</td>
</tr>
</tbody>
</table>
Impact on voltage rise of photovoltaic generation in Swedish urban areas with high PV population

F.4: Bus 9
At Bus 9, the peak load 0.0487 MW appears at 8pm-9pm on the winter day.

*Table Appendix F.4: Risky scenarios of active power flow at Bus 9*

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.0751</td>
<td>8am-9am</td>
</tr>
<tr>
<td></td>
<td>-0.1718</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.1809</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.1950</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.1958</td>
<td>12am-1pm</td>
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<tr>
<td></td>
<td>-0.0879</td>
<td>1pm-2pm</td>
</tr>
<tr>
<td></td>
<td>-0.1245</td>
<td>2pm-3pm</td>
</tr>
<tr>
<td></td>
<td>-0.0495</td>
<td>3pm-4pm</td>
</tr>
</tbody>
</table>

F.5: Bus 10
At Bus 10, the peak load 0.0846 MW appears at 4pm-5pm on the winter day.

*Table Appendix F.5: Risky scenarios of active power flow at Bus 10*

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.1234</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.1230</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.1309</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.1317</td>
<td>12am-1pm</td>
</tr>
</tbody>
</table>

Bus 10 is directly connected to Load 4, a mixed type of load. 12.5% of Load 4 is residential (flats) and the remaining 87.5% is commercial (offices and school) as shown in Appendix C. In this thesis, only the flats are assumed to install PV systems.

F.6: Bus 12
At Bus 12, the peak load 0.0144 MW appears at 7pm-8pm on the winter day.

*Table Appendix F.6: Risky scenarios of active power flow at Bus 12*

<table>
<thead>
<tr>
<th>Case</th>
<th>Active power flow [MW]</th>
<th>Time [Hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>-0.0217</td>
<td>8am-9am</td>
</tr>
<tr>
<td></td>
<td>-0.0467</td>
<td>9am-10am</td>
</tr>
<tr>
<td></td>
<td>-0.0507</td>
<td>10am-11am</td>
</tr>
<tr>
<td></td>
<td>-0.0532</td>
<td>11am-12am</td>
</tr>
<tr>
<td></td>
<td>-0.0534</td>
<td>12am-1pm</td>
</tr>
<tr>
<td></td>
<td>-0.0254</td>
<td>1pm-2pm</td>
</tr>
<tr>
<td></td>
<td>-0.0356</td>
<td>2pm-3pm</td>
</tr>
</tbody>
</table>