Sustainable & smart distribution networks

Thesis

EE BEP Group B

Subgroup A - Topology Design

Pieter Gommers
Loran Ottink

TU Delft

Sustainable & smart distribution networks

Thesis

by

EE BEP Group B

to obtain the degree of Bachelor of Science
at the Delft University of Technology,
to be defended on Monday June 20, 2022 at 9:00 AM.

Student numbers:	5085594 (Loran Ottink), 4923189 (Pieter Gommers)	
Project duration:	April 19, 2022 – June 24, 2022	
Thesis committee:	Dr. P.P. (Pedro) Vergara Barrios,	TU Delft, supervisor
	NK (Nanda) Panda,	TU Delft, daily supervisor

TU Delft

Preface

In this thesis the build plans for a new residential neighbourhoord, Vechtrijk, are used as a basis for an imaginary neighbourhood of the future. All data is converted to fit in this imaginary neighbourhood with an abundance of PV systems, EV charging stations and electric heating inside the houses. While this imaginary neighbourhood often simply is called 'the Vechtrijk neighbourhood', in fact it is not connected to the real build plans and always the imaginary neighbourhood is meant. We thank the project developer, L. Roodbol from Blauwhoed , for sharing detailed maps from the build plans.

We thank our supervisor, Dr. P. P. Vergara and our daily supervisor, N. Panda for their continuing support.

EE BEP Group B Delft, June 2022

Contents

1 Introduction

Tackling global warming is seen by many as one of the biggest challenges mankind faces in the 21st century. Humans cause too much greenhouse gas emission, causing sunlight to warm up the surface of the earth more through the greenhouse effect. This effect results in (possibly irreversible) changes in the climate worldwide, which could lead to catastrophic disasters. In the Netherlands, the residential sector produced 15.4 Tg CO2 equivalent (CO2 and other greenhouse gasses) in 2019 with heating, water heating and cooking, which accounts for 8.5% of the total CO2 equivalent emissions of the Netherlands in 2019. Fossil-fueled road transportation produced 29.6 Tg CO2 equivalent, which accounts for 16.4% of the total CO2 equivalent emission of the Netherlands in 2019 [1]. New technology developments such as electric cars, photovoltaic (PV) systems and electric heating and cooking can reduce the greenhouse gas emissions. However, these newly developed sustainable solutions have a drawback. The current low-voltage (LV) grid is not designed for their combined operation and the increasing penetration of PV systems, EV charging stations and electric heating and cooking could result in more problems like congestion and excessive fluctuations in voltage and frequency. In Amsterdam, congestion already is a big problem [2].

Allowing more energy-sustainable options to be implemented and connected to the grid while preventing problems like congestion will be a challenge for engineers in the upcoming years. Upgrades to the grid and other solutions to cope with this challenge are researched and proposed in this thesis. Following this general introduction, first follows a section that elaborates on the neighbourhood of the future in general. Then a neighbourhood that is being developed right now in the Netherlands is introduced, this neighbourhood will be used as example neighbourhood of the future throughout the thesis. Finally congestion is explained, as coping with congestion is one of the biggest challenges that the neighbourhood of the future will create.

1.1. Neighbourhood of the future

In the neighbourhood of the future, the previously stated residential and road transportation sectors will probably have shifted for a large part to all-electric solutions. The advantage of all-electric solutions is that the source of energy is interchangeable, meaning that fossil fuels can be replaced by sustainable energy sources with a dramatically lower emission of greenhouse gasses like wind or solar energy. In the Netherlands electrical cooking and heating is quickly rising in popularity; the amount of heat extracted from the air with heat pumps for the heating of residential buildings has more than doubled between 2018 and 2020 [3]. Also, the number of electric vehicles (EVs) in the Netherlands has approximately doubled every year from 2017 until 2021 [4]. Finally, the number of photovoltaic (PV) systems installed on residential buildings has also been steadily increasing. It is easily visible when walking outside anywhere in the Netherlands that a lot of households have PV systems on their roofs. While these solutions are effective in reducing our dependence on fossil fuels, they create new challenges for grid operators. First of all, because the grid is not designed for the high currents that will run through it, congestion will occur. Secondly, as part of the power generation is happening outside the control of the grid operators, it is harder to prevent problematic voltage and frequency fluctuations.

1.2. Vechtrijk neighbourhood

In order to design, forecast and optimize a sustainable distribution network, first a neighbourhood needs to be considered. A new developing neighbourhood was found in Weesp in the Netherlands. It consists of 37 total houses, a combination of detached houses, semi-detached houses, terraced houses and apartments, which can be seen in Figure 1.1. It also consists of a central parking area where electric vehicles might be parked and charged. We think this is a good representation of an all-encompassing neighbourhood in the Netherlands and thus a good neighbourhood to design a sustainable grid for [5].

Figure 1.1: The Vechtrijk neighbourhood ground plan

1.3. Congestion: Definition and issues

Grid congestion occurs when an overloaded grid prevents electricity from reaching the consumers. It can be illustrated as a kind of traffic jam, where the electrons in the wire are symbolized by the vehicles on a highway. During rush hour, too many vehicles are present and the flow of traffic may come to a halt. A similar situation occurs on power lines as demand or supply of power is in excess. The high current the power line has to carry can exceed the maximum capacity of the lines. This will eventually lead to power outages and costly repairs on power lines. In the Netherlands congestion is becoming a large issue. Figure 1.2 illustrates the significance of the problem. It is visible, that congestion due to high demand happens the most in urban areas such as the province of North Holland and around Leeuwarden. Furthermore, it is visible that congestion due to high generation happens more in rural areas such as the provinces Drenthe, Overijssel and Gelderland in the east of the Netherlands. In order to avoid power outages Distribution System Operators (DSOs) disconnect parts of the system during power excess. This necessary measure has great impact; generation systems are put on standby or consumers will have to seize their activities. Additionally, the connection to the grid for a newly installed system might take more than a year [6].

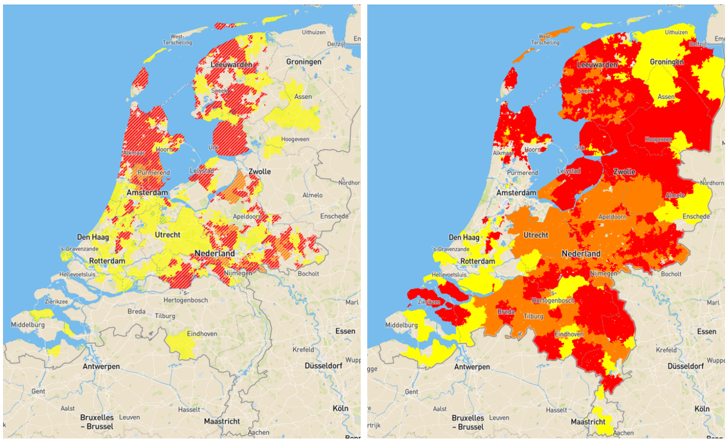


Figure 1.2: Consumption (left) and generation (right) congestion in The Netherlands [7]

1.4. Topology design

The electricity demand will increase significantly with the replacement of gas with electricity as an energy source to, for example, cook and heat the house. In addition, distributed generation elements such as PV systems cause a shift in the distribution networks from a passive system with unidirectional power flow to an active system with bidirectional power flow [8]. In other words, the grid as it stands currently is not designed for this change. When the Dutch grid first took its form, the transmission grid was designed as a meshed structure, connected to the rest of the European transmission grid [9]. The distribution grid had a mostly radial, or in some cases, loop structure. The different topological structures can be seen in Figure 1.3. The arrows signify loads connected to the grid busses and the circle represents the external transmission grid. The goal of the system was to generate power at large electricity facilities, transmit the power to distribution networks and radially distribute the power over the users, without the presence of Distributed Generation (DG) or storage of energy; the power only flows in a single direction. With this design, congestion will only occur when the demand in a part of the distribution network is too high and the current through the cables goes beyond its maximum allowed value.

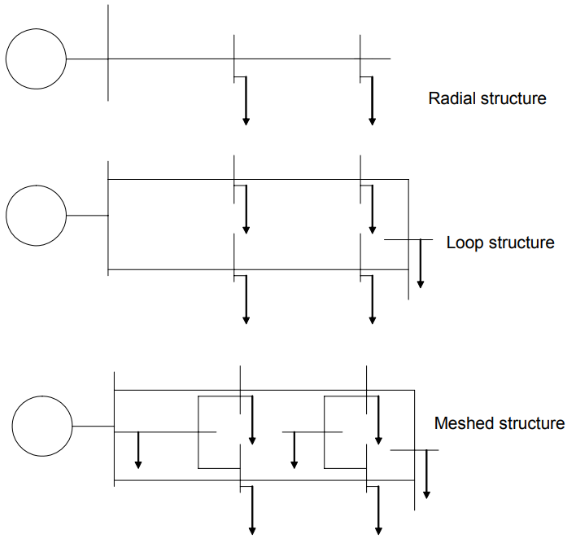


Figure 1.3: Grid topologies: Radial, Loop and Meshed structure

Most distribution networks can be represented by a disjoint radial graph with its root node being a substation and the other nodes being the customers (the load buses) [10]. In a substation there are step-down transformers which connect the transmission network with the distribution network and lower the voltage from the transmission network's 150kV High Voltage (HV) to 10kV for the Medium Voltage (MV) distribution network. Further down in the radial network are smaller transformers that lower the voltage 0.4kV which can be used by the houses [11]. It is at the customer nodes where you can see changes like the increasing amount of generation of electricity by PV systems and the rise in demand for electricity due to for example the installation of heat pumps [12].

Nowadays the grid has to cope with the introduction of bidirectional power flow and facilitate the absorption of power generated at the consumer nodes by PV systems. Because the power generation peak caused by PV during days with strong sun radiance can be much higher than the consumption peak, congestion is more likely to appear. The reason is that the network has limitations on the amount of power that can flow between two nodes, which has the consequence that the network cannot sometimes fully meet the interest [13]. Again, this is illustrated in Figure 1.2. The distribution grid needs to operate without the occurrence of congestion or a large reduction of the power quality, which can be divided into voltage band issues and synchronization issues.

1.4.1. Congestion

The simplest sounding solution to alleviate congestion would be to heavily reinforce the distribution network by over-sizing all network components [14]. This would allow more power flow between nodes and will make sure that the network can always fully meet its interests. However, this would be a very expensive undertaking, especially in urban areas with the presence of many other types of infrastructure. In [14], the authors discuss an optimization process that results in supporting the annual load growth, minimizing the line loss, maximizing the system reliability and improving the voltage profile, all while minimizing construction costs. The implementation of Dispatchable Distributed Generators (DDG) at the MV level is also a discussed topic to alleviate congestion in parts of the distribution network, although this will not be applicable to the LV network that will be designed in this thesis.

Reconfiguration of feeders could be a way to solve congestion in the distribution network [15] [16]. By implementing a Genetic Algorithm to identify the optimal feeder configuration the amount of congestion can be minimized. Even when no congestion occurs, the amount of electrical losses can also be reduced to a minimum. Implementing on-demand DDG stations at smart locations in the MV part of the distribution network can solve high demand peaks locally. This requires the need for information and communication technology to facilitate the control of the system. A large part of this control system comes from smart metering [17]. This will make the grid more data transparent. It is possible to measure the consumption and generation and also retrieve those data via a communication network, which makes the network more manageable and controllable. This will however require control and communication algorithms [18]. The discussion of several strategies to reduce the problems corresponding to congestion is done in [17], all of which are related to software algorithms for disconnecting PV systems. The configuration of feeders is a topic that will be looked after in this thesis, although not through the help of genetic algorithms, since dynamic feeder re-configuration is out of the scope of this project.

Battery Energy Storage Systems (BESS) are receiving increased attention regarding the distribution network issues [19]. The article discusses how the placement of BESS at specific locations on LV feeders can manage power flow and achieve benefits in feeder voltage profiles, cable loading and electricity losses. During peak hours in either demand or generation, BESS can absorb the excess or provide the need for energy. Even though large BESS might not yet be financially feasible, their costs will only decrease as technology advances. In this thesis, BESS will be considered a good solution to the congestion problem and therefore its options discussed.

EV to grid and grid to EV technology is also an interesting way to store energy in the distribution network [20]. The batteries inside EVs are essentially BESS's and can be used as power sources or loads in the local network when connected to the distribution network due to their charging/discharging abilities. When controlled correctly, this leads to load balancing in the network, as well as providing reactive power support and improved efficiency & reliability of the network. Because of the assumption that everybody in the Vechtrijk neighbourhood will own EVs, it is a financially viable option. However, in this thesis, EVs will be handled purely as loads and not as connectable batteries. EV to grid technology requires control software which is not in the scope of this thesis. The control part of the project is done by subgroup C: Optimisation and control.

1.4.2. Voltage band

Feeders inside the distribution network experience a voltage drop due to factors like the length of the feeders and the distribution of the loads [21]. This will only increase when the electricity demand is increasing. This is due to the associated rising current through the cables which results in a larger voltage drop across the cables. A solution mentioned in article [22] is reinforcing the feeder, either by increasing the number of conductors per phase or by increasing the size of the cable (in terms of diameter). This is, as is stated in the article, very expensive. Another topological solution would be the use of an SST (solid-state transformer). In [23], the author states that the solid-state transformer provides isolation between the medium and low voltage network in the distribution network, it can control active and reactive power automatically using power electronic converters and most importantly it can control the voltage fluctuations in the network. The efficiency is however still lower than a low-voltage transformer which is more than 99.5 % and the SST has only reached an efficiency of 98.25 %. The article concludes that further development is needed to successfully integrate it into the power grid.

Since using SST and upgrading the network are not feasible solutions. The thesis will focus on the development of a new distribution network topology which will prevent the power quality and congestion issues. The previously mentioned strategies all show solutions which should help solve the issues occurring in the current distribution network. However, it is better to develop a network which does not have those issues.
The goal is also to develop a network that has no power quality and congestion issues, but is also sustainable. So it needs to be possible to integrate PV systems in the network as much as possible. In [24], the authors state that the insertion of distributed generators like PV systems can cause undesirable voltage deviations. The author states that it is very important to determine the maximum amount of hosting capacity of PV panels. The determination of the maximum amount of hosting capacity shows the impact of the integration of PV systems and will make sure that the resources are deployed efficiently and upgrades of the grid are done when necessary. In [24], the author proposes a method to determine the maximum host capacity of PV systems, this method has been tested extensively on IEEE standard systems (like 8-bus and 123-bus radial distribution grids). However, [25] suggests that the increase in penetration level of PV, effectively its size, does show a positive impact on both losses in the system and voltage profile. Losses are reduced since the generation of power is close to the consumption and therefore power is not dissipated as much over a large part of the transmission lines. Single-phase PV systems should be connected to alternating phases to avoid violation of statutory limits on phase imbalance.

A part of the rise in the electricity demand is due to the integration of electric vehicle charging stations. In [26], the author presents an examination of the impact of the integration of electric vehicles into the distribution grid. The results are that the higher the amount of electric vehicle integration (the number of electric vehicles which are being charged in the distribution grid), the higher the voltage deviations.
In [27], the authors are addressing this issue and use the adapted the Additive Increase-Multiplicative Decrease (AIMD) algorithm which has been used for the alleviation of congestion on the internet. The adapted algorithm changes the charging current of the electric vehicle charging point depending on whether or not its node voltage exceeds the threshold voltage. This solution is for the most part implemented using software. The most important aspect to keep in mind from a topological point of view is that you need a device at each charging node to measure the node voltage and change the charging current. This should not change the structure of the network.

1.4.3. Thesis subdivision

The design of a sustainable and smart distribution network is divided into three subgroups/subprojects. The Topology subgroup (A) will develop a new design of a residential distribution network for the neighbourhood which includes the selection of components in terms of size and capacity. The main goal is to withstand congestion and integrate PV systems and electrical charging points for at least each resident. The Forecasting subgroup (B) will be making two forecasting models based on machine learning. The models will forecast the load and the PV power generation of the neighbourhood and can be used to determine whether congestion or voltage issues will occur. It will use old load data of several households (updated with EV charging and electric heating data), old PV generation data, old weather data and weather forecasts as inputs to forecast the load and generation demand. The Optimization Control subgroup (C) will create a controller for the grid by creating an optimisation function for the power flow. Examples of the decision variables are the rate of charge for the EV batteries and the battery storage system.

1.4.4. Thesis Objective

The objective of this thesis is to make a design of the distribution network to withstand congestion and large penetration of distributed resources. The focus will be on the design of the system itself, defining cables, lengths, topology, and sizing of the components in terms of capacity. The design is being made with the main constraint that it needs to be able to handle the worst-case scenario. The system's voltage must always be between 95% and 105% of the nominal voltage and no component can be overloaded. The system must always be able to provide power to all residents in the neighbourhood and absorb the supplied energy from the PV systems. The validation will be done using a power flow analysis using PowerFactory.

The thesis will make an electrical layout of the network, but will not consider laws regarding building the network. The allowed placement of solar panels on the roof and cables in the ground will not be considered. The medium voltage grid will be regarded as an infinite source for simplicity. The design will also not include intelligent electronic devices and the additional algorithms which can optimize the network. Since the duration of this thesis is only two months, this will be out of the scope of this thesis and as mentioned before the other subgroups will focus on forecasting and optimization algorithms. The neighbourhood of the future for which the design is going to be made is not yet built. This gives the design freedom to build from scratch and allows for flexibility when it comes to current constraints by law.

The thesis is structured as follows: chapter 3 and chapter 4 will be focused on designing the topology for the distribution network in the neighbourhood when only households and when households, EV charging stations and PV systems are connected, respectively. Both these chapters are divided into 4 general parts. The first part will consist of designing the physical electrical layout of the network, the second part will consist of preparing the data which need to be used for the analyses, the third part will discuss the load flow analysis for the worst-case scenario and will motivate the choosing and sizing of components, and the fourth part will consist of quasi dynamic analyses for the year 2013 and the expected future. Chapter 5 will discuss possible solutions for improving the distribution network designed in chapter 4. The last chapter will be the conclusion.

2

Programme of Requirements

Must have:

1. The system must be almost self-sustaining, managing energy needs as much as possible from local generation and using the grid only when demand is higher than supply.
2. Every house must have a PV installation.
3. All parking spaces must have charging stations for EVs.
4. The system must consider the design of transformers (in terms of capacity, configuration and type) and the cables (in the terms of type and length) needed.
5. The system's voltage must always be between 95% and 105% of the nominal voltage.
6. The validation of the network design will be done by power flow analysis using PowerFactory.
7. The system must make sure that electricity can be provided to all the residents in the neighbourhood and that the supplied energy can be absorbed.

Should have:

1. Parking spaces with shared PV installation.
2. Power lines and other grid components should be placed in areas that are easy to access (and preferably out of sight) for potential maintenance.
3. The reactive power in the system should be compensated.
4. The system should have an Electrical Storage System which can be either a centralized (shared) or distributed system.
5. The components like transformers should be designed for the capacity and the configuration.

Could have:

1. A short-circuit analysis of the design using the PowerFactory software in order to validate short-circuit safety.
2. A contingency analysis of the design using the PowerFactory software in order to simulate the design with contingency/contingencies.

Won't have:

1. Design system in the house, i.e. after house connection.
2. The system will not include algorithms that make sure that the elements inside the system are optimally controlled.

3

Network Design Considering only Consumer Loads

In this chapter, the focus will be on designing the topology for the distribution network in the neighbourhood when only the households are connected.

3.1. Feeder Design

In total there are 37 households of different house types in the Vechtrijk XB2. These house types can be categorised into 4 categories: a terraced house, an apartment, a detached house and a semi-detached house. All these houses have a different electricity demand profile.

The goal is to connect all these types of houses to the distribution network without the occurrence of congestion and without exceeding the boundaries of the voltage profile. To accomplish that, the strategy is not to use a single long feeder but split it into a few shorter feeders. The feeders will consist of houses which are already grouped together. This will make the addition of components like electrical chargers (which will be explained in the next chapter) easier and this will keep the feeder short. Houses on opposite sides of the neighbourhood will not be connected to the same feeder to avoid having long cables. The electrical losses in a single core cable can be calculated as

$$P_{loss} = \frac{I^2 \cdot \rho \cdot l}{1000 \cdot A} \; [kW] \tag{3.1}$$

where I is the current through the cable, $\rho_{cu} = 1.68 \cdot 10^{-8}$ $[\Omega m^{-1}]$ is the electrical resistivity of copper or $\rho_{al} = 2.65 \cdot 10^{-8}$ $[\Omega m^{-1}]$ for aluminium, l is the length and A is the cross-sectional area of the cable. From Equation 3.1 can be concluded that the power loss scales linearly with the length of the cable and therefore the length should be reduced as much as possible. Houses opposite of each other will not be connected to the same feeder for this reason.

Figure 3.1: The Vechtrijk neighbourhood feeder design with feeder selection.

In Figure 3.1 you can see the residents selected for each feeder marked by coloured lines. In the design, the strategy was to place the transformer box at the centre of the mass if you consider the rated power consumption of the households as weights. This way, the largest currents will have to travel not very deep into the network from the transformer which reduces the losses and the voltage drop over the feeder. In [28], an overview has been given of the annual consumption of each previously mentioned type of house. The detached and semi-detached houses have approximately 2 times the demand than that of an apartment. So the 11 apartments at the bottom of figure 3.1 is equivalent to 5.5 detached/semi-detached houses. You can see 3 detached/semi-detached houses at the top so the centre of mass will be more towards the apartment building. Furthermore, it can be seen in the figure that there are more terraced houses on the left than on the right which means that the centre of mass is more towards the left. Even though the houses on the right are bigger, they do not have twice as much rated power consumption. The houses that are left at the bottom and the top have approximately the same rated power consumption. It is taken into consideration that the transformer is not placed on the property of a household but onto public grounds, whilst not disturbing living comfort due to visual pollution or blocking driveways. It is also still easily accessible for maintenance purposes. The final location of the transformer box can be seen in Figure 3.2 where it is visualised as the red box just north of house number 01. The feeders as selected in Figure 3.1 were drawn to scale according to their shortest path connection as can be seen in Figure 3.2. The drawing of the feeders was done in CAD software to precisely gather the feeder lengths. From the main feeder line, a line is drawn to the centre of the electrical cabinet in each house.

Figure 3.2: The Vechtrijk neighbourhood feeder design.

3.2. Load Data Preparation

For the Load Flow analysis, PowerFactory will look at the rated power of the connection to each household. This is the maximum allowable amount of power that can flow through the connection at each building provided by the Distribution System Operator (DSO) [29]. For most households, this will be a 3x25 connection which stands for a 3-phase 25A connection. Each phase has a voltage of 230V and a current of 25A can flow at maximum, resulting in a total power of

$$P_{max,house} = 3 \cdot 230V \cdot 25A = 17.25\ [kW] \tag{3.2}$$

The apartment complex will receive a 3x160 connection as a whole. This will result in a power of

$$P_{max,apt} = \frac{3 \cdot 230V \cdot 160A}{11} = 10.04\ [kW] \tag{3.3}$$

per apartment. The total real power of the neighbourhood will be

$$P_{max} = 26 \cdot 17.25kW + 11 \cdot 10.04kW = 558.90\ [kW] \tag{3.4}$$

which will give a maximum apparent power of

$$S_{max} = \frac{P_{max}}{\cos\phi} = \frac{558.90}{0.98} = 570.31\ [kVA] \tag{3.5}$$

with a power factor of 0.98. In [30], the authors mention that the power factor in residential areas in the United States equals 0.92 due to air-conditioners that are running. However in the Netherlands - and thus in the Vechtrijk neighbourhood - air-conditioners are not usually installed and therefore are not reducing the power factor. According to the article, the power factor equals 0.99 most of the time when air-conditioners are not powered by the network. A power factor of 0.98 is taken to make sure a small inductive load of another type is taken into account. The total active current from the transformer is calculated as:

$$|I_{active}| = \frac{S_{max}}{\sqrt{3} \cdot V_L} = \frac{570.31kVA}{\sqrt{3} \cdot 400V} = 823.17\ [A] \tag{3.6}$$

The location where the maximum load current is the smallest, is through the cable from a feeder to a household. In this case the active current is

$$|I_{active,house}| = \frac{P_{max,house}}{\sqrt{3} \cdot V_{LL} \cdot \cos\phi} = \frac{17.25kW}{3 \cdot 0.4kV \cdot 0.98} = 25.41\ [A] \tag{3.7}$$

The feeder with the largest load connected is the purple feeder, ranging from house 01 to house 10; A total of 10 houses. The maximum load on that feeder is therefore $172.5kW$ and the active current is $|I_{active,feeder3}| = 10 \cdot 25.41A = 254.06A$. The cables need to be sized accordingly to these current values through each part of the feeder.

PowerFactory needs time characteristic data to perform a Quasi Dynamic simulation. Smart Meter data from Liander is used to prepare the time characteristic [31]. The data consists of the electricity and gas consumption collected by the smart meters of 80 households of different types of households in 2013. All 37 households have been assigned a type of house for a realistic load profile. Residents 27 to 37 are apartments, resident 18 is a detached house, residents 5 to 12 are semi-detached houses and the other residents are terraced houses.

The houses in the data set did not all have a description, some houses had already a PV system and some houses had incomplete data. So they have been filtered out. The electricity consumption data is given per 15 minutes in kWh and the gas consumption is given per hour in m^3 for a whole year (2013). In order to convert the energy consumption into power consumption the gas energy consumption is equally divided over 15-minute intervals. The electricity and gas energy consumption can then be converted to power consumption using the Equation 3.8:

$$P[kW] = \frac{E[kWh]}{1/4[h]} \tag{3.8}$$

where E is the energy in kWh per 15 minutes and P is the power during 15 minutes. The gas power consumption needs to be corrected because devices like heat pumps are for example more efficient than central heating boilers. According to the website [32], about 75% of the gas is being used for heating your house, 20 % of the gas is being used for heating water and the remaining 5 % is being used for cooking. Heating the house and water can be done using a heat pump with approximately a COP of 3 [33]. This can be used in formula 3.9 to calculate 95% of the gas power converted to equivalent electrical power.

$$P_{el}[kW] = \frac{P_{gas}[kW] \cdot 0.95 \cdot \eta_{\text{boiler}}}{\text{COP}_{\text{heat pump}}} \tag{3.9}$$

The remaining 5% can be converted using formula 3.10.

$$P_{el}[kW] = \frac{P_{gas}[kW] \cdot 0.05 \cdot \eta_{\text{furnace}}}{\eta_{\text{induction}}} \tag{3.10}$$

where η_{furnace} = 85% and $\eta_{\text{induction}}$ = 35% [33]. These steps have been translated into programming code and can be found in subsection A.2.1.

3.3. Load Flow Analysis

To validate the theoretical component sizing done in Section 3.2 a load flow analysis is performed. This analysis will look at the maximum load possible for each house and validate the network components accordingly. In practice, this level of loading will rarely occur, but the network should be designed for at least this.

3.3.1. Single Line Diagram

The feeder design in Figure 3.2 was translated to a single line diagram in PowerFactory as can be seen in Figure 3.3. The MV bus is connected to an external grid and has a nominal voltage level of 10kV. The LV and MV buses are connected by a transformer which transforms the voltage down to the LV level of 0.4kV. The LV bus and transformer are connected by two cables of 30m. The large current due to the low voltage is the reason for the two parallel cables. The cable library in PowerFactory does not support cables for currents as large as calculated in Equation 3.6. From the LV bus, the four feeders connect to all the households. Each cable length is accurately taken from the CAD drawing in Figure 3.2. Each house was made as a junction node (drawn as a vertical line) with a load connected (drawn as a triangle). This way a PV system can be easily added later. All households got their rated power as calculated in Equation 3.2 and the apartment building got a rated power for a single apartment as calculated in Equation 3.3 scaled by a factor of 11. This scaling factor will likely lead to overloading problems because instead of spreading peaks along 11 different households, the single peak is multiplied by 11 which is not realistic. In the data, however, there is only one apartment available and therefore it was aggregated using this method to avoid using invalid data.

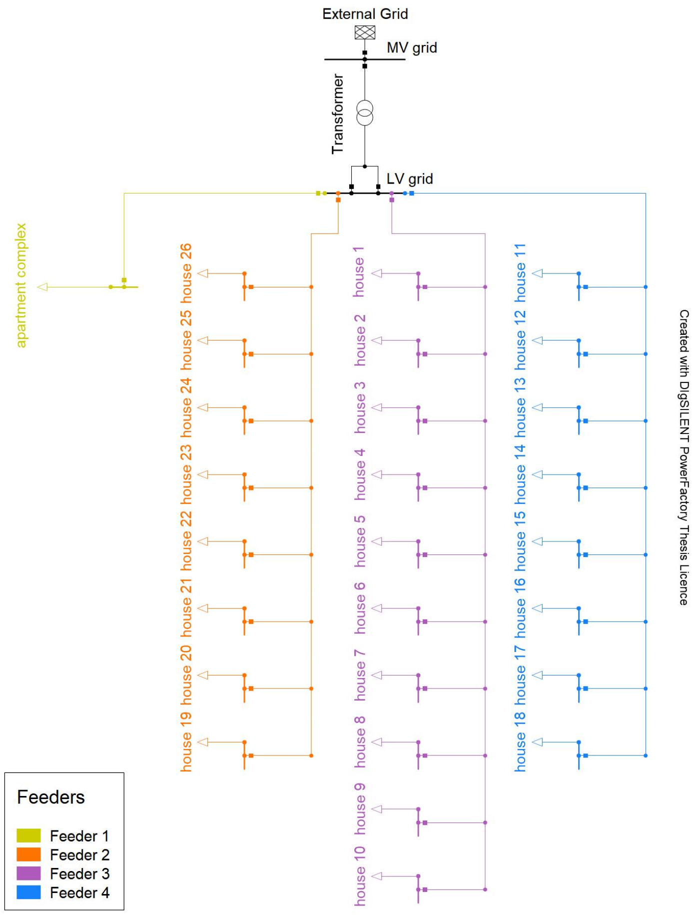


Figure 3.3: The feeder single line diagram. Full diagram in Figure A.1.

3.3.2. Component Sizing

The network components that need to be picked are the transformer and the cables. These will be picked from the standard equipment library available in PowerFactory. They are picked based on the theoretical requirements determined in section 3.2 and the Load Flow Analysis done in this section. A full component design and analysis is out of the scope of this thesis. It is also cheaper to pick components that are available than completely build your own. The transformers are available in different apparent power levels and winding configurations. As became clear in Equation 3.5 the nominal apparent power of the transformer for the network needs to be above $570.31kVA$. The first transformer upwards in the library has an apparent power of $630kVA$. This value will be used during the analysis. The transformer will have a delta wye configuration. The secondary wye-connection coils, make sure that the possible unbalances between the phases in the LV network are smoothed at the primary side of the transformer. The primary side has a delta-connected winding which can trap the third harmonic current, due to the magnetization of the core of the transformer [11]. The output of the transformer is set in such a way that the LV bus will have a voltage of approximately 1 per unit, taking the voltage drop over the connecting cables into account.

The most important cable factors to determine are conductor material, insulator material, cross-sectional area and wire configuration. In the PowerFactory equipment library, two types of conductor material are available for cables: copper and aluminium. Even though copper has better electrical characteristics than aluminium (i.e. lower resistivity and thus lower losses), it is not available in abundance and therefore not very sustainable or economically viable. Because the longest feeder in the design is not longer than 200m the losses or the extra material needed will not outweigh the more sustainable aspect of aluminium in the long run. For aluminium to have a similar resistance as copper the cross-sectional area needs to be approximately 1.6 times larger. The insulation material used is PVC, because it is cost-effective and has 25 to 30 years of service life. The material is also easy to recycle which makes it also make it more sustainable. Another important aspect is that PVC is fire retardant which is not the case for VPE for example. For the aluminium and PVC cable the cross-sections correspond to nominal current values according to Table 3.1.

Cross sectional area	Nominal current
$50mm^2$	$140A$
$95mm^2$	$210A$
$120mm^2$	$240A$
$150mm^2$	$270A$
$185mm^2$	$310A$
$240mm^2$	$365A$
$300mm^2$	$410A$

Table 3.1: Aluminium PVC cable: area-current relation.

The currents through each cable have been analysed with the load flow results and the cable cross-section areas have been assigned accordingly by taking the value upwards (see Table 3.1). This is visualised in Figure 3.4 where every different cross-sectional area is coloured according to the legend. The cables that connect the LV bus to the transformer are made from copper because the aluminium cables in the standard PowerFactory library are not able to carry the same amount of cables the current calculated in Equation 3.6.

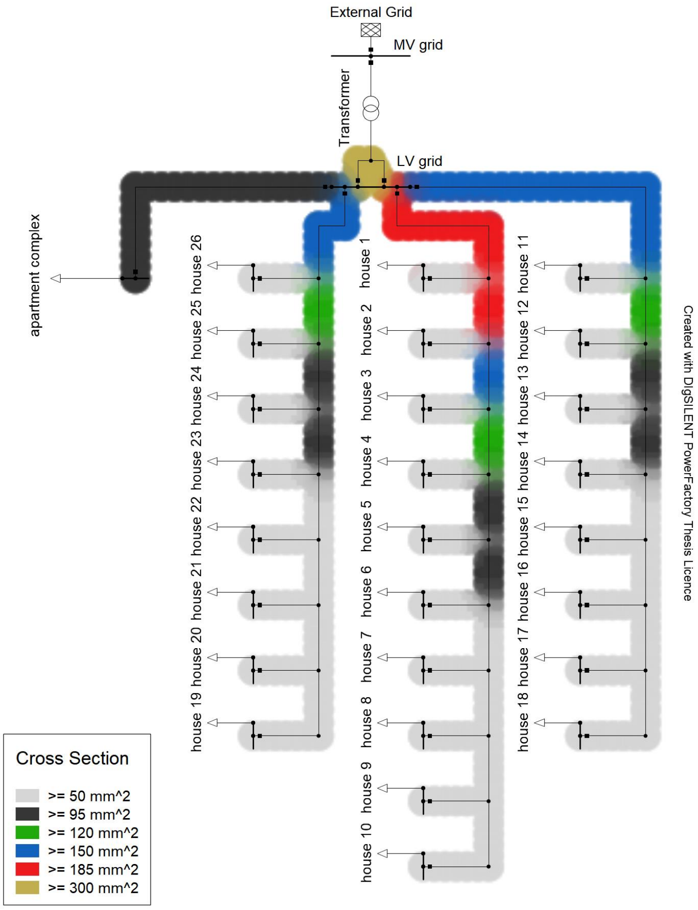


Figure 3.4: Single line diagram with cable cross-sections. Full diagram in Figure A.2.

The result of the load flow analysis can be seen in Figure 3.5. The network components coloured orange/red are in the 80%-100% loading range, meaning that they are operating close to their nominal capacity. The cable coloured in orange is at 85% loading, and the transformer is at 93%. When taking into account that load flow analysis is the worst-case scenario in terms of maximum power, one can conclude that the network is designed according to the requirements that were set and it is able to withstand full load on every household connection.

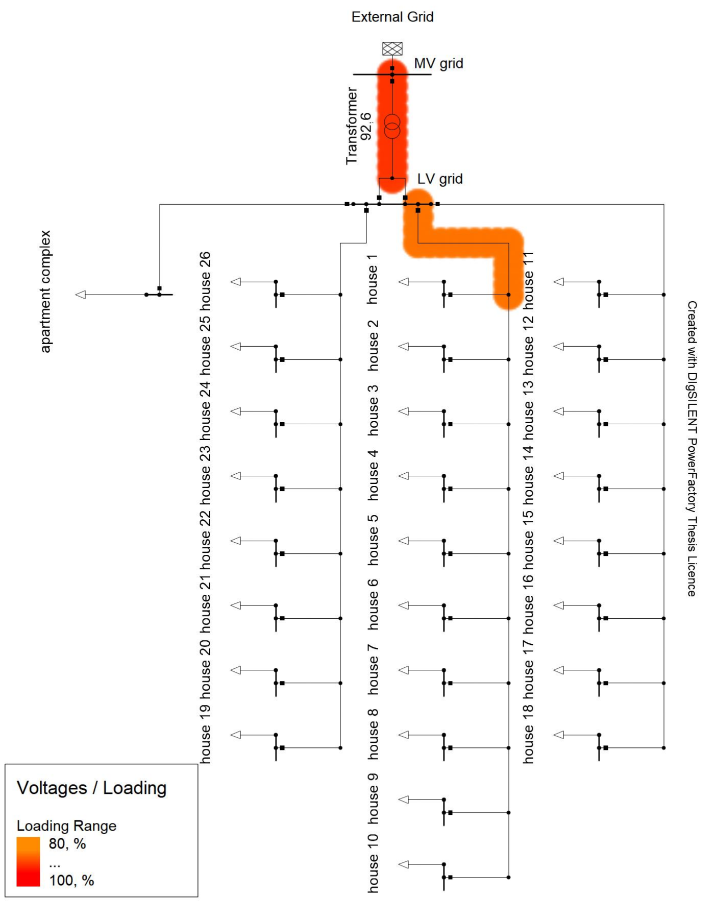


Figure 3.5: Consumer load flow. Full diagram in Figure A.3.

The feeder voltage profile is shown in Figure 3.6. It can be concluded that the system is designed according to the voltage requirement that was set. The longest feeder, Feeder 4, has the largest voltage deviation of -3.3% of the nominal voltage at the last node. From 3.6 can also be seen that cable length is a larger contributor to voltage drop along a feeder than the amount of load that is put on it. Feeder 3 has for example 2 more households - which accounts for 34.5kW more power - than Feeder 4, whereas its voltage deviation from the nominal voltage at the last node is only -2.7%. Due to the higher load power, the voltage of Feeder 3 does drop more quickly than the voltage of Feeder 4.

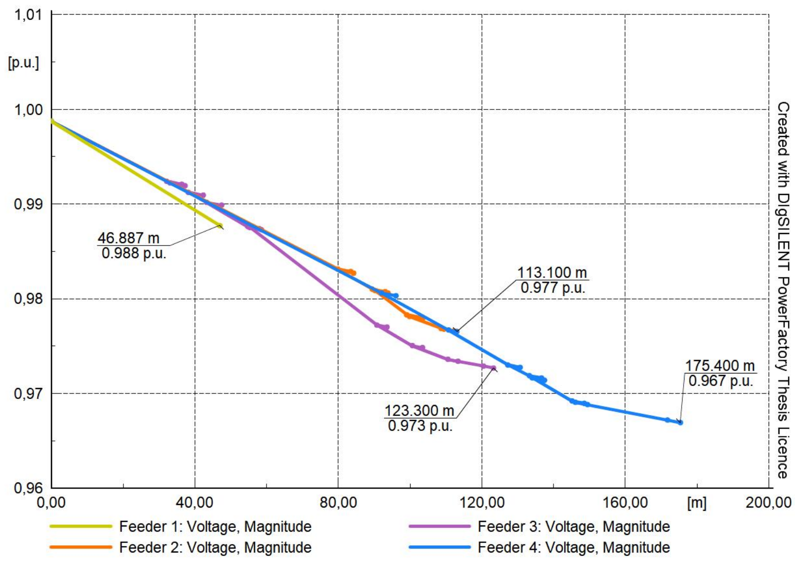
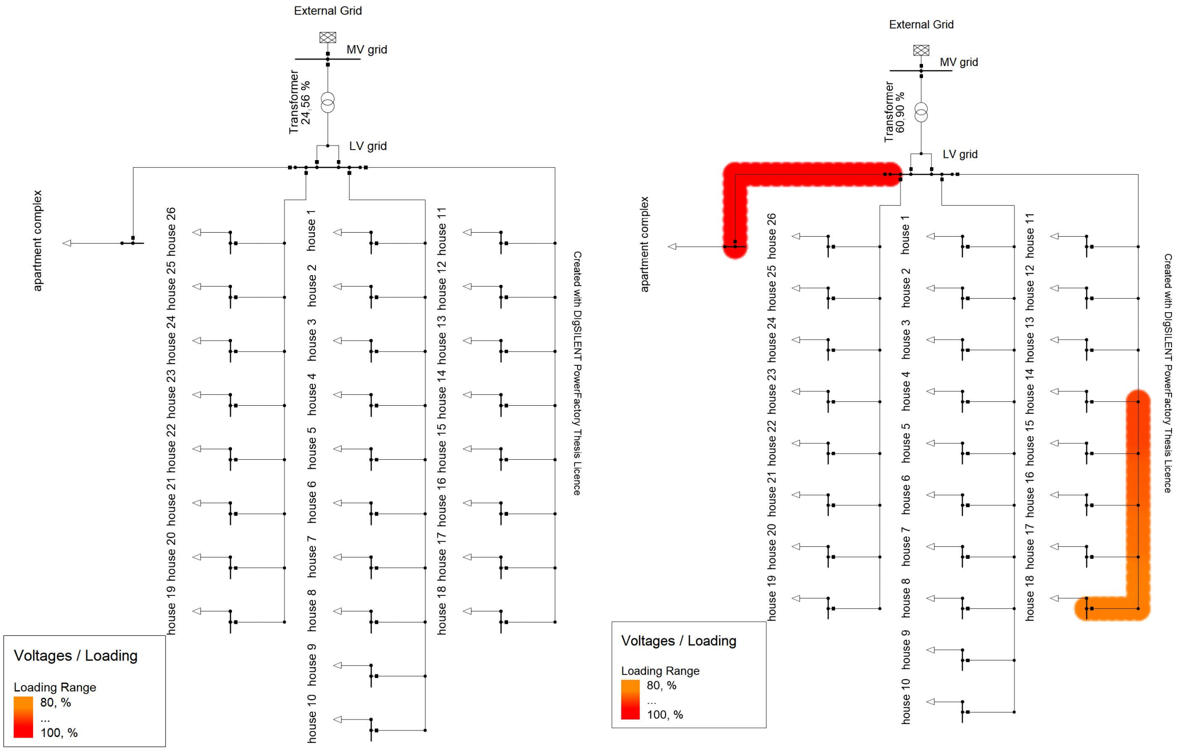


Figure 3.6: Consumer feeder voltage profile. Full diagram in Figure A.6.

3.4. Quasi Dynamic Analysis

The quasi-dynamic analysis will perform a load flow analysis for every time step it has data on. The time characteristic data as explained in Section 3.2 is the electrical load data in 15-minute intervals for the year 2013. It is known for the electricity use in residential areas to increase each year by approximately 1% according to [34]. This is taken into account by doing several analyses with different load scale factors, namely 100%, 110%, 120%, 130% and 270%. Because the 100% scale factor is equal to the data in 2013, the 110% scale factor is approximately the load data in 2022. The 120% and 130% scale factors are equal to the data in the coming 20 to 30 years and the 270% scale factor is theoretically equal to the electrical load data in 2113, approximately 100 years from 2013. The result of the analyses will show the worst-case moment during the year based on the given data.

In Figure 3.7 the loading of the network components is visualised. At the 110% load scaling which represents the year 2022 which is shown in Figure 3.7a no issues occur. Not a single component is close to its nominal capacity, and the transformer is loaded for only 24.50% at maximum. However, in one hundred years (with an average year-on-year increase of 1%) some problems will become apparent. At the apartment complex, the cable is loaded over 100%. This was expected due to the factor 11 multiplied by the factor 270% without spreading the peaks as explained in subsection 3.3.1. The problem starting at house 18 has also to do with data. This consumer has power peaks that are equal to the maximum connection a household can get, which can technically happen, but is not realistic because this is equivalent to turning on about 17 washing machines at the same time in a single house. By scaling these (unrealistic) peaks with a factor of 270% overloading problems will occur on the cables that were sized to be just enough for the worst-case scenario. The demand will go beyond what is possible on the current house connection of 3x25 A. In practice, the power will be cut and the cable will not be overloaded, unless the connection is upgraded. The rest of the network is able to handle the expected electrical load in one hundred years.



(a) At 110% load (year 2022).

(b) At 270% load (year 2113).

Figure 3.7: Component loading at different load scale factors. Full diagrams in Figure A.4 and Figure A.5 respectively.

The loading of the transformer for the 100-130% scaling range is plotted in Figure 3.8. The seasonal effect of less power consumption during the summer is well visible. It can be seen that the maximum loading for the 130% load scaling is just below 30%. This suggests that the transformer is heavily oversized when compared to the actual power that is flowing through it. This effect becomes even more clear when looking at the cumulative loading distribution of the transformer in Figure 3.9. In Figure 3.9a can be seen that even though the highest loading percentage is just rarely 30%, the transformer is loaded more than 15% for only 5% of the time. Figure 3.9a shows that the highest loading percentage is just above 60%, although the loading of the transformer is only above 30% for 5% of the time.

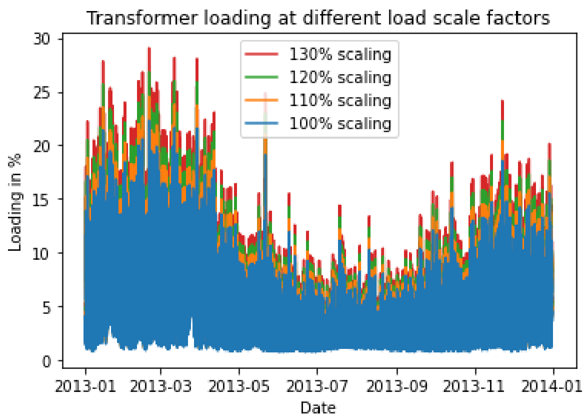
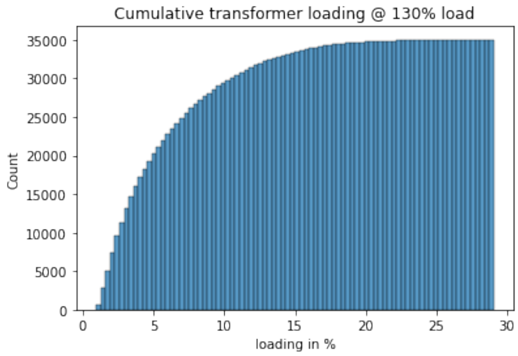
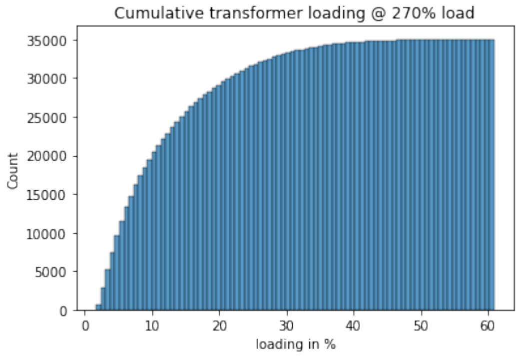


Figure 3.8: Transformer loading at different load scale factors. Full diagram in Figure A.7.



(a) At 130% load (year 2048).



(b) At 270% load (year 2113).

Figure 3.9: Cumulative loading distributions. Full diagrams in Figure A.8 and Figure A.9 respectively.

4

Network Design Considering EV loads and PV systems

In this chapter, the focus will be on designing the topology for the distribution network in the neighbourhood with the addition of PV systems and Electric Vehicle (EV) charging stations.

4.1. Feeder Design

The neighbourhood has private parking spaces on the properties of households and public parking spaces in the middle and on the outside of the neighbourhood. In total there are 54 parking spaces which all have a charging station. The amount of electric vehicles are growing rapidly it registered for example a 40% year-on-year increase in 2019 [35]. This is why the assumption is made that the neighbourhood of the future will only have electric cars. These cars need to be charged so every parking spot has also a EV charging station.

In 2025 the government of the Netherlands wants to make it obligatory to place solar panels on every new building with a roof surface above $250m^2$ [36]. That is why in the future neighbourhood this is extended to placing solar panels on every roof. The solar panels have a surface area of 1.7 m^2, this leads to the placement of 1178 panels in the neighbourhood. The panels are placed on the roof with the same orientation as the building as much towards the south which is the most optimal orientation on the northern hemisphere [37].

The EV charging stations are connected to new feeders. The new feeders will consist of EV charging stations for parking spaces which are already grouped together. The EV charging stations are hubs that have 1 or 2 or 4 charging points. The solar panels are connected as separate systems for each house and are connected to each house or in case of the apartment complex to the whole apartment complex. Every group of parking spots in the middle of the neighbourhood has a canopy of solar cells, which are connected as entire PV systems at the end of each new EV feeder. The new design can be seen in Figure 4.1.

Figure 4.1: The Vechtrijk neighbourhood feeder design

In the figure you can see the new feeders shown as coloured lines. The red dots on the lines represent the charging stations. Almost all the charging stations have 2 charging points except for the dark green feeder in the middle of the neighbourhood and house number 11 which has 4 charging points and 1 charging point per charging station respectively. The PV panels as part of the PV systems are shown as yellow rectangles.

4.2. EV and PV Data Preparation

The households with 2 parking spots on the property will receive a larger 3x50 connection because of the connection of 2 charging stations. This results in a maximum power of:

$$P_{max,\text{ house 12 and 13}} = 3 \cdot 230V \cdot 50A = 34.5\ [kW] \tag{4.1}$$

The household with 1 parking spot on the property will receive a 3x35 connection because of the connection of 1 charging station. This results in a maximum power of:

$$P_{max,\text{ house 12}} = 3 \cdot 230V \cdot 35A = 24.15\ [kW] \tag{4.2}$$

There is not much real data from EV charging stations. So most of the available data are actually based on models. In [25], EV charging data is provided based on a model that determines when people are charging EV. This translated into data means that the power is set to 0 when the charging station is not used and is set to the rated power of the charging station when it is in use. The data uses a L2 charging stations of 6.6kW per port, however with the increasing battery capacity [38] in cars and the availability of 11 kW charging points [39], this number has been changed to 11kW.

The PV power produced is based on weather data available on [40] and will be modeled as a negative load which means that it is supplying power to the grid. For the quasi dynamic analysis a time characteristic is created for the PV data by using irradiance data from 2019 in Weesp where the neighbourhood is situated.In [40], a dataset is provided with both direct and diffused irradiance values with a period of one hour. First, the period is transformed to 15m intervals in order to match with the load data set. This is done by adding the direct and diffused irradiances and keeping the values constant for one hour and adding 15 minute intervals. The irradiance value is multiplied by the efficiency of a solar panel $\eta_{panel} = 20\%$ this number will be higher in the future since already a record efficiency over 40% is achieved on lab scale [41], however to also take system losses into account and the scale of the PV system, this number has been set kept at 20%. The irradiance is also multiplied by the efficiency of an inverter $\eta_{inv} = 95\%$ [42]. This number is then multiplied by the area of a PV panel which is 1.7 m^2 to get the power of a PV system consisting of 1 panel. This number can be scaled in order to determine the power of each PV system. Altogether the PV system power can be calculated as shown in Equation 4.3

$$P_{\text{PV system}}\,[kW] = (E_{\text{direct}}\,\frac{[kW]}{[m^2]} + E_{\text{diffuse}}\,\frac{[kW]}{[m^2]}) \cdot \eta_{\text{panel}} \cdot \eta_{\text{inv}} \cdot A_{\text{panel}}\,[m^2] \tag{4.3}$$

where E_{direct} and E_{diffuse} are the direct and diffuse irradiance respectively in $\frac{kW}{m^2}$ and A_{panel} is the area of 1 module in m^2. However the sun does not shine during the night so the maximum real power of the neighbourhood will not be affected by it as can be seen in Equation 4.4

$$P_{max} = 23 \cdot 17.25kW + 11 \cdot 10.04kW + 2 \cdot 34.5kW + 24.15kW + 54 \cdot 11kW = 1194.34\,[kW] \tag{4.4}$$

which will give a maximum apparent power of

$$S_{max} = \frac{P_{max}}{\cos\phi} = \frac{1194.34}{0.98} = 1218.71\,[kVA] \tag{4.5}$$

The total active current from the transformer is calculated as:

$$|I_{active}| = \frac{S_{max}}{\sqrt{3} \cdot V_L} = \frac{1218.71kVA}{\sqrt{3} \cdot 400V} = 1759.06\,[A] \tag{4.6}$$

The cables need to be sized accordingly in order to enable such a power flow.

4.3. Load Flow Analysis

4.3.1. Single Line Diagram

The feeder design in Figure 4.1 has been translated to a single line diagram in PowerFactory as can be seen in Figure 4.2. The maximum current through the transformer has been increased (as calculated in Equation 4.6), so the amount of cables connecting the transformer to the LV grid has been extended to 4 cables with a $300mm^2$ cros section. The single line diagram is also extended with PV systems and some EV charging stations at the residential nodes. They are both modeled as general loads (drawn as rectangles). The PV System is modeled as a negative load with a 330 Wp rated power. And the EV charging points are modeled like the residents, but with a rated power of 11 kW. Also 5 feeders have been added in order to connect also the EV charging stations. The EV charging points are drawn separately for simplicity, however the cable sizes are adjusted in such a way that the feeders in PowerFactory resemble the feeders shown in Figure 4.1.

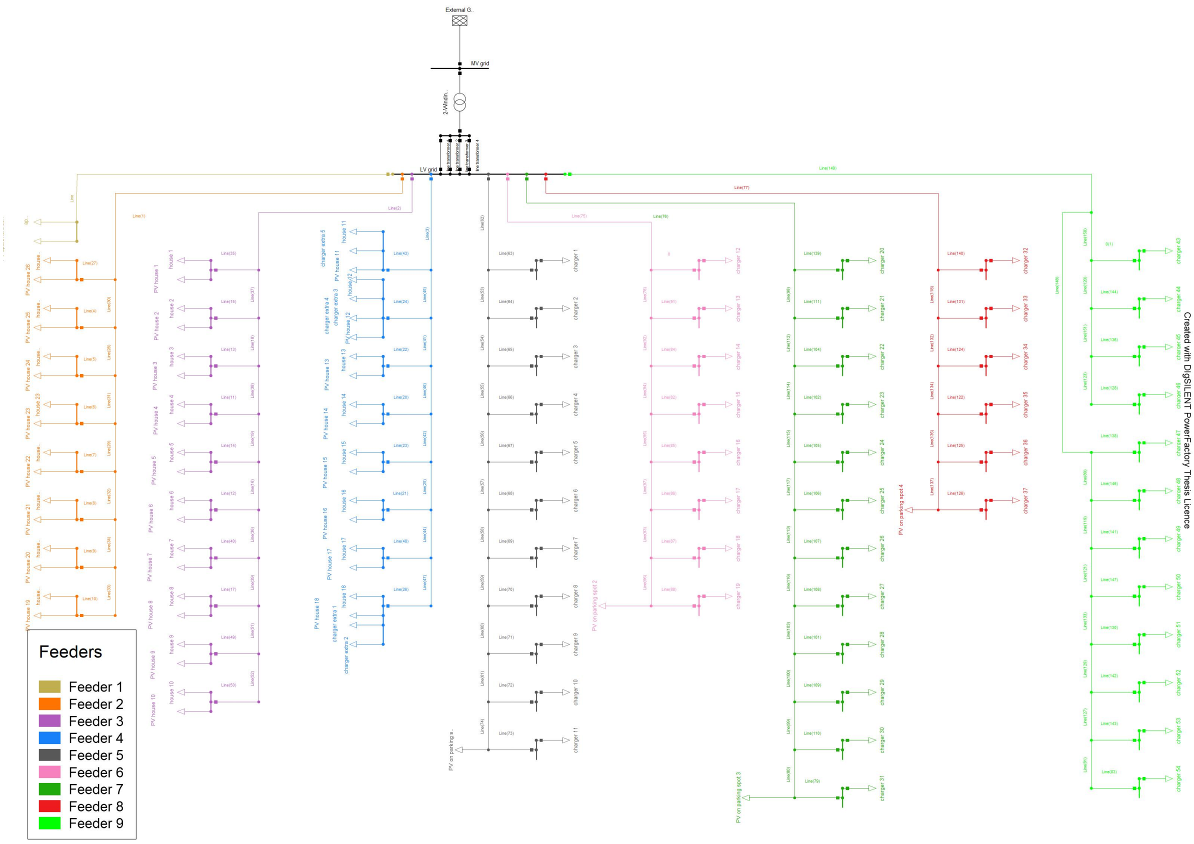


Figure 4.2: Single line diagram with loads, PV and EV charging stations. Full diagram in Figure A.10.

4.3.2. Component sizing

A similar component sizing approach is taken as explained in subsection 3.3.2. The cables and the transformer will again be taken from the standard equipment library available in PowerFactory. The nominal apparent power of the transformer for the network needs to be above $1218.71 kVA$ as calculated in Equation 4.5. The first available transformer has a nominal power rating of 1.25 MVA. The currents through each cable have been analysed by looking at the load flow results and the cable cross-section areas have been assigned accordingly by taking the value upwards (see Table 3.1). This is visualised in Figure 4.3 where every different cross-sectional area is coloured according to the legend. The cables that connect the LV bus to the transformer are again made from copper.

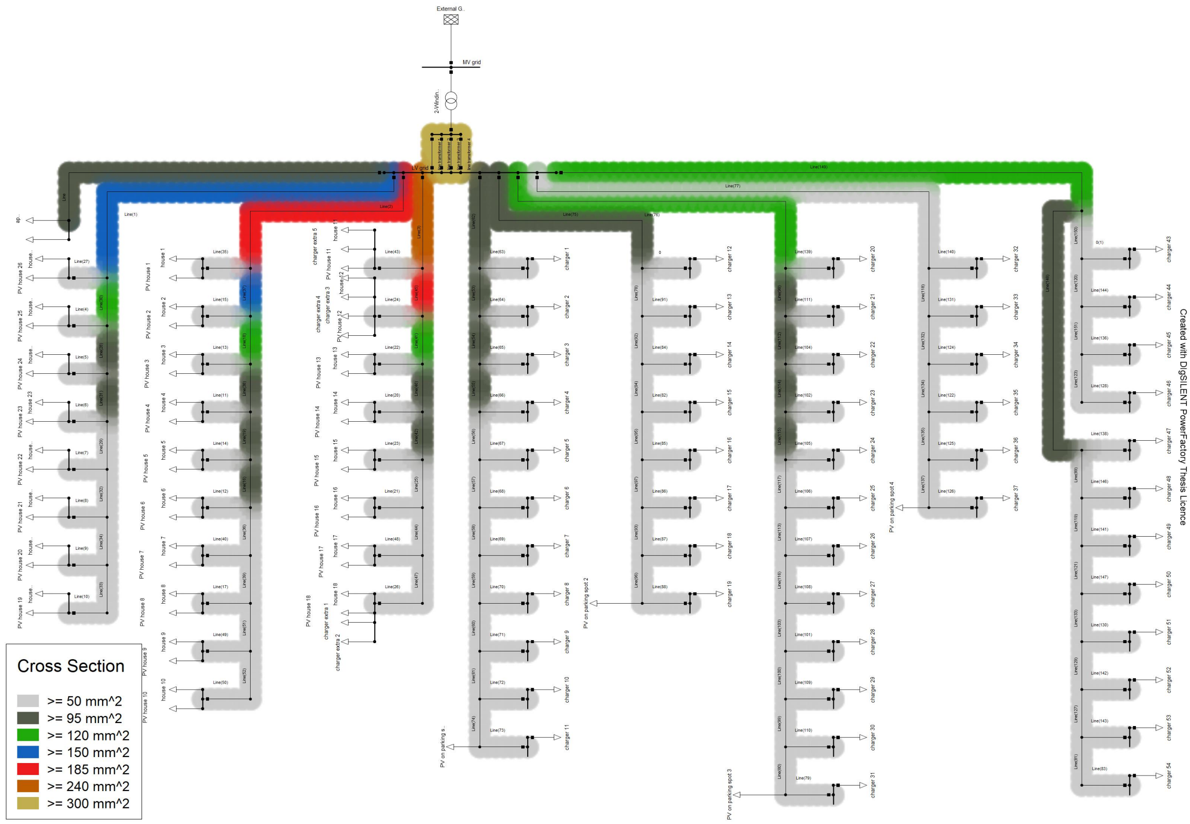


Figure 4.3: Single line diagram with cable cross-sections. Full diagram in Figure A.11.

There are 3 extreme scenarios considering demand and supply when looking at power flows. The first scenario is that PV systems are operating at full power and all the households and EV chargers are demanding maximum power. The second scenario is that only the EV chargers and household loads are demanding maximum power. The third scenario is that there is no demand and the PV systems are operating at full power. The results of the load flow analyses for the three scenarios can be seen in Figure 4.4, Figure 4.5 and Figure 4.6, respectively for each of these scenarios. In Figure 4.5 it can be seen that there are some components overloaded, whereas in the other figures only a part of the components or no components are overloaded. This suggests that the second scenario - when the households and the EV chargers are demanding maximum power - will be regarded as the worst case scenario. Also the transformer is the most loaded in scenario 3, in scenario 1 the transformer is loaded for 63,5%, in scenario 2 the transformer is loaded for 94,2% and in scenario 3 the transformer is loaded for 29,0%.

When it is taken into account that scenario 2 is the worst case scenario in terms of maximum power, it can be concluded that the network is designed according the requirements that were set and it is able to withstand full load on every household connection. The cables that are coloured orange in Figure 4.5 are close to their nominal operating range, but all are within the limits (not dark red below 100%).

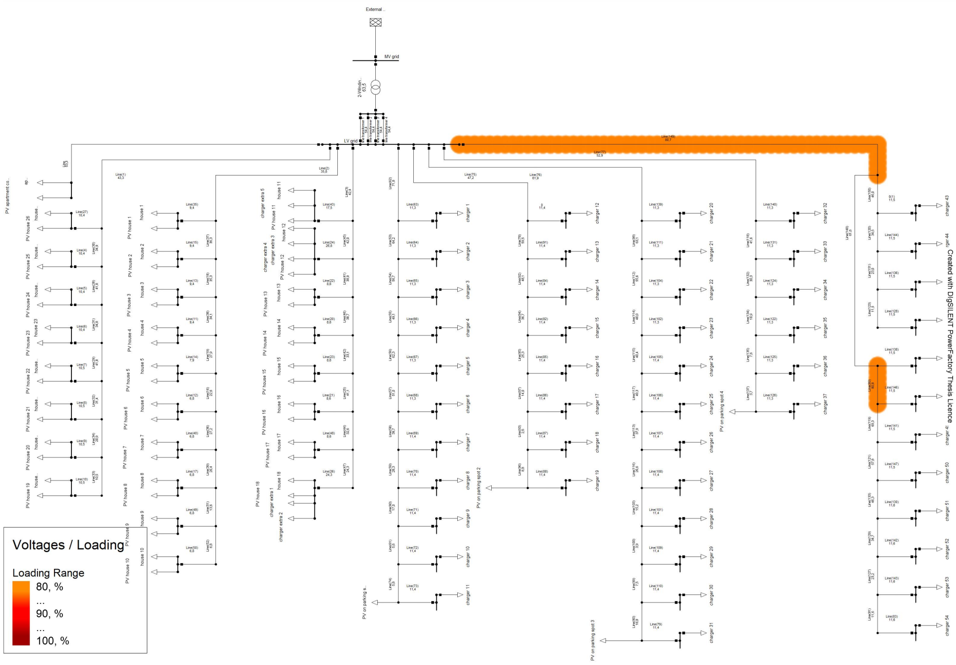


Figure 4.4: Load Flow with loads, PV and EV charging. Full diagram in Figure A.12.

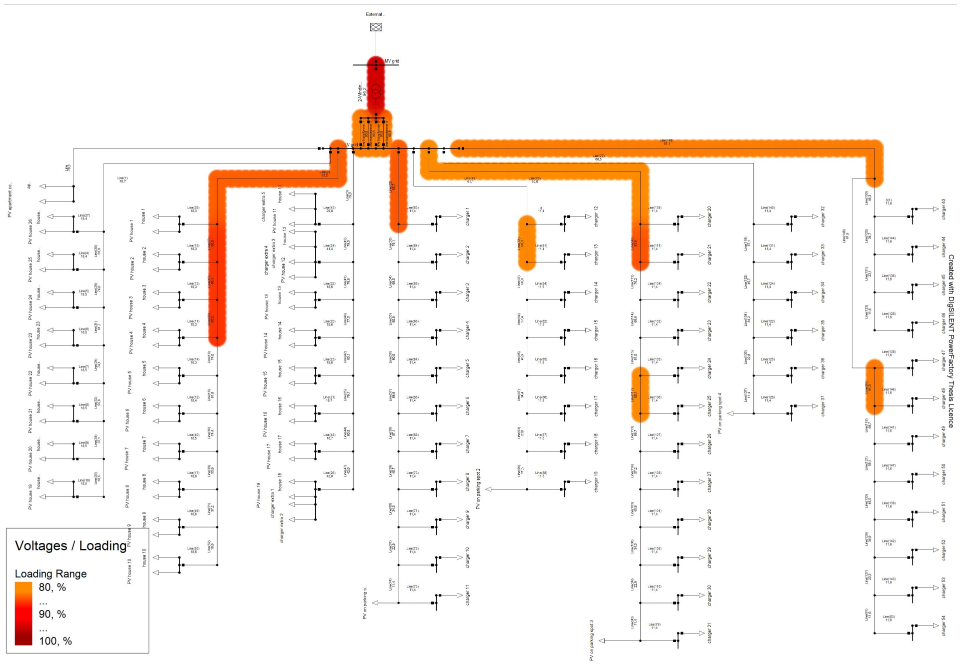


Figure 4.5: Load Flow with loads and EV charging only. Full diagram in Figure A.13.

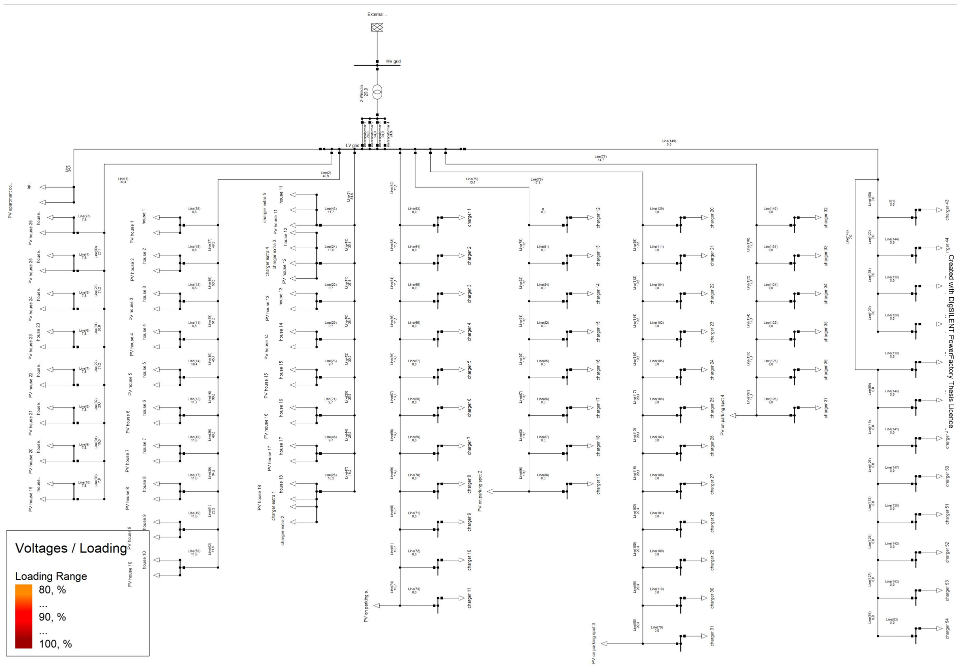


Figure 4.6: Load Flow with PV only. Full diagram in Figure A.14.

In Figure 4.7 the voltage profiles of the feeders can bee seen. The voltage drops of feeders 1 to 4 are comparable to its voltage profiles shown in Figure 3.6. The blue feeder (feeder 4) has still the largest voltage drop, but still within the 0.95 and 1.05 limits. The other new feeders have a similar voltage profile which is between the voltage profiles of feeder 3 and 4.

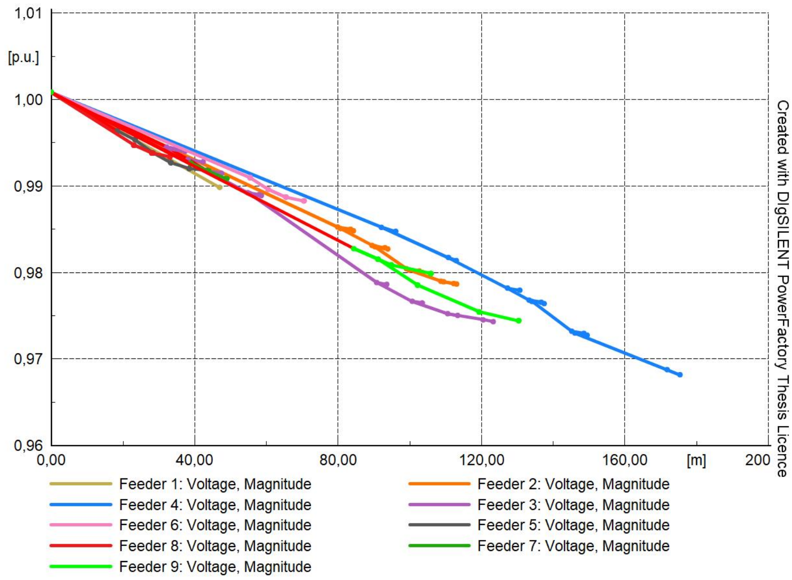


Figure 4.7: Voltage profile for feeders with loads and EV charging only. Full diagram in Figure A.15.

4.4. Quasi Dynamic Analysis

The Quasi Dynamic Analysis is performed in a similar method as done and explained in Section 3.4. However, the focus will be on the 110% and 270% load scaling representing the year 2022 and 2113 respectively. All loads including EV are taken into account when scaling. The PV systems are not scaled because it is not expected for the PV to increase in output in coming years. In Figure 4.8 the component loading is visualised for 2022. There are no visible overloading problems, which indicates that the cable sizes have been assigned correctly. However, in Figure 4.9 some overloading problems are visible for the year 2113. The most left two L-shaped coloured areas are the same problems explained in Section 3.4. The other issues signify that these parts of the feeders will be close to their maximum capacity. This should be taken into account when installing the system. By applying small step up in size right now, network alteration around 2113 can be avoided.

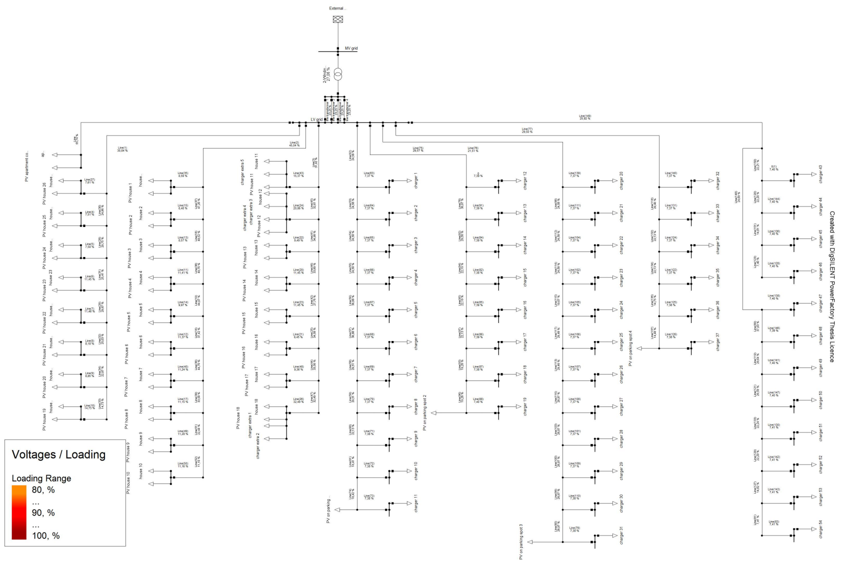


Figure 4.8: Component loading at 110% Load (year 2022). Full diagram in Figure A.16.

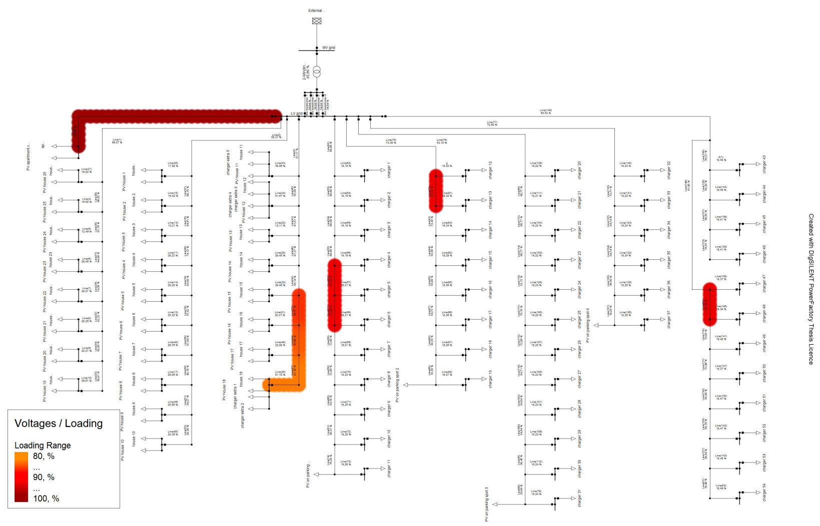
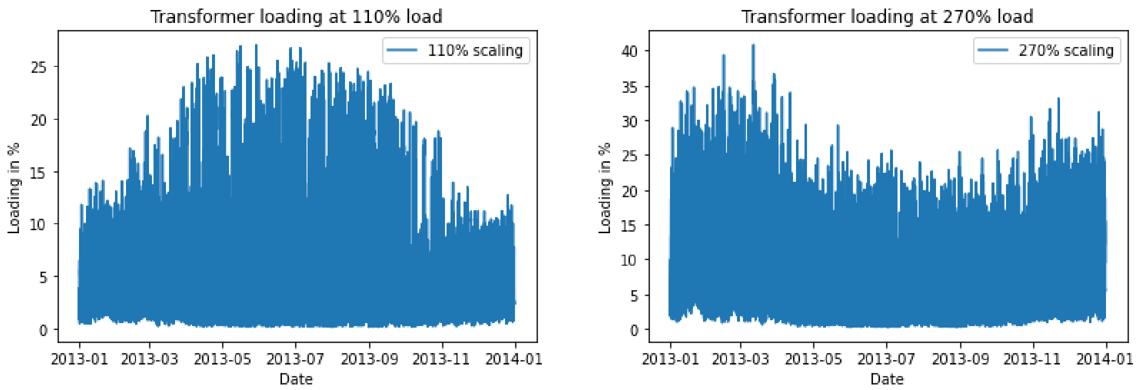


Figure 4.9: Component loading at 270% Load (year 2113). Full diagram in Figure A.17.

In Figure 4.10 the percentual loading of the transformer can be seen for the two load levels. In Figure 4.10a the power generated by PV in the summer is so large compared to the overall load power that the dutch seasonal loading profile - peak power during the winter due to electrical heating, as seen in Figure 3.8 - can not be recognised. Instead a the power peak is centered around the summertime. This effect signifies the total difference in power between supply and demand during the summer months. In Figure 4.10b the load power is more comparable to the PV power and an almost horizontal graph is formed during the year.

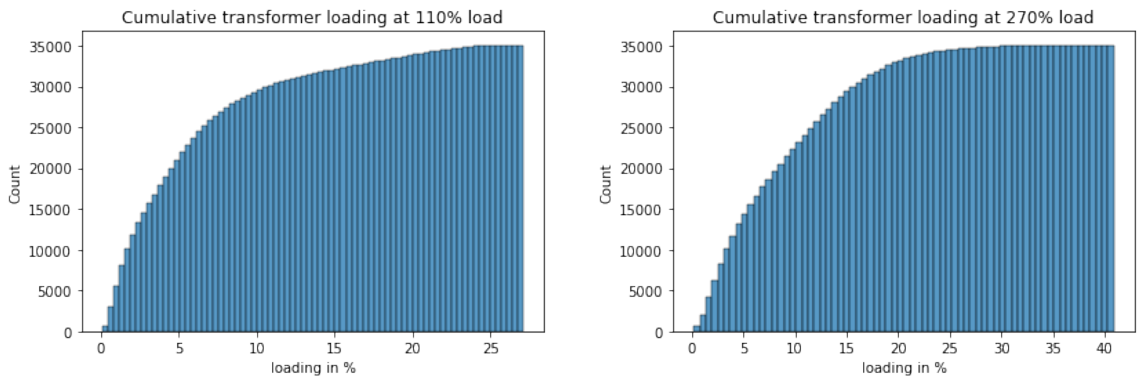


(a) At 110% load (year 2022).

(b) At 270% load (year 2113).

Figure 4.10: Transformer loading. Full diagrams in Figure A.18 and Figure A.19 respectively.

The cumulative loading distributions of the (in this chapter) chosen 1.23 MVA transformer can be seen in Figure 4.11. The highest percentage of loading in Figure 4.11a is only 28% which indicates that the transformer is oversized in the quasi-dynamic analysis, even though the transformer was sized according to the load flow analysis. In Figure 4.11b it can be seen that the maximum loading percentage is still only 41%, even after one hundred years. These results suggest that sizing the transformer based on load flow analysis results in over-sizing.



(a) At 110% load (year 2022).

(b) At 270% load (year 2113).

Figure 4.11: Cumulative transformer loading distributions. Full diagrams in Figure A.20 and Figure A.21 respectively.

5 Discussion

In this chapter, the focus will be on discussing further solutions for improving the distribution network in the neighbourhood when the households, EV charging stations and the PV systems all are connected.

5.1. Improving worst-case scenario

The network needs to be able to withstand the worst-case scenario shown in the load flow analyses of chapter 3 and chapter 4. However, the Quasi dynamic analyses done in the same chapters show that that leads to using components with a larger capacity than would be chosen based on the Quasi dynamic analyses. The maximum power transformed by the transformer and flowing through the cables to the load needs to be reduced in order to bring the load flow results of the worst-case scenario closer to quasi dynamic results.

5.1.1. Reducing the demand

This can be done by reducing the maximum electricity demand of all households and EV charging stations. A method would be reducing the connection to the households and EV charging stations. This is however a more brute-force method because this is not a solution but rather a reduction of the problem. The customer would be forced to use less power by having the power cut when the power demand is exceeding the connection limit. This is not acceptable, because this will limit the freedom of the customer of using power. It will also be costly because the fuses need replacement more often.

Another method would be to use demand response which means that you will change the customer power demand behaviour. This solution would not change the network topology outside the houses. It would however require the cooperation of the customer and consumer flexibility in order to work. A customer is needed who can change their behaviour according to signals from the energy market. Also, full information sharing between players, retailers and other consumers leads to better results. However, privacy is a major concern [43].

5.1.2. Adding power sources

Another solution would be using power sources at the households/EV charging stations or at the end of the feeders. In order to reduce the worst-case power required from the transformer and flowing through the main cables. These sources need to turn on and inject active power when the electricity demand is worst-case.

One option is to use batteries located at the houses or one larger battery at the end of the feeder which can be charged (when the demand is not worst case) by the grid or by the PV system. This is however not ideal since the batteries/battery will slowly discharge [44], so they need to be recharged. Since the worst-case scenario rarely happens (as can be seen in the Quasi dynamic simulation in chapter 3 and chapter 4), this eventually results in regularly charging a battery which continuously wastes energy unless the worst-case scenario happens. Also if you would like to make every house able to withstand the worst-case scenario for 24 hours by providing them 1 kW of power out of the battery.

A battery of at least 24 kWh would be needed for each house. That is equivalent to about 2 Tesla Powerwalls which only will be used when the worst-case scenario happens, so this is very costly. The network will be overloaded after 24 hours when the worst-case scenario continues since the batteries will not be able to provide power since they are empty and they can not be filled unless there is sun or no worst-case scenario. So when every house has bought the 2 Tesla Powerwalls, there is still a risk of overloading. A hospital for example is able to withstand the worst-case scenario (no power from the grid) for several days.

Another option would be to use a hydrogen energy system which consists of a tank and fuel cells in order to provide the houses with power during the worst-case scenario of all loads demanding maximum power. This system has the advantage that it is a seasonal energy storage system. So it is not needed to refill the tank as often as you would need to recharge the battery. Since the worst-case scenario rarely happens, this is very beneficial. An electrolyzer could be added that can produce green hydrogen using power from the PV systems. The whole system will unfortunately be very expensive because the system will consist of at least a tank, gas infrastructure and fuel cells which need to be assembled too. Also the round-trip efficiency of such a system is very low, below 25% [45]. An investment of a significant amount of money and energy would be necessary. An advantage of this system is that it can provide the network with power for several days in the worst-case scenario (like a hospital). The hydrogen tank can be refilled with hydrogen (delivered by for example trucks) when the tank is almost getting empty.

5.2. Optimisation supply and demand

All the mentioned solutions except for the demand response are topological solutions. These are however not the only possible solutions for improving the network. There are also solutions which incorporate intelligent electronic devices. These devices enable monitoring and control of the network using software [27]. This can alleviate congestion and allows you to use smaller cables in the network.

Further improvement can be made by using software which can solve an optimization problem provided with constraints. The output of this software provides the control settings for the components in the network (as for example the controllers of EV charging stations) that make sure that the network is used optimally and not overloaded. One of the inputs is the measured electricity demand and the supply of power from the PV systems. The optimisation will improve when the demand and supply are forecasted. So the use of intelligent electronic devices together with forecasting and optimisation software is an interesting solution. This will potentially not only solve the oversizing problem, but it can also make sure that the network is optimally used. So less energy is wasted and the life expectancy of components can be improved. This solution is treated by subgroups B and C of which subgroup B is in charge of the development of data-driven algorithms to forecast customers' demand and renewable generation and subgroup C is in charge of the development of optimal energy resources operation algorithm. This algorithm will be in charge of controlling all the available energy resources based on the forecast data.

6
Conclusion

The objective of this thesis was to make a design of the distribution network to withstand congestion and large penetration of distributed resources. The design needed to be made with the main constraint that it needs to be able to handle the worst-case scenario. The system's voltage must always be between 95% and 105% of the nominal voltage and no components can be overloaded. The system must always be able to provide power to all residents in the neighbourhood and absorb the supplied energy from the PV systems.

The transformer has been placed in the centre of mass (when the load is regarded as weights) to make sure that the large currents do not have to travel very deep into the network. The feeders are kept short and consist of houses and some EV chargers that are already grouped together to make sure that the voltage drop is within 105% and 95% of the nominal voltage.

Most cables used are made of aluminium because of the availability of the material which makes it more sustainable and economically viable than copper. Only the cables connecting the transformer to the LV grid are made of copper, because of the large current that needs to go through the cables. The transformer configuration is delta-wye to make sure that any possible unbalance between the phases in the LV network is smoothed out at the primary side of the transformer, and to trap the third harmonic current due to the magnetization of the core of the transformer at the primary side.

The capacity of the components is determined using the results of the load flow analyses and the design has been verified using the quasi dynamic analyses. These analyses showed that the design is able to operate even in one hundred years. The quasi dynamic analyses show that making the design able to withstand the worst-case scenario leads to choosing components with a larger capacity than you would based on the analyses. This can be improved by technical solutions like the use of a battery, however, that is costly and requires a regular supply of energy. Another more viable solution would be the use of intelligent electronic devices together with forecasting and optimisation software. This will potentially not only solve the oversizing problem, but it can also make sure that the network is optimally used. So less energy is wasted and the life expectancy of components can be improved.

Bibliography

[1] P. R. et al., “Greenhouse gas emissions in the netherlands 1990–2019, national inventory report 2021,” 2021. https://www.rivm.nl/bibliotheek/rapporten/2021-0007.pdf, accessed on: 29/04/2022. Doi: 10.21945/RIVM-2021-0007.

[2] N. Brannan, “Liander niet goed voorbereid op overvol stroomnet, gemeente overvallen door problemen,” 2022. shorturl.at/ruzH9, accessed on: 18/05/2022.

[3] M. J. L. et al., “Hernieuwbare energie in nederland - buitenluchtwarmte,” 2021. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2021/hernieuwbare-energie-in-nederland-2020?onepage=true#c-7--Buitenluchtwarmte, accessed on 29/04/2022.

[4] C. B. voor de Statistiek (CBS), “Aantal stekkerauto’s, 2014-2021,” 2021. https://www.cbs.nl/nl-nl/maatwerk/2021/41/aantal-stekkerauto-s-2014-2021, accessed on: 29/04/2022.

[5] “Aanbod vechtrijk xb2.” https://account.woneninweespersluis.nl/aanbod-vechtrijk/.

[6] “Netcapaciteit en netcongestie.” https://www.rvo.nl/onderwerpen/zonne-energie/netcapaciteit-netcongestie.

[7] “Capaciteitskaart nederland.” https://capaciteitskaart.netbeheernederland.nl/?_ga=2.56067567.538483043.1651476493-1899990241.1649077574.

[8] M. AlMuhaini, “Chapter 10 - impact of distributed generation integration on the reliability of power distribution systems,” in *Distributed Generation Systems* (G. Gharehpetian and S. M. Mousavi Agah, eds.), pp. 453–508, Butterworth-Heinemann, 2017.

[9] F. S. S. D. P. Angelo L’Abbate, Gianluca Fulli, “Distributed power generation in europe: technical issues for further integration,” 2007.

[10] D. Deka and M. Chertkov, “Chapter 12 - topology learning in radial distribution grids,” in *Big Data Application in Power Systems* (R. Arghandeh and Y. Zhou, eds.), pp. 261–279, Elsevier, 2018.

[11] P. Schavemaker and V. d. S. Lou, *Electrical Power System Essentials*. John Wiley & amp; Sons, Inc., 2017.

[12] B. Reveron Baecker and S. Candas, “Co-optimizing transmission and active distribution grids to assess demand-side flexibilities of a carbon-neutral german energy system,” *Renewable and Sustainable Energy Reviews*, vol. 163, p. 112422, 2022.

[13] I. Kalogeropoulos and H. Sarimveis, “Predictive control algorithms for congestion management in electric power distribution grids,” *Applied Mathematical Modelling*, vol. 77, pp. 635–651, 2020.

[14] I. Ziari, G. Ledwich, A. Ghosh, and G. Platt, “Optimal distribution network reinforcement considering load growth, line loss, and reliability,” *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 587–597, 2013.

[15] M. H. Shariatkhah and M. R. Haghifam, “Using feeder reconfiguration for congestion management of smart distribution network with high dg penetration,” in *CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid*, pp. 1–4, 2012.

[16] S.-A. Yin and C.-N. Lu, “Distribution feeder scheduling considering variable load profile and outage costs,” *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 652–660, 2009.

[17] C.-H. Lo and N. Ansari, "Alleviating solar energy congestion in the distribution grid via smart metering communications," *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 9, pp. 1607–1620, 2012.

[18] K. De Brabandere, K. Vanthournout, J. Driesen, G. Deconinck, and R. Belmans, "Control of microgrids," in *2007 IEEE Power Engineering Society General Meeting*, pp. 1–7, 2007.

[19] T. Yunusov, D. Frame, W. Holderbaum, and B. Potter, "The impact of location and type on the performance of low-voltage network connected battery energy storage systems," *Applied Energy*, vol. 165, pp. 202–213, 2016.

[20] M. Kumar, S. Vyas, and A. Datta, "A review on integration of electric vehicles into a smart power grid and vehicle-to-grid impacts," in *2019 8th International Conference on Power Systems (ICPS)*, pp. 1–5, 2019.

[21] D. Zhu, A. K. Jain, R. Broadwater, and F. Bruna, "Feeder voltage profile design for energy conservation and pv hosting capacity enhancement," *Electric Power Systems Research*, vol. 164, pp. 263–271, 2018.

[22] R. A. Shayani and M. A. G. de Oliveira, "Photovoltaic generation penetration limits in radial distribution systems," *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 1625–1631, 2011.

[23] D. K. Mishra, M. J. Ghadi, L. Li, M. J. Hossain, J. Zhang, P. K. Ray, and A. Mohanty, "A review on solid-state transformer: A breakthrough technology for future smart distribution grids," *International Journal of Electrical Power & Energy Systems*, vol. 133, p. 107255, 2021.

[24] J. Yuan, Y. Weng, and C.-W. Tan, "Determining maximum hosting capacity for pv systems in distribution grids," *International Journal of Electrical Power & Energy Systems*, vol. 135, p. 107342, 2022.

[25] K. Balamurugan, D. Srinivasan, and T. Reindl, "Impact of distributed generation on power distribution systems," *Energy Procedia*, vol. 25, pp. 93–100, 2012. PV Asia Pacific Conference 2011.

[26] E. Ucer, M. C. Kisacikoglu, and A. Cafer Gurbuz, "Learning ev integration impact on a low voltage distribution grid," *2018 IEEE Power & amp; Energy Society General Meeting (PESGM)*, 2018.

[27] E. Ucer, M. C. Kisacikoglu, M. Yuksel, and A. C. Gurbuz, "An internet-inspired proportional fair ev charging control method," *IEEE Systems Journal*, vol. 13, no. 4, p. 4292–4302, 2019.

[28] U. Author, "Energy consumption private dwellings type of dwelling and regions," 2021. `https://opendata.cbs.nl/#/CBS/en/dataset/81528ENG/table?searchKeywords=Rotterdam`, accessed on 30/05/2022.

[29] Liander, "Soorten aansluitingen," 2022. `https://www.liander.nl/consument/aansluitingen/soorten-aansluitingen`, accessed on: 02/06/2022.

[30] W. Peng, Y. Baghzouz, and H. Salim, "Local load power factor correction by grid-interactive pv inverters," pp. 1–6, 06 2013.

[31] Liander, "Beschikbare data," 2022. `https://www.liander.nl/partners/datadiensten/open-data/data`, accessed on: 29/04/2022.

[32] V. de Vastelastenbond, "Gasverbruik: Gasverbruik in jouw huishouden," 2020. `https://www.vastelastenbond.nl/energie/gasverbruik-in-uw-huishouden/`, accessed on: 31/05/2022.

[33] R. Khezri, A. Mahmoudi, and D. Whaley, "Optimal sizing and comparative analysis of rooftop pv and battery for grid-connected households with all-electric and gas-electricity utility," *Energy*, vol. 251, p. 123876, 2022.

[34] M. R. Hannah Ritchie and P. Rosado, "Energy," *Our World in Data*, 2020. https://ourworldindata.org/energy.

[35] IEA (2020), "Global ev outlook 2020," *IEA*, Paris. https://www.iea.org/reports/global-ev-outlook-2020, accessed on 06/06/2022.

[36] B. van de Weier, "Kabinet wil vanaf 2025 verplicht zonnepanelen op grote daken," *Volkskrant*, May 2022.

[37] E. González-González, J. Martín-Jiménez, M. Sánchez-Aparicio, S. Del Pozo, and S. Lagüela, "Evaluating the standards for solar pv installations in the iberian peninsula: Analysis of tilt angles and determination of solar climate zones," *Sustainable Energy Technologies and Assessments*, vol. 49, p. 101684, 2022.

[38] M. TRENDS, "Battery trends 2022: an industry view on the development of the electric vehicles market (infographic)," *IDTechEx*, 2022. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2021/hernieuwbare-energie-in-nederland-2020?onepage=true#c-7--Buitenluchtwarmte, accessed on 07/06/2022.

[39] Gemeente Utrecht, "Eigen laadpaal," 2022. https://www.utrecht.nl/wonen-en-leven/duurzame-stad/elektrisch-vervoer/eigen-laadpaal/, accessed on 07/06/2022.

[40] S. Pfenninger and I. Staffell, "Scientific solar and wind data," 2022. https://www.renewables.ninja/, accessed on: 02/06/2022.

[41] E. Saleem, K. Mehmood, and F. Rashid, "The efficiency of solar pv system," 07 2019.

[42] C.-Y. Park, S.-H. Hong, S.-C. Lim, B.-S. Song, S.-W. Park, J.-H. Huh, and J.-C. Kim, "Inverter efficiency analysis model based on solar power estimation using solar radiation," *Processes*, vol. 8, p. 1225, 10 2020.

[43] C. Silva, P. Faria, Z. Vale, and J. Corchado, "Demand response performance and uncertainty: A systematic literature review," *Energy Strategy Reviews*, vol. 41, p. 100857, 2022.

[44] R. Trócoli, A. Morata, C. Erinmwingbovo, F. La Mantia, and A. Tarancón, "Self-discharge in li-ion aqueous batteries: A case study on limn2o4," *Electrochimica Acta*, vol. 373, p. 137847, 2021.

[45] E. Bernier, J. Hamelin, K. Agbossou, and T. K. Bose, "Electric round-trip efficiency of hydrogen and oxygen-based energy storage," *International Journal of Hydrogen Energy*, vol. 30, no. 2, pp. 105–111, 2005. Fuel Cells.

A

Appendix

A.1. High Resolution Images

A.1.1. Consumer loads

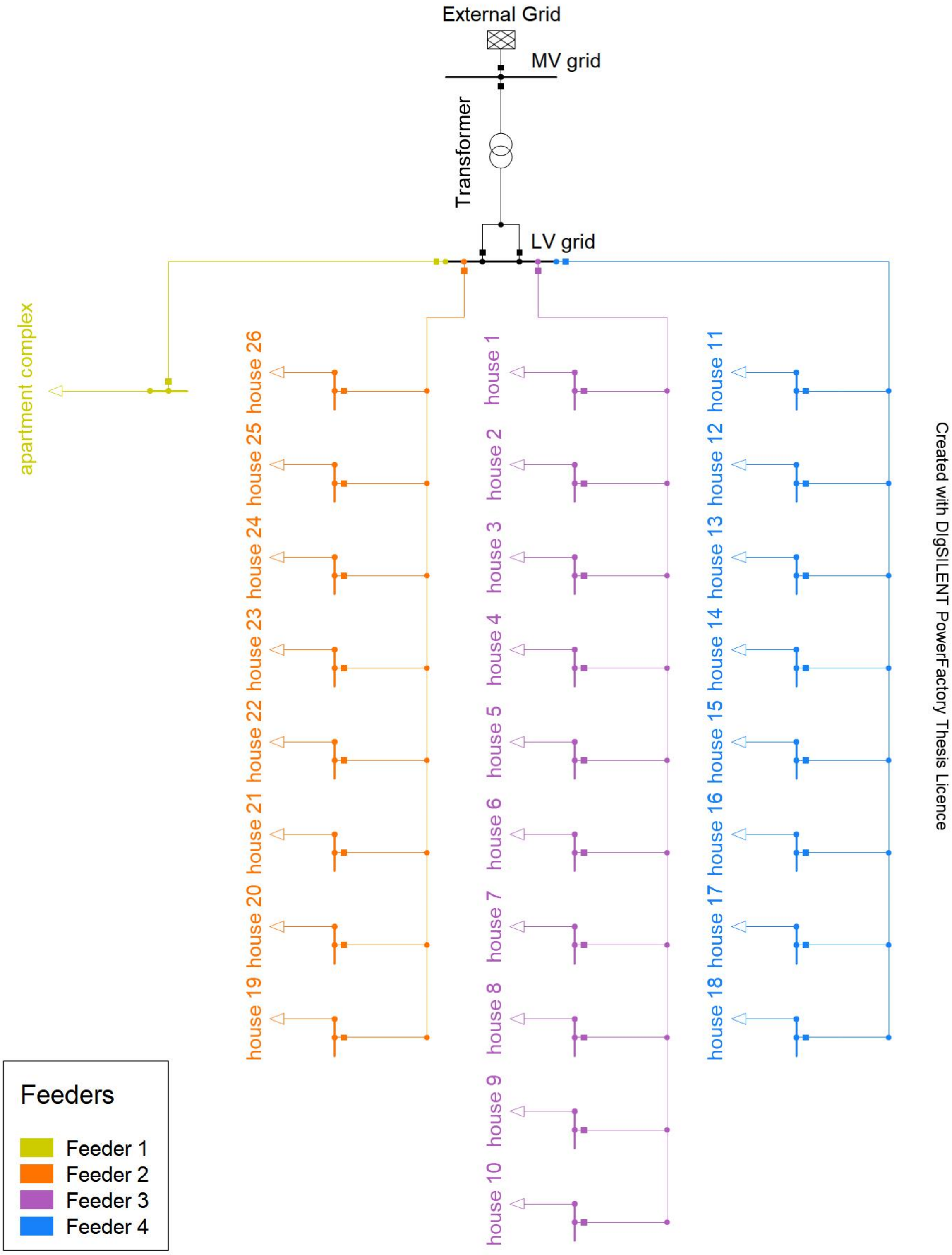


Figure A.1: The feeder single line diagram.

Figure A.2: Single line diagram with cable cross-sections.

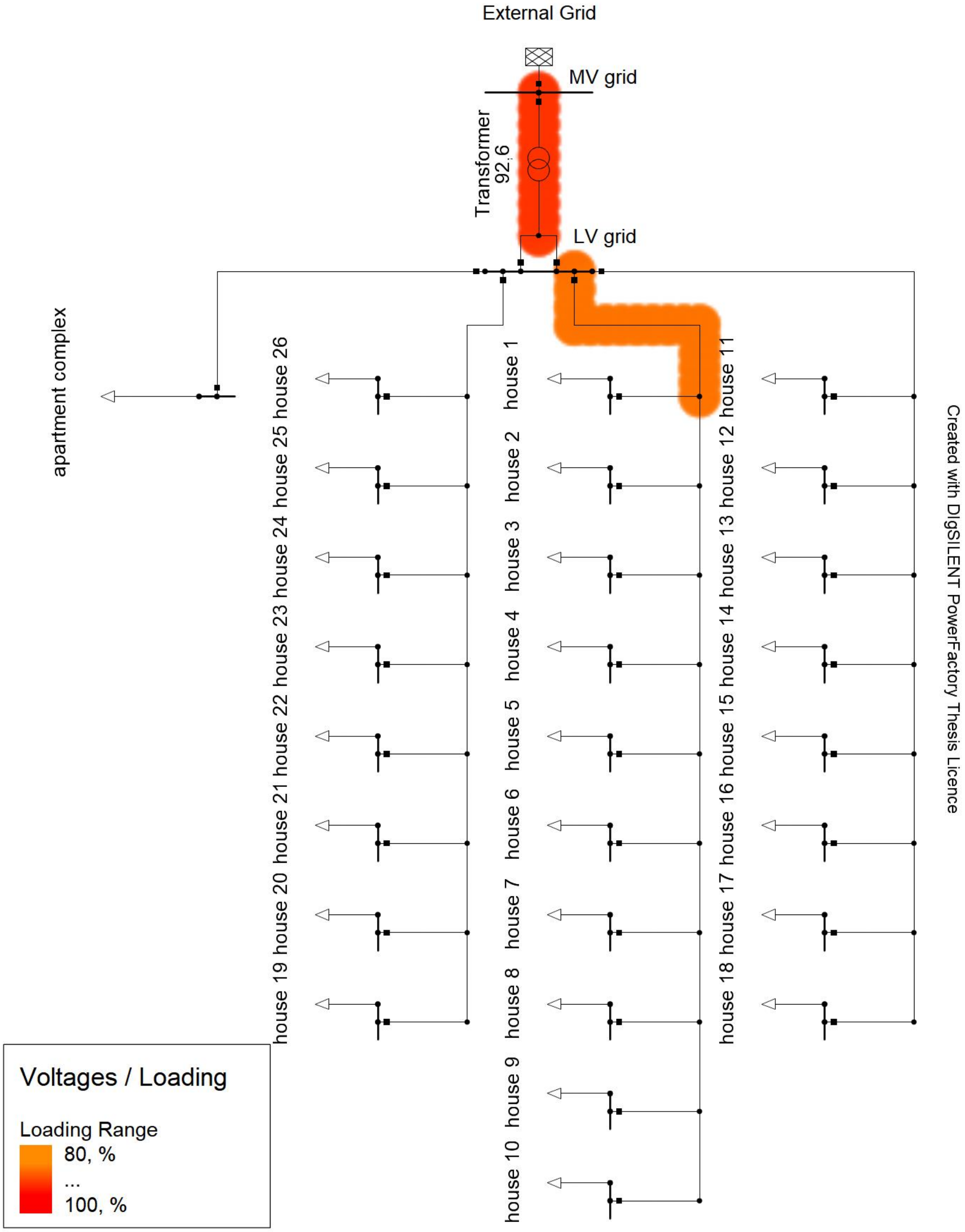


Figure A.3: Consumer load flow.

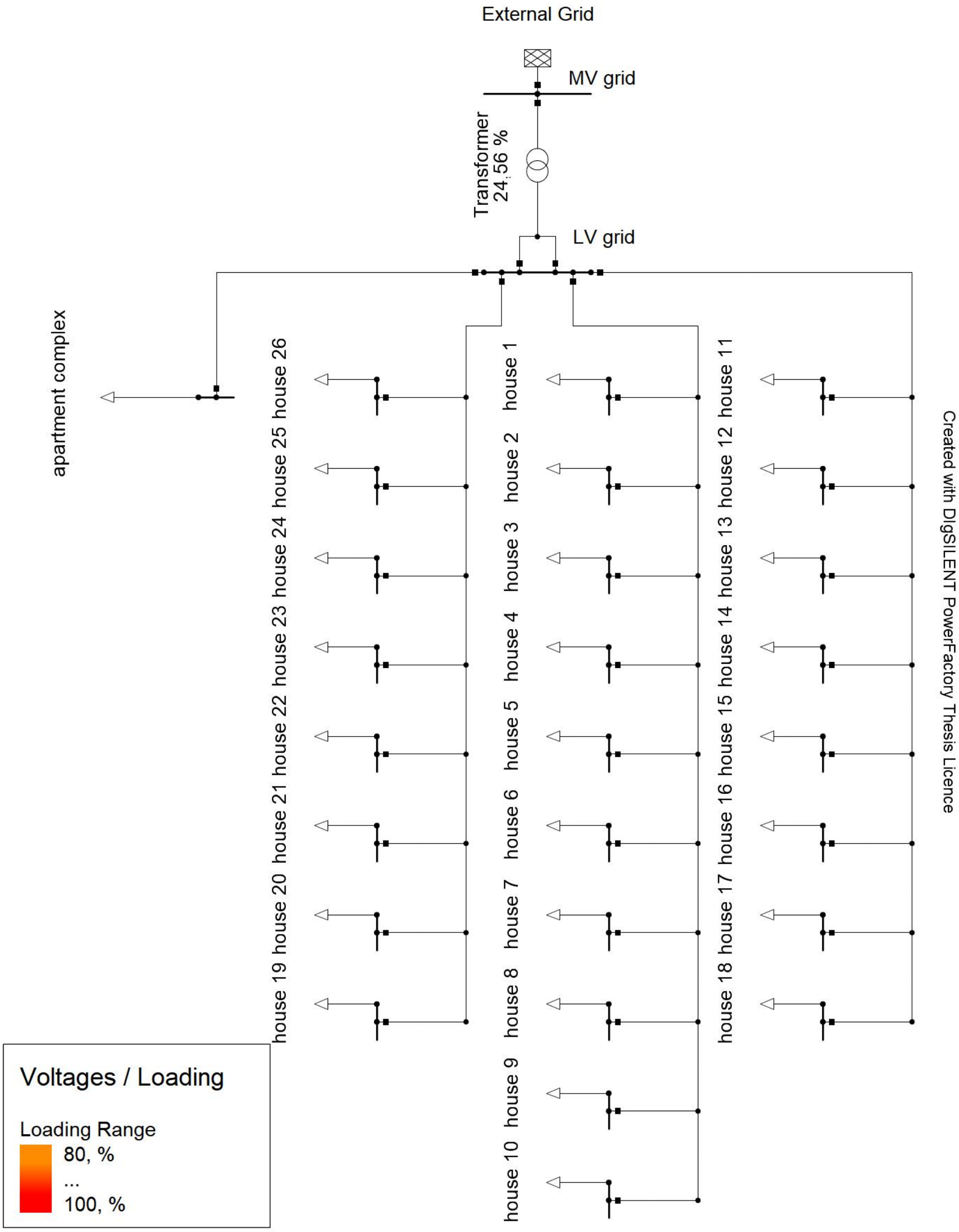


Figure A.4: Quasi-Dynamic analysis at 110% load (year 2022).

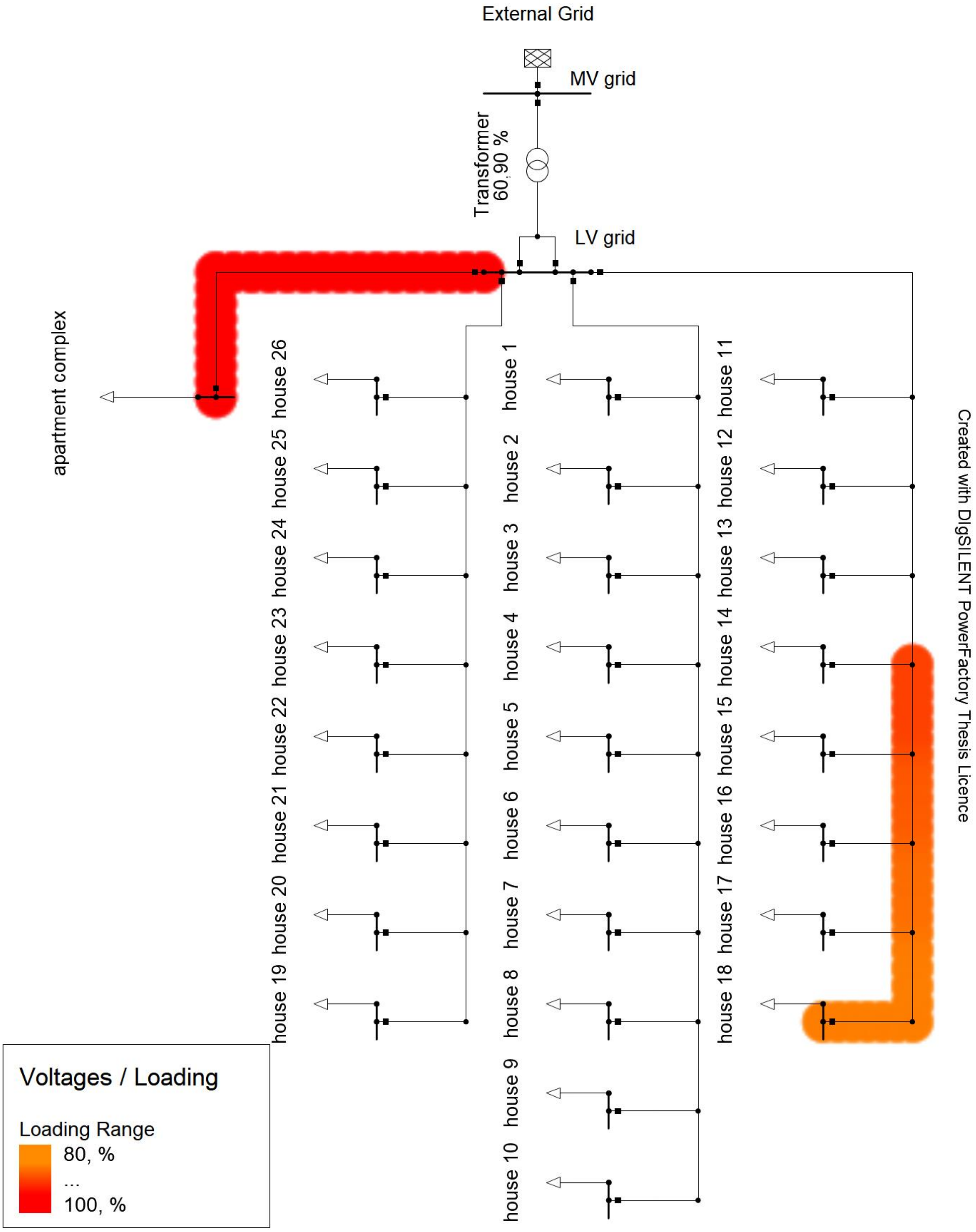


Figure A.5: Quasi-Dynamic analysis at 270% load (year 2113).

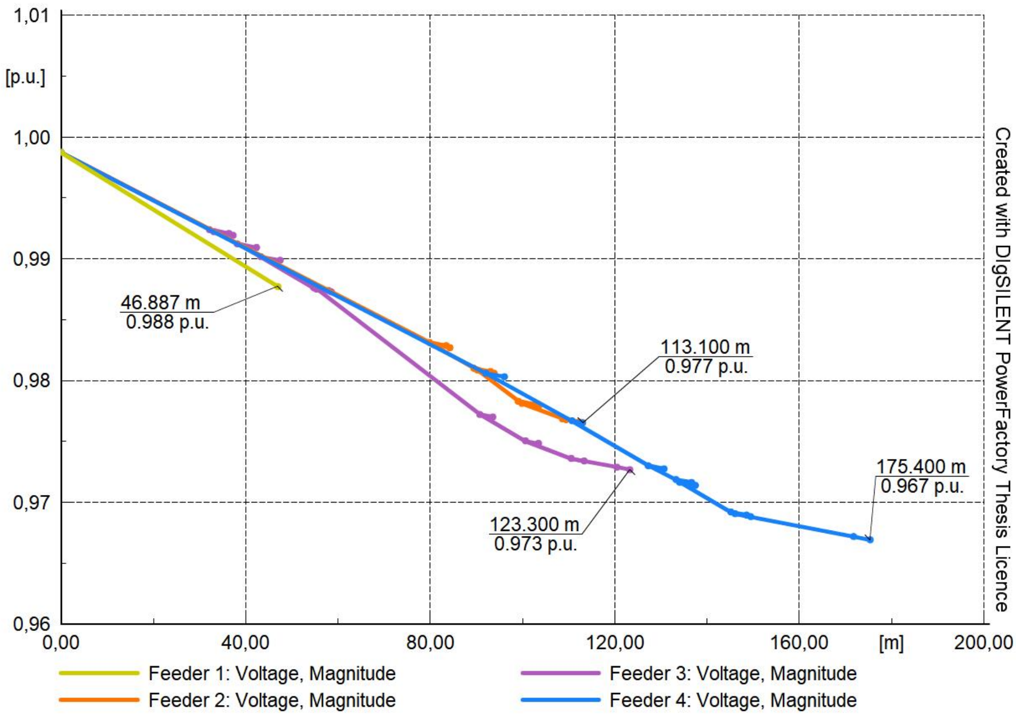


Figure A.6: Consumer feeder voltage profile.

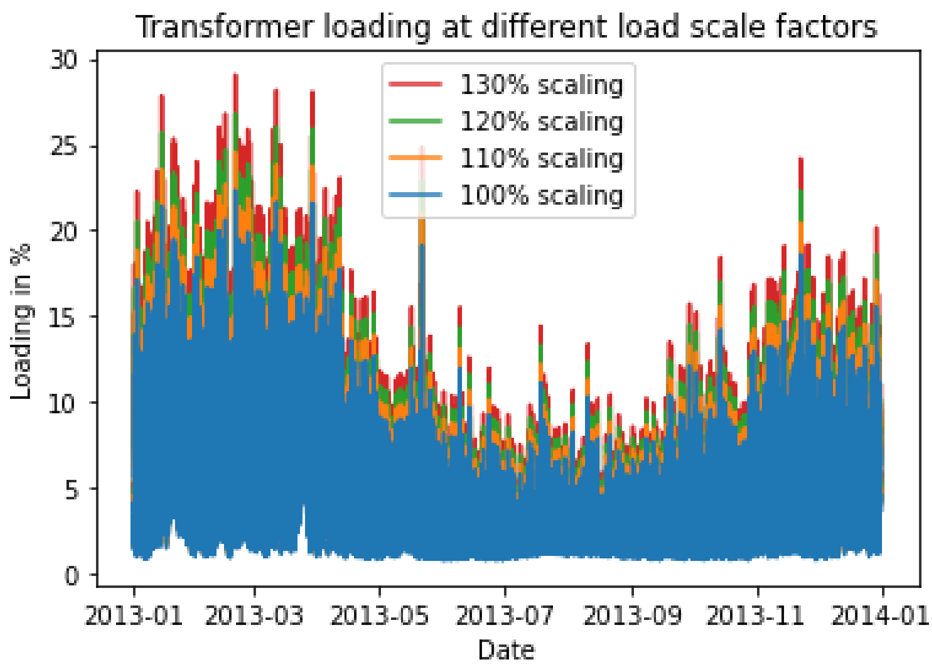


Figure A.7: Transformer loading at different load scale factors.

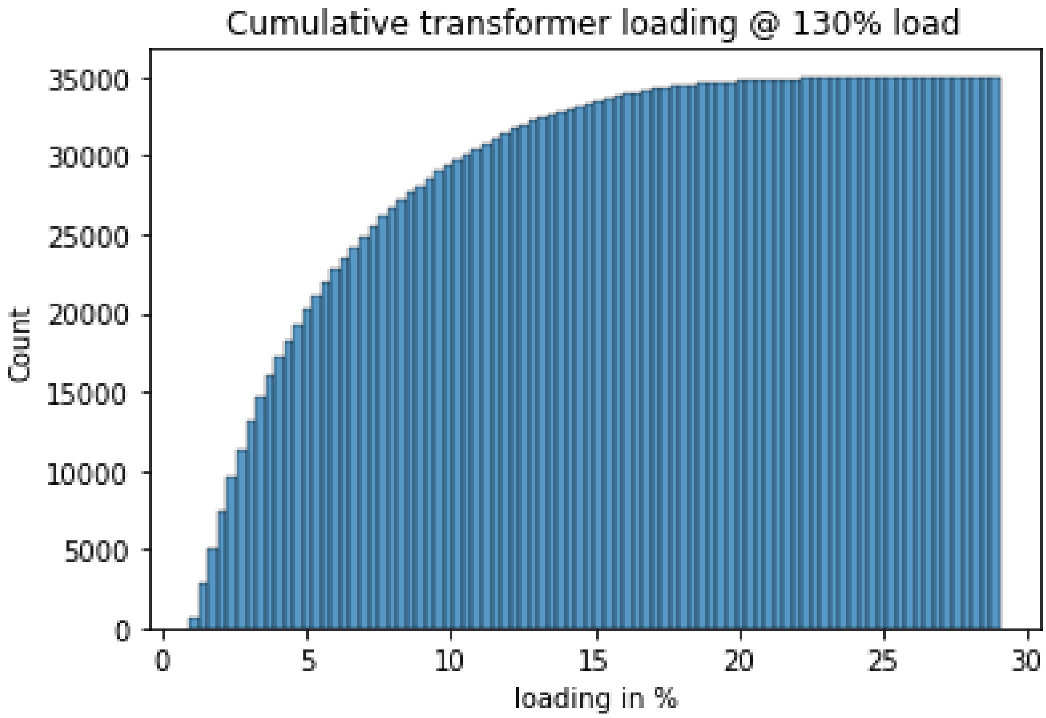


Figure A.8: Cumulative transformer loading at 130% load (year 2048).

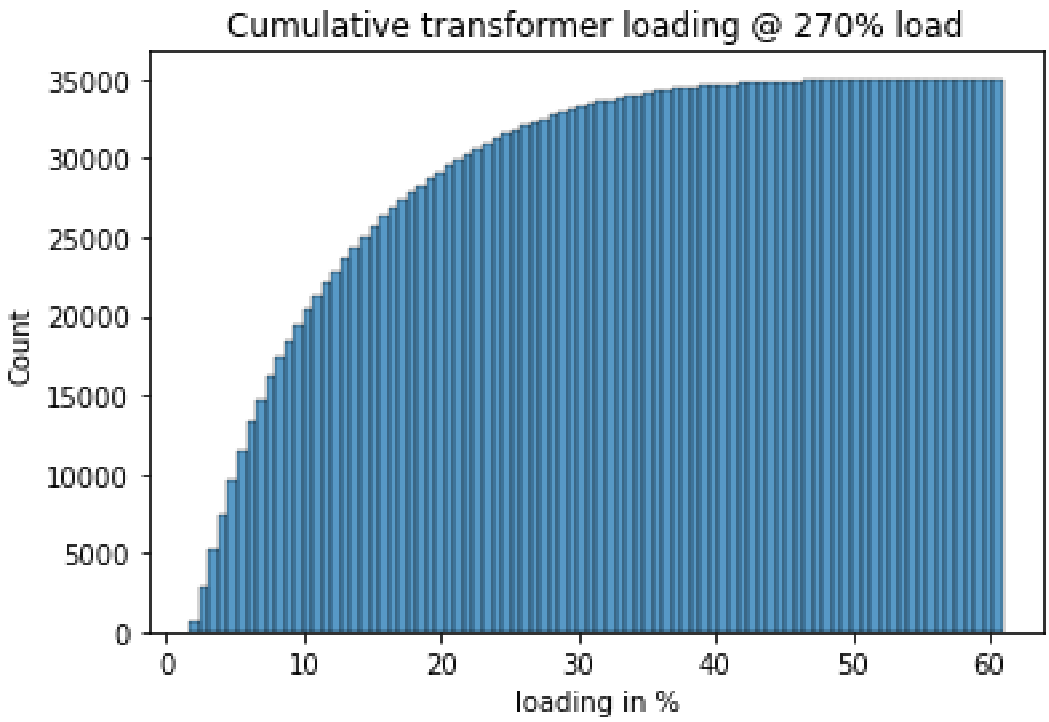


Figure A.9: Cumulative transformer loading at 270% load (year 2113).

A.1.2. EV loads and PV systems

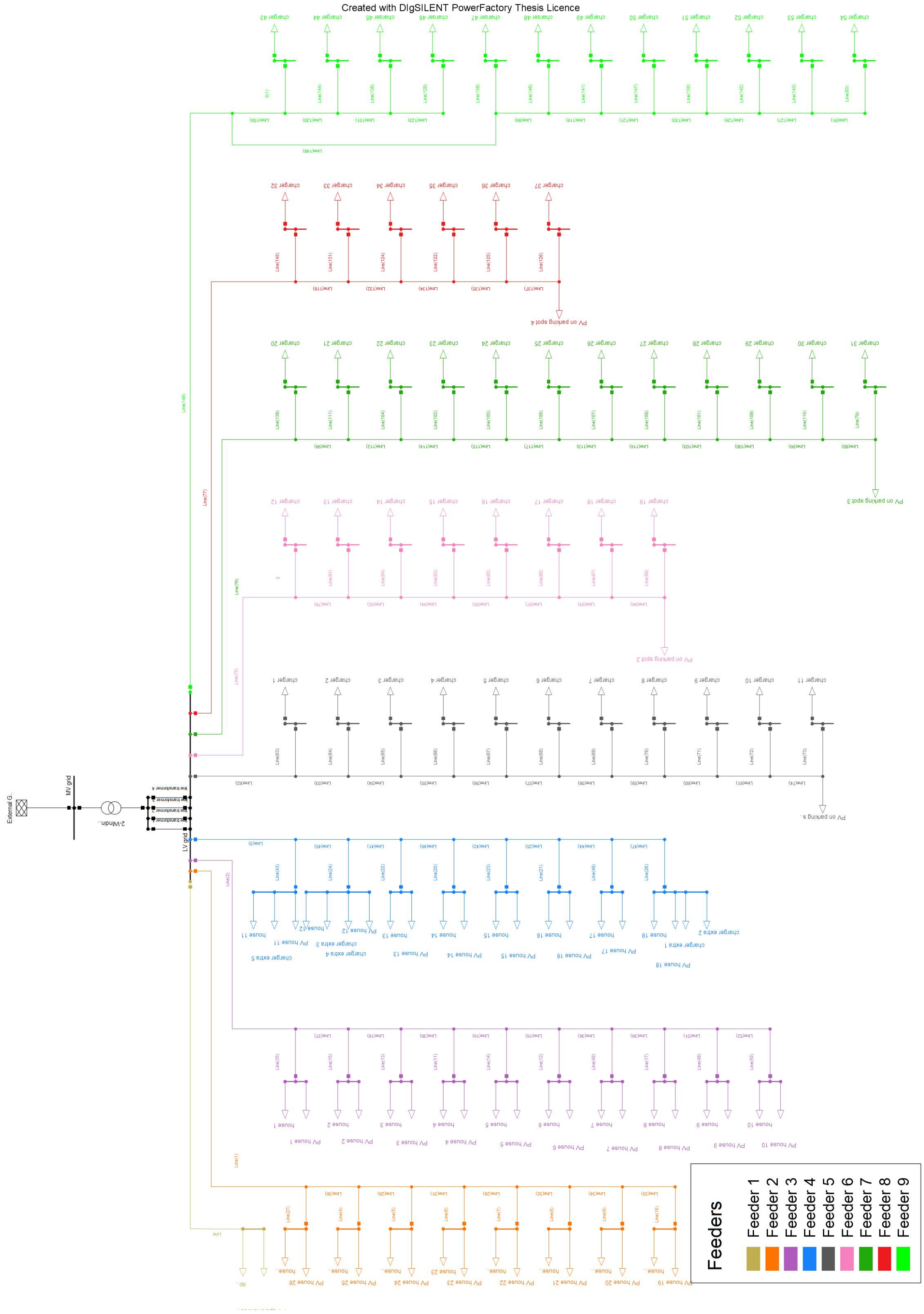


Figure A.10: Single line diagram with loads, PV and EV charging stations

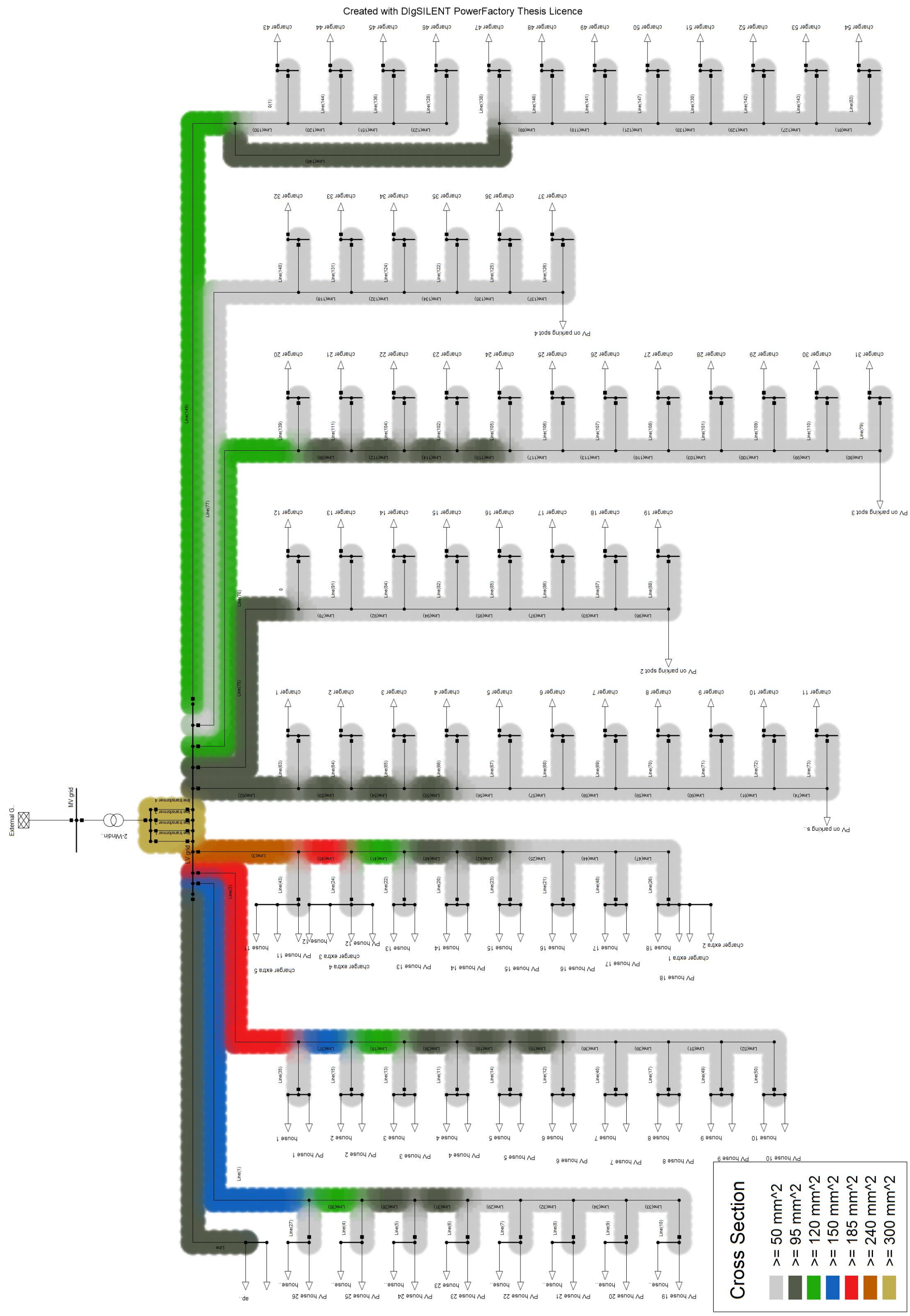


Figure A.11: Single line diagram with cable cross-sections.

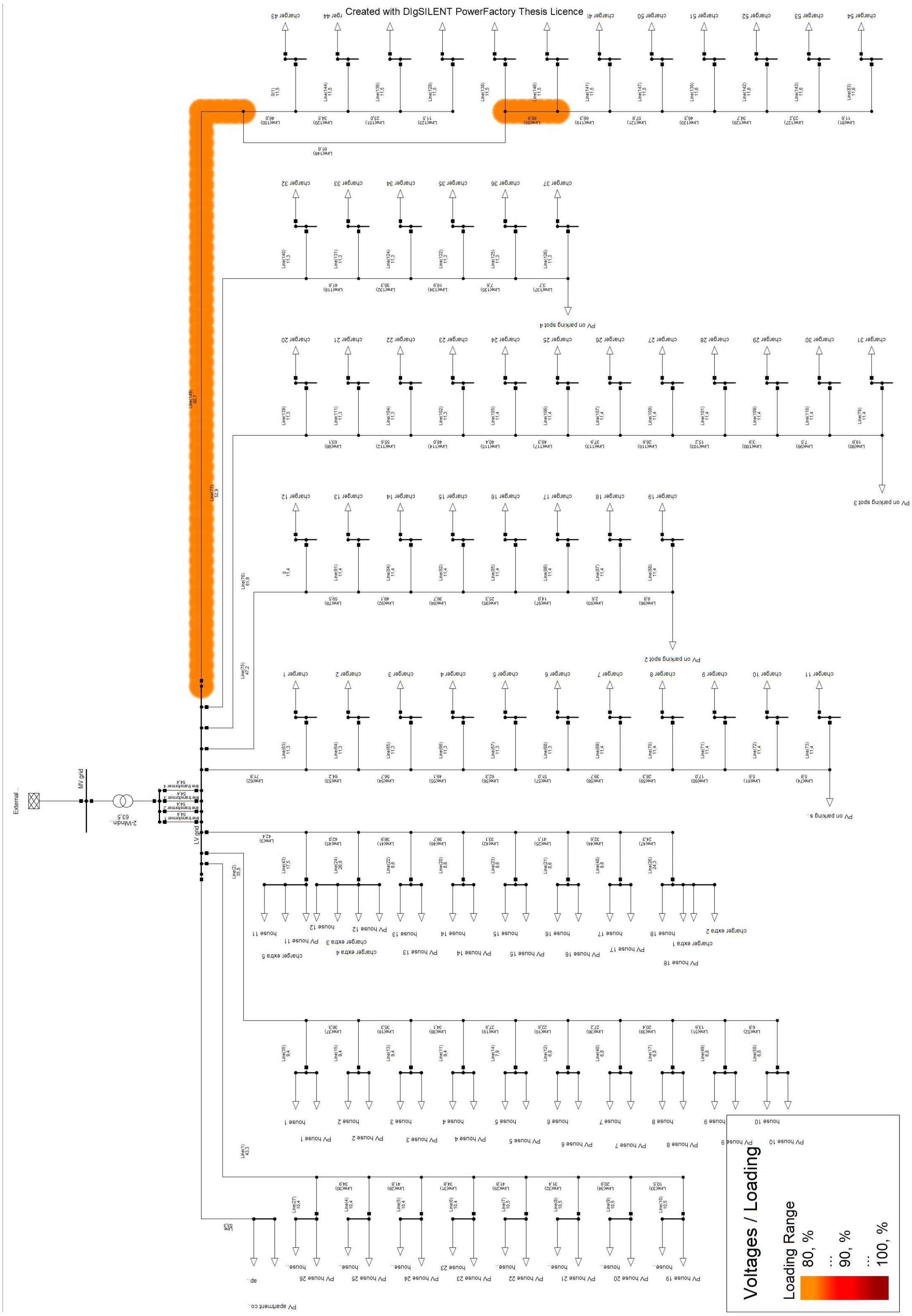


Figure A.12: Load Flow with loads, PV and EV charging.

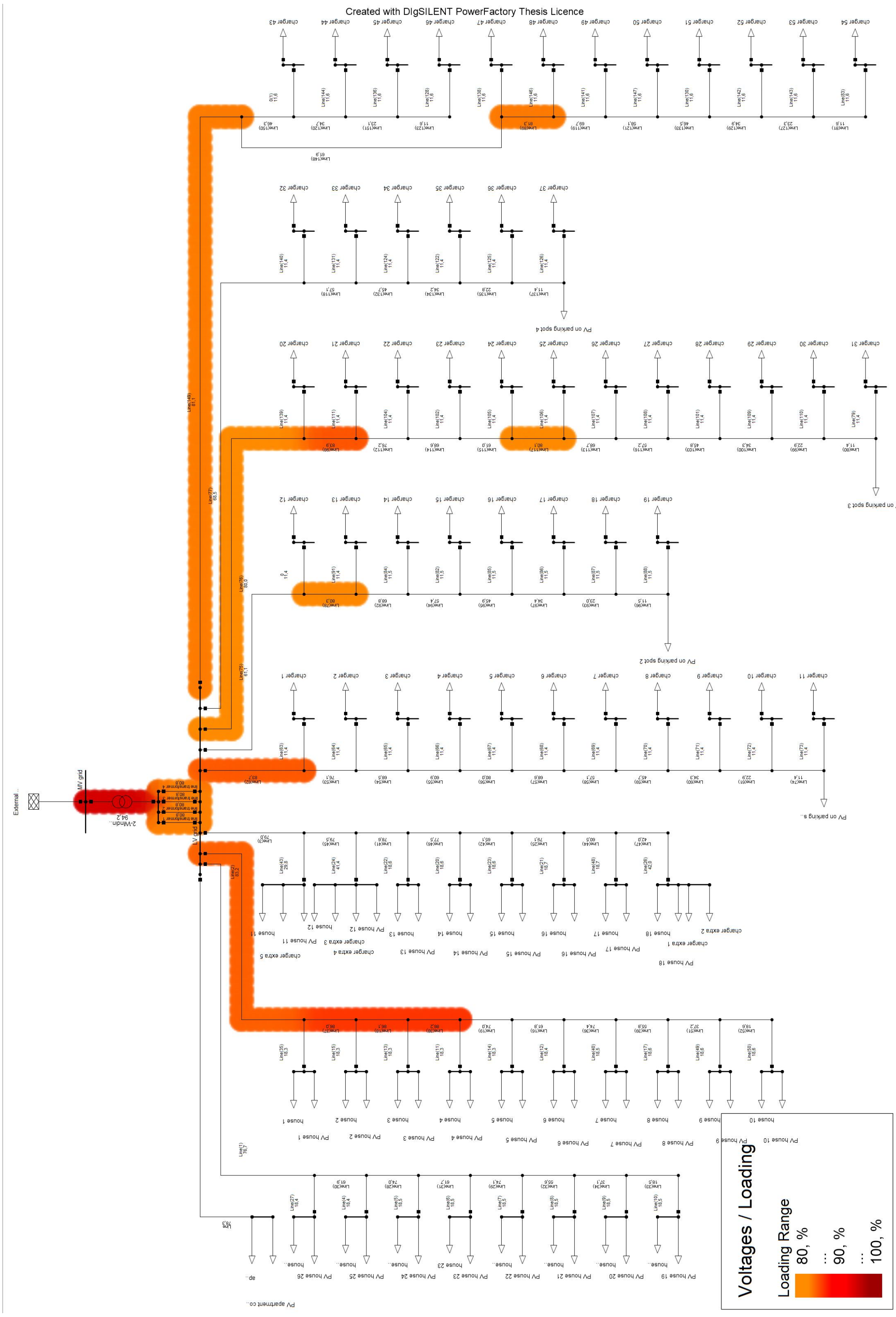


Figure A.13: Load Flow with loads and EV charging only.

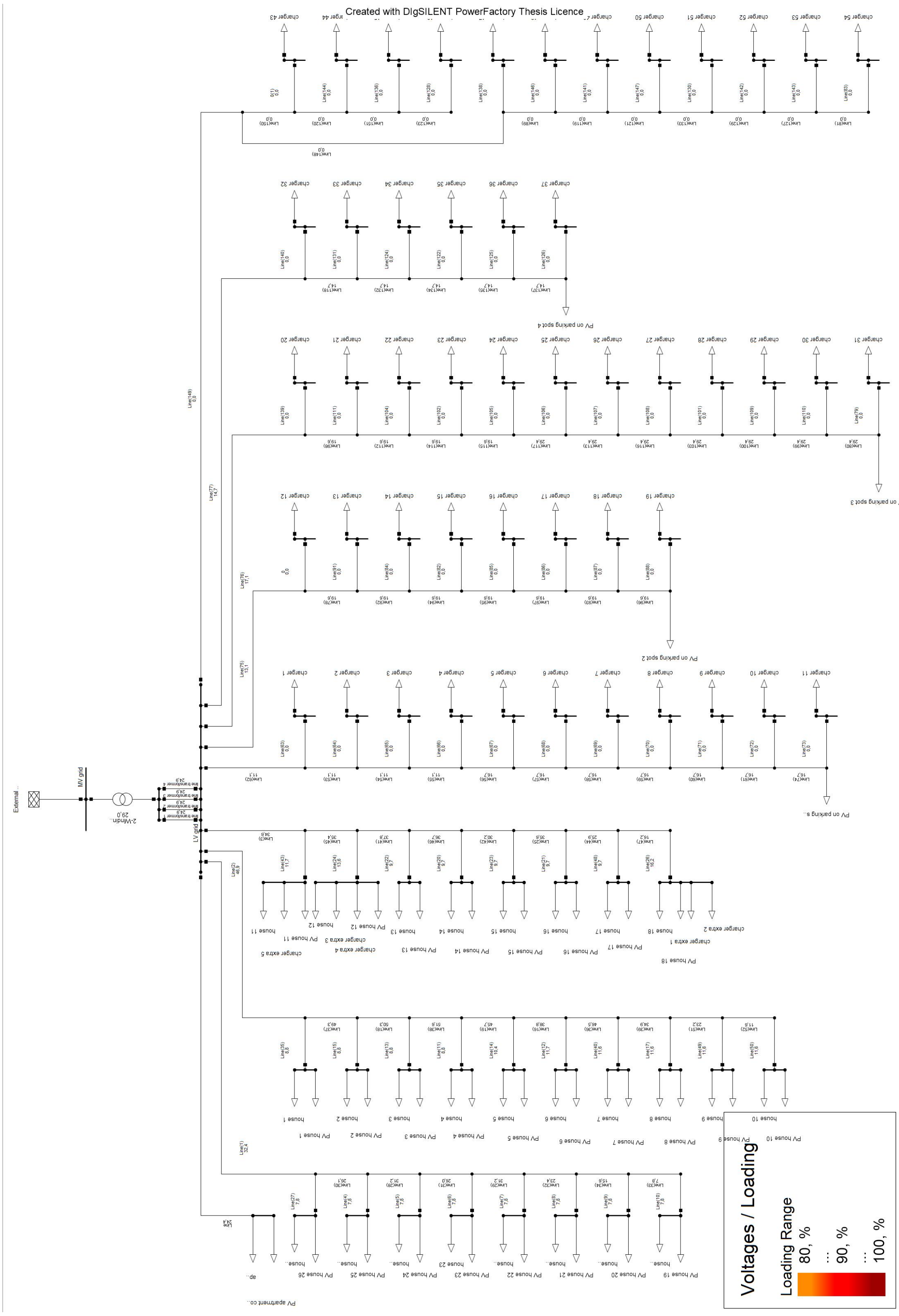


Figure A.14: Load Flow with PV only.

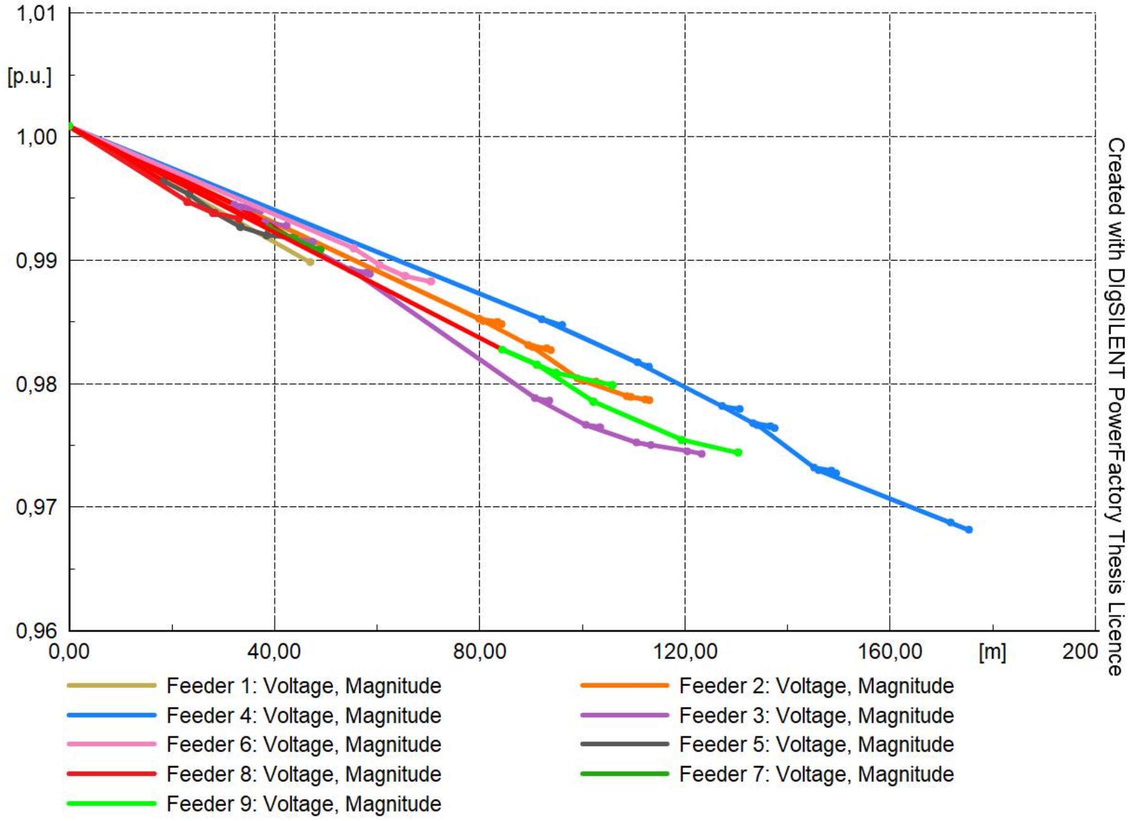


Figure A.15: Voltage profile feeders with loads and EV charging only.

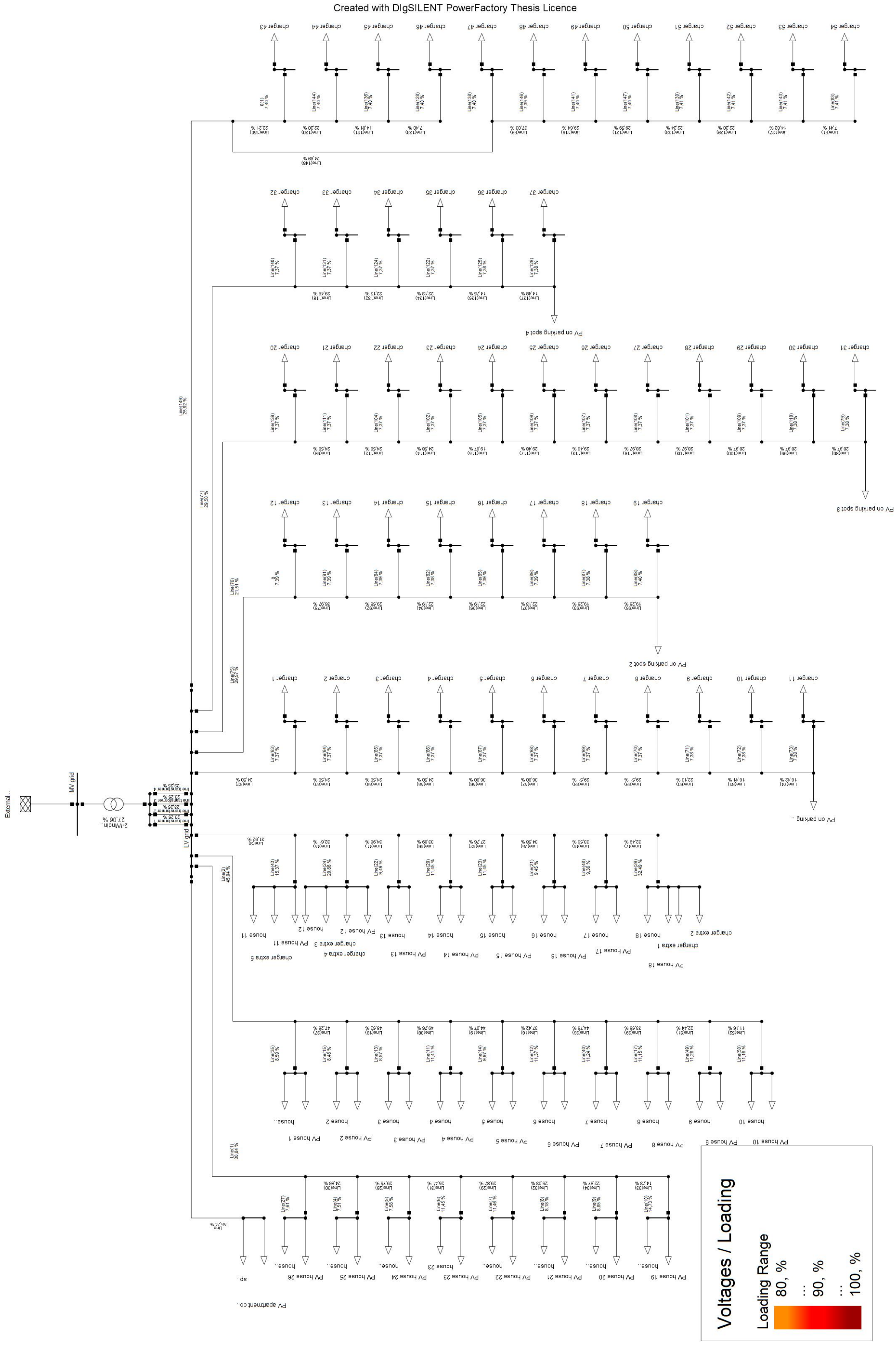


Figure A.16: Component loading at 110% Load (year 2022).

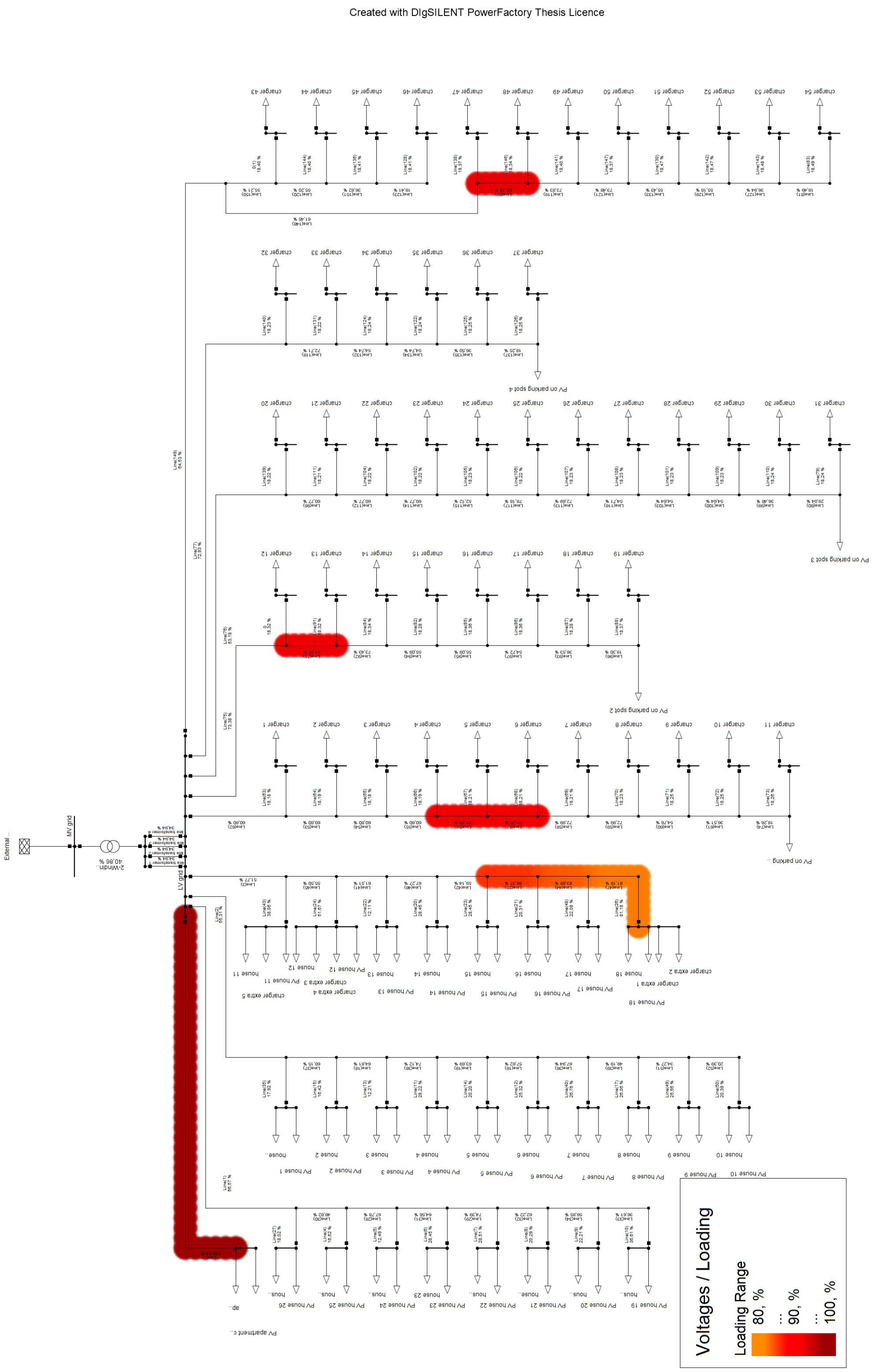


Figure A.17: Component loading at 270% Load (year 2113).

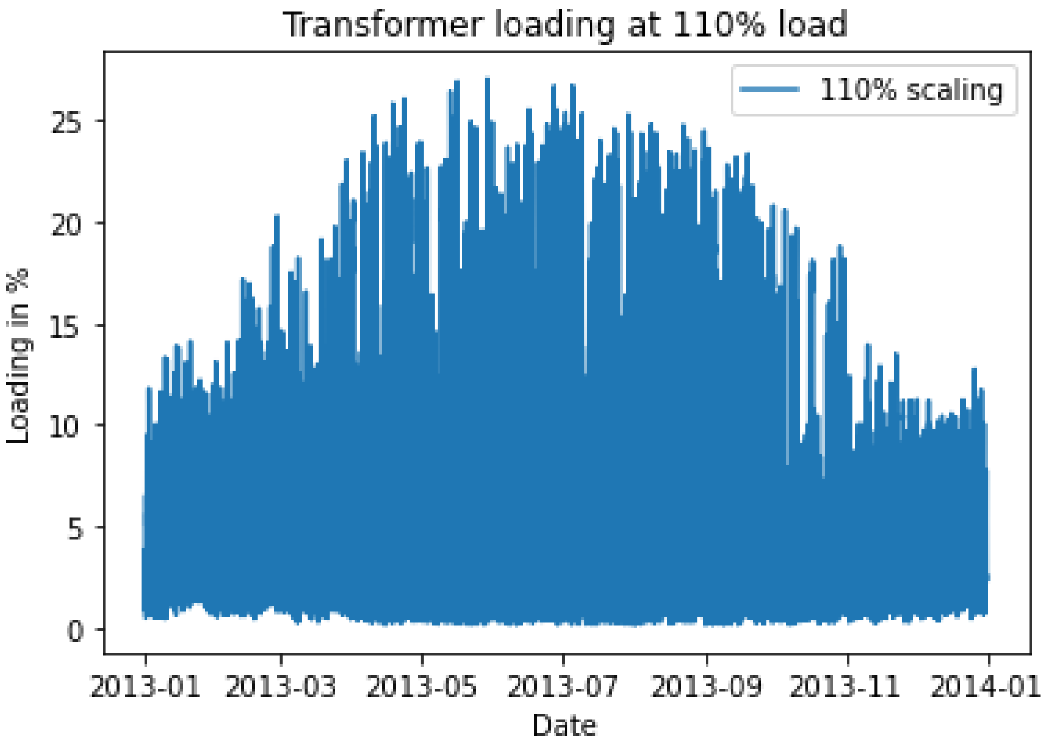


Figure A.18: Transformer loading at 110% (year 2022).

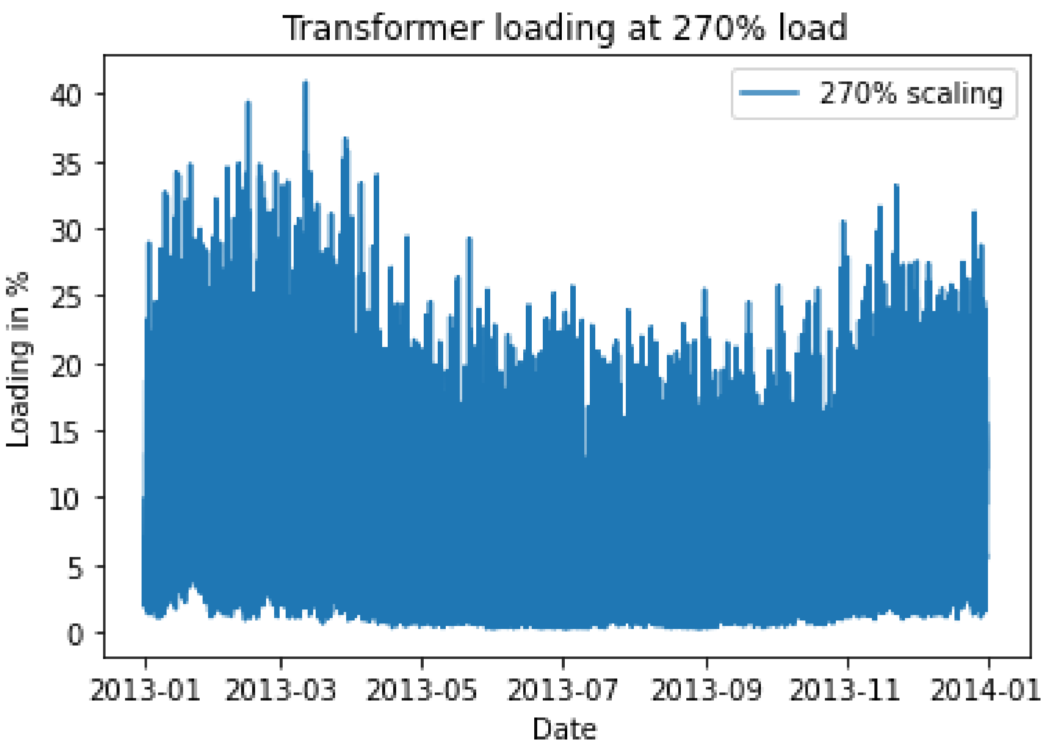


Figure A.19: Transformer loading at 270% (year 2113).

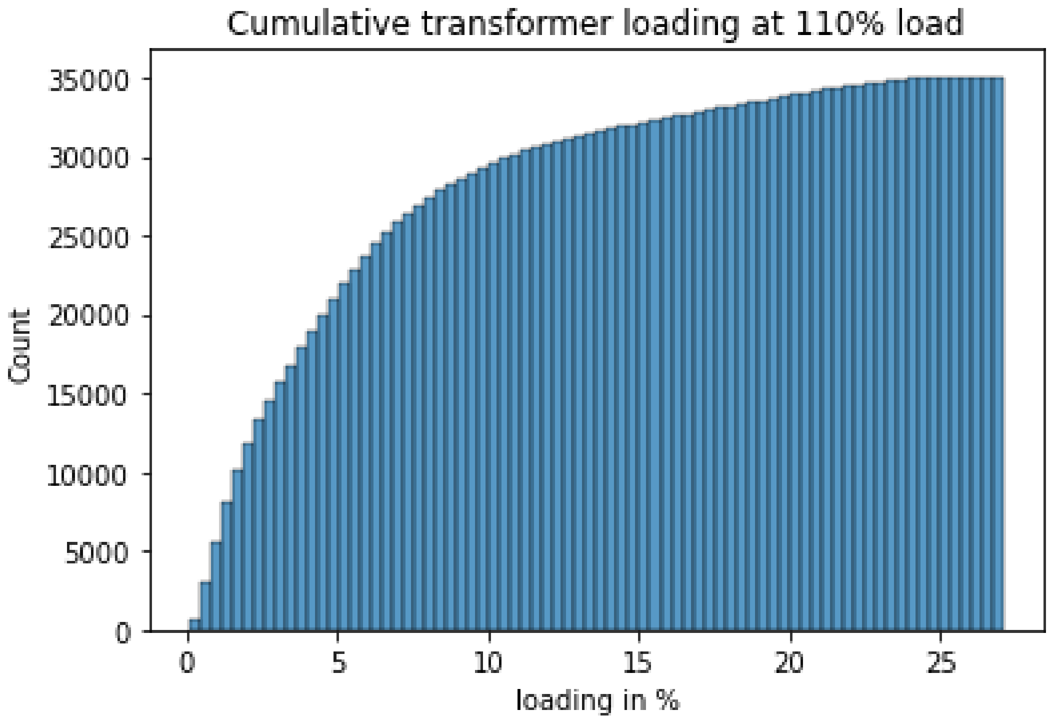


Figure A.20: Cumulative transformer loading at 110% (year 2022).

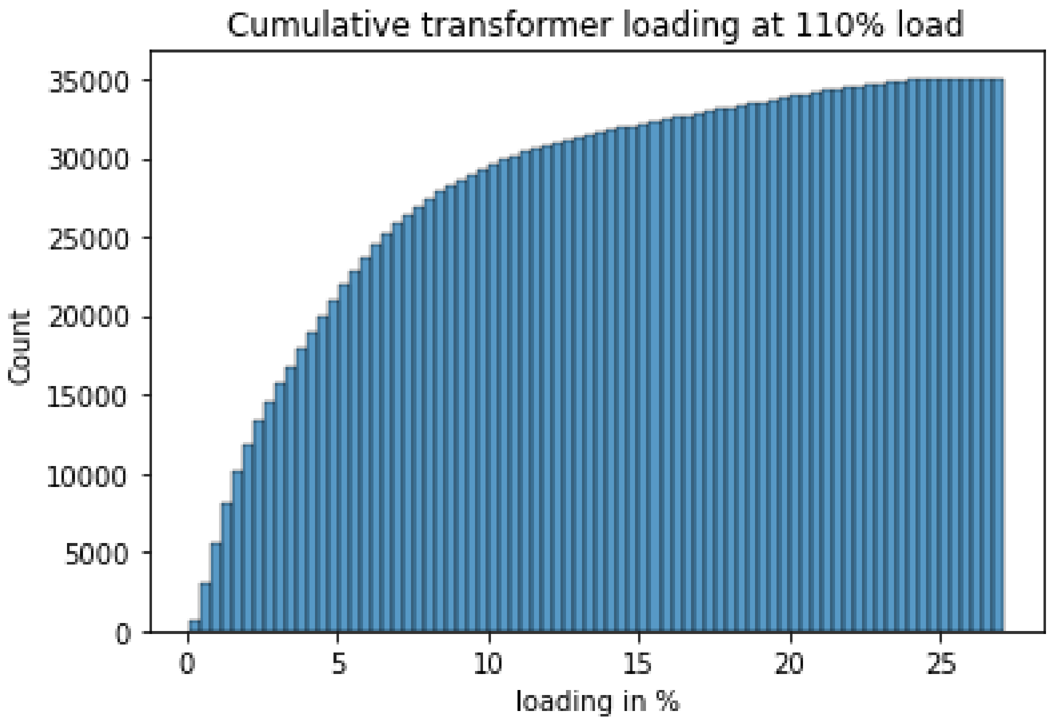


Figure A.21: Cumulative transformer loading at 270% (year 2113).

A.2. Python Code

A.2.1. Liander E&G Data - Conversion

```python
import pandas as pd

# Variables
predefinedIndices = [4, 30, 72, 77, 78] # customer indices to be skipped manually

# Importing data from csv to dataframes
dataFrameReturn = pd.read_csv('Ruwe data/Zonnedael - slimme meter dataset - 2013 - Teruglevering.csv', header=None, delimiter=';', on_bad_lines='skip', low_memory=False)
dataFrameElectrical = pd.read_csv('Ruwe data/Zonnedael - slimme meter dataset - 2013 - Levering.csv', delimiter=';', on_bad_lines='skip', low_memory=False)
dataFrameGas = pd.read_csv('Ruwe data/Zonnedael - slimme meter dataset - 2013 - Slimme meter.csv', delimiter=';', on_bad_lines='skip', low_memory=False)
dataFrameGas = dataFrameGas.loc[:, dataFrameGas.columns != 'Klant 77']


def timePrep():
    # Getting the timestamp in a single column
    dataFrameDateTime = dataFrameElectrical[:35040]['datetime']
    # Applying small fix to times before 10am
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 0:', ' 00:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 1:', ' 01:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 2:', ' 02:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 3:', ' 03:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 4:', ' 04:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 5:', ' 05:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 6:', ' 06:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 7:', ' 07:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 8:', ' 08:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 9:', ' 09:'))
    print('Datetime ready...')
    return dataFrameDateTime


def getUserIndices(dataFrameReturn, predefinedIndices):
    # Select user indices without solar panels
    firstrow = dataFrameReturn.iloc[0]
    indices = []

    for i in range(len(firstrow)):
        if type(firstrow[i]) == str and int(firstrow[i]) == 0:
            indices.append(i)

    for index in predefinedIndices:
        if index in indices:
            indices.remove(index)

    print('Indices ready...')
    return indices


def ePrep(indices):
    # Converting the electrical data from Wh to kW
    dataFrameE_prep = dataFrameElectrical.iloc[:35040, indices]
    dataFrameE_prep = dataFrameE_prep.apply(lambda x: x * 4 / 1000) # Conversion to kW

    print('E-prep ready...')
    return dataFrameE_prep


def gPrep(indices):
    # Converting the gas data from m^3 to kW and applying gas to electricity correction
    dataFrameG_prep = dataFrameGas.stack().str.replace(',', '.').unstack().iloc[:, userIndices]
    dataFrameG_prep = dataFrameG_prep.astype(float)
    dataFrameG_prep = dataFrameG_prep.apply(lambda x: x * 35.17 / 3.6)  # Conversion from m^3 to kW
    dataFrameG_prep = dataFrameG_prep.apply(lambda x: x * 0.05 * 0.412 + x * 0.25 * 0.333 + x
```

```
     * 0.7 * 0.333)  # Correction

    dataFrameG_ext = pd.DataFrame(columns=dataFrameG_prep.columns)

    # Extending from once per hour to once per 15m
    for i in range(len(dataFrameG_prep)):
        for j in range(4):
            dataFrameG_ext = dataFrameG_ext.append(dataFrameG_prep.iloc[i], ignore_index=True
    )

    print('G-prep ready...')
    return dataFrameG_ext


# Prepare time column
dfTime = timePrep()

# Prepare Gas and Electricity columns for the right customers
userIndices = getUserIndices(dataFrameReturn, predefinedIndices)
dfGas = gPrep(userIndices)
dfElectricity = ePrep(userIndices)

# Add Gas and Electricity and convert to MW for PowerFactory
df_full = dfElectricity.add(dfGas, fill_value=0)
df_full = df_full.apply(lambda x: x / 1000) # Conversion from kW to MW

# Add time column to dataframe
dfFullData = pd.concat([dfTime, df_full], axis=1)

# Convert data to csv format
dfFullData.to_csv('ElectricityGasDataFull.csv', index=False)
```

A.2.2. Irradiance to PV - Conversion

```
import pandas as pd

# Import datasets
NinjaPVdata= pd.read_csv('Ruwe data/ninja_pv_clean_weesp_2019.csv',
                                  delimiter=';', on_bad_lines='skip', low_memory=False)
dataFrameElectrical = pd.read_csv('Ruwe data/Zonnedael - slimme meter dataset - 2013 -
    Levering.csv',
                                  delimiter=';', on_bad_lines='skip', low_memory=False)


def timePrep():
    # Getting the timestamp in a single column (This dataset has correct timestamp column)
    dataFrameDateTime = dataFrameElectrical[:35040]['datetime']
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 0:', ' 00:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 1:', ' 01:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 2:', ' 02:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 3:', ' 03:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 4:', ' 04:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 5:', ' 05:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 6:', ' 06:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 7:', ' 07:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 8:', ' 08:'))
    dataFrameDateTime = dataFrameDateTime.apply(lambda x: x.replace(' 9:', ' 09:'))
    print('Datetime ready...')
    return dataFrameDateTime


def PVPrep():
    df_irradience = NinjaPVdata['irradiance_direct'].add(NinjaPVdata['irradiance_diffuse'],
    fill_value=0).to_frame(
        name="total_irradience") # Adding direct and diffuse irradiances

    # Interpolating to 15m intervals from 1h intervals
    df_irradience_interpolated = pd.DataFrame(columns=df_irradience.columns)
    for i in range(len(df_irradience)):
        if i == 2190: print('25% Irradience Interpolation')
        if i == 4380: print('50% Irradience Interpolation')
```

```
        if i == 6570: print('75% Irradience Interpolation')
        if i == 8755: print('100% Irradience Interpolation')
        for j in range(4):
            df_irradience_interpolated = df_irradience_interpolated.append(df_irradience.iloc
    [i], ignore_index=True)

    df_P_panel = df_irradience_interpolated.apply(lambda x: x * 1.7)  # Conversion to power [
    W] (from irradiance [W/M^2])
    df_P_panel.columns = ['power']  # Change column name to power
    df_P_panel = df_P_panel.apply(lambda x: x * 0.20)  # Applying the solar panel efficiency
    df_P_panel = df_P_panel.apply(lambda x: x * 0.95)  # Applying the inverter efficiency
    df_P_panel = df_P_panel.apply(lambda x: x / 1000000)  # Convert to MW
    df_P_panel = df_P_panel.apply(lambda x: x * -1)  # Convert to negative load

    return df_P_panel


df_Time = timePrep()
df_P_panel = PVPrep()

# Concatenate the timestamp column with PV power data column
Full_df = pd.concat([df_Time, df_P_panel], axis=1)
Full_df.head(40)

# Exporting data to csv format
Full_df.to_csv('PV_15m_MW.csv', index=False)
```