Simulating the Effects of Smart Grid Technologies on Power Quality

Master's Thesis

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Abstract

A transition in the energy sector is going on. Formerly, electricity was only generated centrally and distributed to consumers in the low voltage network. Nowadays, more residents in the low voltage network start to produce their own electricity. This thesis is about the effects of this distributed generation in the low voltage on the power quality and how smart grid technology can help to improve the power quality.

A high penetration of distributed generation can lead to increased voltage levels, harmonics and fluctuations of the voltage level in the low voltage network. These aspects influence the power quality of the electricity delivered to the consumers. Overloading of the network might occur as well. Demand side management could help to mitigate these problems and improve the power quality by balancing consumption and production.

To cope with the integration of more distributed generation and large loads in existing networks, demand side management (DSM) methodologies are developed. Network structures and models are added to the DSM methodology and energy stream simulator, TRIANA, developed by the University of Twente. Additionally, a load-flow algorithm is implemented to calculate the voltage levels and currents flowing through the network. These models provide the means to evaluate the effects of distributed generation in the low voltage network and allows the simulator to fully exploit the models for the planning stage. The first implementation with the integration of network models uses load-flow information as feedback to alter the planning.

The accuracy of the implementation is evaluated by comparing the calculated voltage levels with those resulting from the more advanced network simulator Gaia by Phase to Phase. The maximum deviation in voltage level was found to be 1.3 V. The computation time of the implemented algorithm only takes 1.3ms, whereas Gaia usually requires a second to find the values.

An existing Dutch low voltage network is modeled for simulations. A total of 121 households are modeled after a futuristic model with a varying penetration of photovoltaics, electrical vehicles, heat pumps and smart appliances. Simulations show that large loads lead to voltage drops during the winter. With demand side management, the minimum voltage level is locally as low as 204 V, lower then the minimum allowed by the Dutch regulations. Using load-flow information as feedback improves the voltage level with a minimum of 212 V. The maximum cable usage is also reduced from 88.5% to 66.3%. These results are obtained with similar DSM performance results.

The results show that large loads can have influence on the power quality in a network as well. With a high penetration of either distributed generation or large loads the simulated network is close to its limits, or even exceeds these limits. Demand side management does not necessarily lead to a better power quality, but can even decrease the power quality. The main reason for this is the imbalance introduced in the network at certain points. This research shows that incorporating load-flow calculations in DSM can overcome this problem and incorporate power quality optimization objectives in DSM. A smart-grid should therefore balance production and consumption both globally as locally to improve the power quality.

Samenvatting

Er is een verschuiving gaande in het energielandschap. Van oudsher werd elektriciteit centraal opgewekt om verbruikt te worden door consumenten in het laagspanningsnet. Tegenwoordig beginnen steeds meer consumenten hun eigen energie op te wekken. Dit onderzoek gaat over de effecten van deze decentrale opwekking in het laagspanningsnet op de spanningskwaliteit en hoe slimme netten kunnen bijdragen aan een verbetering hiervan.

Grote hoeveelheden decentrale opwekking kunnen leiden tot spanningsstijgingen in het netwerk, harmonischen en fluctuaties van het spanningsniveau in het netwerk. Deze aspecten hebben invloed op de kwaliteit van de geleverde elektriciteit, beter bekend als spanningskwaliteit. Tevens kan het netwerk overbeleast raken. Door middel van afstemming van energieconsumptie en -productie kunnen deze effecten echter mogelijk worden tegengegaan. Dit vereist wel planning en coördinatie tussen apparatuur, een belangrijk onderdeel binnen slimme netten.

Om meer decentrale opwek en grote lasten in bestaande netten te kunnen integreren wordt gebruik gemaakt van vraagsturing. Om de effecten van decentrale opwekking in een laagspanningsnet te onderzoeken, zijn netwerkstructuren en modellen van netwerkcomponenten toegevoegd aan de DSM methode en energiestromen simulator TRIANA die ontwikkeld is aan de Universiteit Twente. Daarnaast is een load-flow algorithme geïmplementeerd om de spanningsniveau's en stromen in het netwerk te bepalen. Hierbij ligt de focus op een compact en snel algorithme. Op deze manier kan de simulator deze modellen mee-nemen bij de planning van apparatuur. Een eerste implementatie van deze integratie gebruikt de resultaten van load-flow berekeningen als terugkoppeling voor de sturing van apparatuur om de spanningskwaliteit te verbeteren.

Evaluatie van de implementatie laat zien dat de nauwkeurigheid van de load-flow berekeningen maximaal 1.3 V afwijkt ten opzichte van meer geavanceerde simulaties met het programma Gaia van Phase to Phase. Hierbij worden de berekeningen in 1,3ms uitgevoerd ten opzichte van de seconde die Gaia doorgaans nodig heeft.

Een bestaand Nederlands laagspanningsnet is gemodelleerd voor simulaties. Hierin zijn 121 woningen gemodeleerd naar een toekomstig model. Variërend bevatten deze woningen zonnepanelen, elektrische auto's, warmtepompen, accu's en slimme apparatuur. Simulaties laten zien dat tijdens winterdagen de grote verbruikers het spanningsniveau lokaal doen laten zakken tot 204 V, waarmee de eisen die gespecificeerd zijn in de Netcode worden overschreden. De terugkoppeling met load-flow berekeningen laat verbetering van de spanningsniveau tot een minimale waarde van 212 V zien zonder noemenswaardige daling van DSM resultaten. Tevens wordt de maximale kabelbelasting verminderd met 22,2 procentpunt van 88,5% tot 66,3%.

Uit de resultaten doet blijken dat niet alleen decentrale opwekking, maar ook zware lasten veel invloed hebben op de spanningskwaliteit in een netwerk. Bij een grote penetratie loopt het netwerk tegen zijn limieten aan, of gaat daar zelfs overheen. Het afstemmen van consumptie en productie om pieken weg te werken leidt daarbij zeker niet altijd tot verbetering van de spanningskwaliteit en kan deze zelfs verslechteren. De oorzaak hiervan is lokale onbalans in het netwerk. Dit onderzoek laat zien dat met behulp van load-flow berekeningen bij vraagsturing deze problemen kunnen worden voorkomen en de spanningskwaliteit tegelijkertijd kan worden geoptimaliseerd. Het is dan ook nodig om een intelligent netwerk zowel lokaal als globaal in balans te houden om de spanningskwaliteit te kunnen verbeteren.

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1
Introduction

1.1 Motivation

We use electricity on a daily basis. Electricity is what keeps our factories and households running. A stable supply of electricity is what customers expect and demand from the electricity distribution companies. Failing in doing so, i.e. with a *blackout* in which no power is delivered to the customer, can have large economic consequences when production is stopped and has to be restarted again. It has also consequences on social and safety aspects such as lighting streets and powering hospitals. Even a voltage drop in the grid can have huge impact on sensitive equipment, with the possibility of damage to equipment.

There are a lot of aspects when it comes to the quality of the supplied electricity. Those aspects are described in [9] and include voltage and current variation, phase shifts and harmonic distortion. The term *power quality* is used as general term for all these aspects. Utilities must meet certain requirements with respect to this power quality to make the power distribution network function properly.

Definition 1. *Power quality describes the quality of the supplied voltage, depending on voltage level, frequency and harmonic distortion.*

For decades, electrical energy has been produced centrally at large plants. This electricity was transported through the *high voltage* (HV) grid down to the *low voltage* (LV) distribution network. Most consumers were connected in the low voltage network. But there is a change ongoing in the low voltage network. Households start to install photovoltaic cells on their rooftops and windmills arise in the landscape. The *consumers* are becoming *producers* as well and their *energy* is fed into the lower voltage levels of the grid.

This shift from centralized energy production in high quantities at high voltage levels to decentralized small production, but in large numbers, at low voltage levels causes new challenges [10, 66]. The current grid that is deployed in most areas was never designed for this use. Investments at the transformers may be needed to solve issues regarding power quality. But additional cables to transport all the electrical energy might be needed as well. Research [54, 57] shows that *distributed generation* in the low voltage grids can lead to severe voltage rises, especially at the end of the feeder.

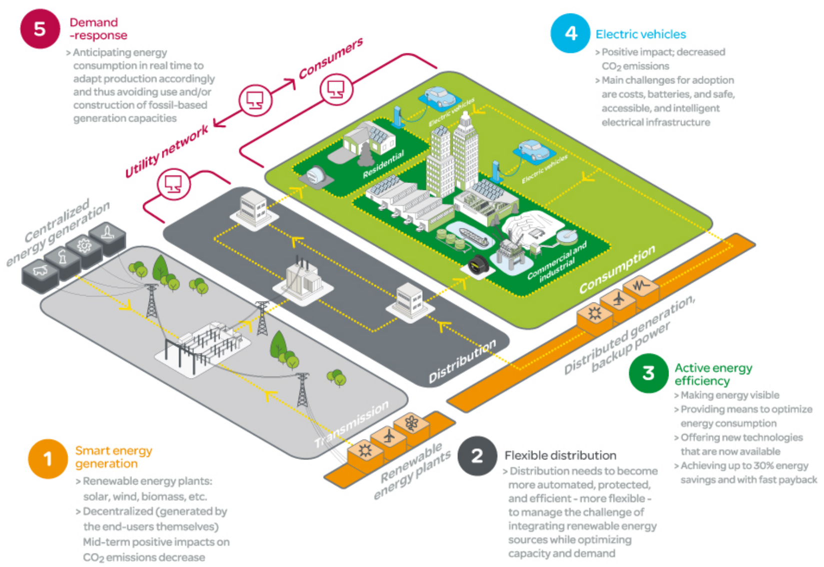

Figure 1.1: *A future grid with a large penetration of electric vehicles and renewable energy where ICT is used to monitor and improve the transport of energy (source: Schneider Electric).*

Also the usage of electrical energy has changed and will continue to do so in the future. Nowadays electrical furnaces are installed more often. Some new houses even lack a connection with the gas grid and completely depend on electrical energy for their energy supply. A large penetration of electric vehicles in the future will lead to an even higher usage of electrical energy. At the same time, more consumers start to produce their own energy and inject electricity they cannot consume their selves into the grid. Figure 1.1 shows a future grid setting.

However, the grid itself is changing as well with the introduction of smart grid technology. The following definition for smart grids is given in [49]:

Definition 2. *A Smart grid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies.*

The data from smart meters can be used by software to make a planning based on predicted demand and production of electrical energy. Smart appliances must conform to this planning to keep production and consumption in balance. Adding information and communication technology to the grid might be of use to keep the power quality at acceptable levels as well.

A lot of research is done on planning in smart grids. Energy losses and waste of renewable energy can be reduced by matching production and consumption locally. A control strategy for smart grids, called TRIANA [39], is developed at the University of Twente. This strategy consists of three steps. The first is to do a forecast on the demand and production. Then a planning is made for the next period. The third step is real-time control to handle unpredicted changes in production and consumption.

1.2 Problem statement

All these new developments within the low voltage grid form a challenge when it comes to the network capacity required to make the low voltage network function correctly. At the utilities, the question arises what changes must be made to the existing low voltage grids to accommodate large penetrations of distributed generation. Voltage rise due to distributed generation in the distribution network, especially at the end of the feeder, is becoming a major problem [10]. New transformers might be needed as well as additional cables to deliver the required capacity in the low voltage network.

The increasing amount of distributed generation is a challenge for these utilities. However, the introduction of the smart meters, in combination with smart appliances, increases the possibilities of monitoring and controllability of the net. Furthermore, the integration of electric vehicles adds storage to the grid that can possibly be exploited. Combining these developments in the grid with ICT, yields perspective to utilize the net better and prolong the current grid infrastructure without the need for grid reinforcements. Also new grids could possibly be dimensioned with less capacity to reduce the costs. Simulations on the grid are required to evaluate whether this is true.

A simulator using the TRIANA approach is already written to evaluate the performance of the control strategy. In [5] details about the implementation of this simulator are given. All the energy flows within the simulator run from producers to consumers via *pools*. All these pools must be in balance, i.e. the incoming energy must be equal to the outgoing energy. However, these energy flows are simulated with a simplified view of the grid. The planning does not take into account the effects this has on the grid. It might be possible that another planning has more positive effect on both the required capacity and the correct functioning of the low voltage net. Where correct functioning is defined as a steady supply of electricity conform the applicable regulations.

The correct models for grid functioning are not available in the simulator at this moment. This is the first research issue that has to be tackled. Creating such models and doing simulations allows to evaluate the effects of higher penetrations of distributed generation on the low voltage network. With these results the minimum required capacity for a net can be determined.

However, integrating such simulations in the planning approach allows further enhancements. With the models, effects on the net of individual components can be analyzed. These results can be used to further enhance the planning algorithm. The second research issue is about optimizing the planning to see whether the required capacity can be lowered even further.

1.3 Research questions

The main goal of this research is to model and simulate the distribution grid with smart grid technology and a high penetration of distributed generation. With these simulations, open topics regarding required network capacity and the possible influence of smart grids can be answered. The focus of the research will be mainly on the problems of voltage rise within distribution grids with distributed generation. With this goal in mind, the first research question is formulated:

> *"What is the impact of high penetration of distributed generation on correct functioning of the low voltage network?"*

The answer to this question depends on the factors that are required for a net to function correctly. There are certain tolerances, but the limits on these factors need to be met. High penetration of distributed generation could have impact on these factors. To answer this research question, the following sub-questions are formulated:

1. *"What are the important factors that define whether a network is functioning correctly or not?"*
2. *"In which way does distributed generation influence these factors?"*
3. *"How can these components be modeled and factors be simulated?"*

The second research question covers the smart grid part. Once the effects of distributed generation are discussed, the possible solutions using smart grids can be explored. The following research question is formulated regarding this topic:

> *"Can smart grids help to lower the minimum required capacity in the low voltage network?"*

The answer to this question depends on the amount of distributed generation and the ability of distributed generation to improve the factors that determine the minimum required capacity. To answer this research question, the following sub-questions are formulated:

1. *"What would a typical low voltage network and residential area look like?"*
2. *"What would be the required capacity in the low voltage network with high penetration of distributed generation without planning?"*
3. *"Which components can have a positive effect on the required network capacity?"*

Answers on these questions will provide enough information to give the answers to the main research question.

1.4 Aproach

This research consists of two phases. The first phase is a literature study to give answers to the first main research question. This literature study will mainly be conducted in the field of low voltage networks and distributed generation. More specific of factors which have effect on the network capacity and the correct behaviour of the network are points of interest. Studies on the effects of adding distributed generation to low voltage networks are also used in this part.

Then a comparison between different simulation methods and tools is conducted. This is partly a literature study. A decision on the tools to be used for simulation will be made. The literature will be evaluated to give an answer on the first research question together with some initial simulations.

The second part of the research consists of the actual simulations and analysis of the results to evaluate the effects of distributed generation (DG) and demand side management (DSM) on a network using load-flow calculations.

Definition 3. *Distributed generation is decentralized production of energy using multiple small energy sources.*

Definition 4. *Demand Side Management steers demand for energy using incentives such as different pricing during the day, usually with the goal to reduce the need in network investments by reducing peak consumption.*

Definition 5. *Load-flow calculations on network models are used to obtain voltage levels, distribution losses and other network information for a certain scenario. These calculations are used in network design to validate that the required capacity will be realized.*

For this purpose network models and a load-flow calculations have to be added to the TRIANA simulator. This is done using a quick load-flow algorithm to do analysis. Additionally, coupling with a sophisticated load-flow calculator is made to test and validate the performance of the implementation. Additionally, the sophisticated external load-flow calculator can be used to obtain more accurate results when desired. The results of load-flow calculations are used as feedback in DSM to enhance the power quality. The background on electricity networks is required for the network modeling, load-flow algorithms and to determine how power quality can be improved using DSM with load-flow feedback.

One use-case is to be defined defined. These test cases put numbers on the amount of installed photovoltaic energy, number of houses and so on. Models of these test cases will be created and simulated using a simulator. After simulation, an analysis can be done on the power quality in the simulated network. This will be the baseline on which further optimizations can be performed. The details obtained from the literature study are used to further improvements on power quality. These results will be analyzed and compared to the baseline in order to give an answer to the second research question.

1.5 Outline

The outline of the rest of this thesis is as follows. The next chapter will cover the background on distribution networks. Details about the general structure of these networks are given. It also outlines problems that can occur in networks when introducing DG in this network. Possible solutions from literature are also given as well as simulators available to evaluate the effects.

Chapter 3 discusses the requirements for the research part of this thesis. Power quality contains a lot of aspects, that cannot be covered within the time available for a master's thesis. A choice is to be made in what will be done and what is left for future work. In chapter 4 network models required to meet the requirements are detailed. For simulation, analysis of algorithms in literature is also done. An effective algorithm is to be chosen for simulation.

The chosen algorithm is implemented in the TRIANA simulator and this is discussed in chapter 5. Chapter 6 discusses the simulation results of networks with a high penetration of DG and how smart grid solutions can help to lower network capacity. Additional analysis are done in chapter 7 to determine where room for improvement can be found for future solutions. The research questions presented in this chapter will be answered in the concluding chapter 8.

2 Background

The first part of this chapter will briefly explain how distribution networks work. This theory should give more insight in why distributed generation might lead to problems in a low voltage (LV) distribution network. The general layout of Dutch LV networks will also be discussed, with as example the LV network located in Lochem. It will conclude with pointing out what factors are important for a correct functioning LV network.

The second part consists of a study on the effects of distributed generation in the LV network and how these affect the power quality experienced by the end users. Proposed solutions to mitigate problems with distributed generation will be discussed in the third part. Furthermore, this part will also outline proposed solutions to allow more distributed generation within the LV network.

Simulation techniques and simulators will be covered in the last section. Several simulators already exist on the market to simulate the LV network. The focus is on how these simulators might be used in combination with the TRIANA simulator written at the University of Twente [5]. This exploration includes a study on simulation techniques for LV networks.

2.1 Distribution networks

This section will cover the basics of distribution networks. The outline is as follows. First the basic topology of transmission and distribution networks will be discussed. Also the commonly used hardware to regulate the distribution will be covered. Next, some details about a coorporation of Dutch citizens from the village Lochem that actively participate to accelerate the transition to renewable energy are given. Experiments within this community give insight in problems and solutions for distributed generation. The section will conclude with regulations regarding power quality that have to be met by distribution system operations.

In order to answer the research questions and to show how distributed generation impacts the low voltage grid, it is good to have a look at the layout and the theory behind distribution grids and distributed generation. Without the theory, it will not be possible to understand the effects of feeding in energy by generation. Nor would it be possible to verify whether models and the results of simulations are correct.

2.1.1 Dutch distribution network

In [51] the typical Dutch LV networks are described. Electricity is transported using alternating current (AC). The LV distribution network in the Netherlands uses a three phase 230/400 V 50 Hz network. These networks consist mainly of underground cables. Only some areas have overhead lines due to ground conditions. Most of the medium voltage (MV) networks are operated at 10 kV, but 6, 12, 20, 25 and 33 kV levels are also applied. The MV network delivers the electrical energy to the LV network where most of the households and companies are connected to. Bulk energy production is done in the HV level, which is the transmission layer. Figure 2.1 shows the layout of such a network.

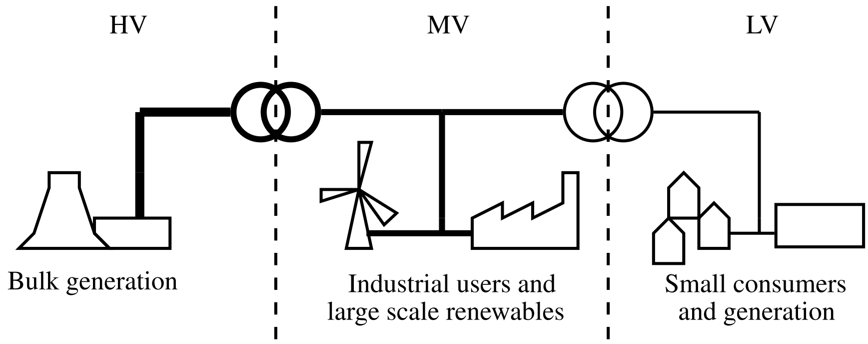

Figure 2.1: *Layout of the transmission and distribution grid with bulk energy production at the HV level. Large users and producers are connected to the MV level. Houses, offices and small production is located in the LV network. The voltage levels are changed using transformers.*

Figure 2.2 shows a more technical layout of the distribution network. In this figure, the HV and MV network are coupled using an automatic tap changer transformer. This means that the transformer ratio can be changed by altering the number of used windings. This makes it possible to keep the voltage level on the secondary side of the transformer (the MV network) stable. The automatic tap changer reacts when the voltage level in the MV network is higher or lower than a certain thresholds. There will be no reaction when the voltage level is within these thresholds, which is called a *deadband*.

Most of these MV networks have a ring structure with about 40 MV/LV transformers per ring. The energy in the MV network is transported over a cable, also called a feeder. A feeder is a cable that transports energy to other connection points such as transformers and household connections. However, there is a voltage drop over MV feeders. The MV/LV transformers are also called *boosters* as they boost the voltage level in some parts to compensate the voltage drop.

The LV networks were designed in a meshed structure, but typically operated *radially*. This means that feeders are connected to multiple points, but during normal operation, only one connection is active. The connections can be changed using a *normally opened point* (NOP), which is usually situated close to the center of a circle. Radial and meshed topologies are shown in Figure 2.3. In case of a fault in a feeder, the NOP can be closed so that part of the faulted feeder can be fed by another feeder. This feeder can be either connected to the same MV/LV transformer or another one. This temporary solution can deliver energy to the customers until the fault is repaired and service can be restored to the normal situation with the NOP being opened. Nowadays, Dutch LV networks are usually designed radially and lack NOPs.

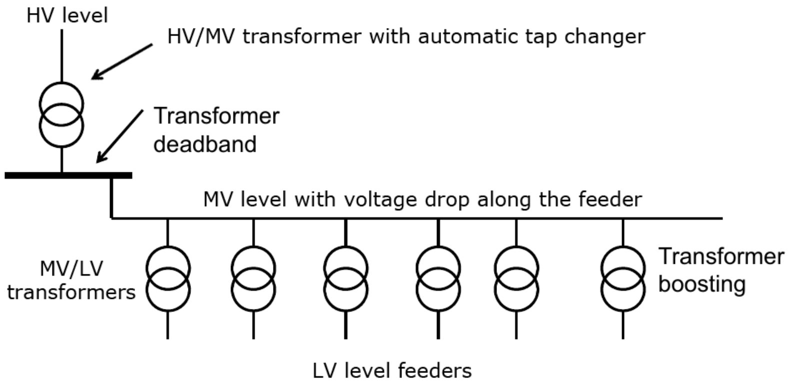

Figure 2.2: *Voltage distribution with through HV, MV and LV feeders using transformers [10].*

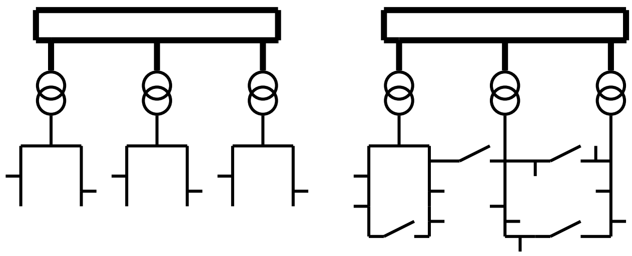

Figure 2.3: *Two LV networks connected to a MV ring. The left picture shows a radial structure of the LV network. A meshed structure is used on the right side where LV networks are connected. The NOP points are opened, which results in a radial operated meshed network.*

The energy is transported over three conductors within a cable. These conductors are also referred to as *phases* as the voltage phase on these cables differs from each other. There is a 120 degrees phase shift between two consecutive phases. Households are connected to either one or three phases and the neutral. This results in a a nominal voltage level of 230 V between one of the phases and the neutral. In the first situation, the ideal configuration would mean an balanced distribution of household connections and loads over the three phases. In a balanced network, no currents will flow through the neutral conductor. With unbalanced networks, there will flow current through the neutral, leading to additional voltage drops. As a result, the voltage level of the neutral will not be equal to ground level.

2.1.2 Proeftuin LochemEnergie

A Dutch LV network that is used for evaluating future networks can be found in Lochem. Citizens from this Dutch village started a cooperative union LochemEnergie with the goal to generate renewable energy for its members [1]. Over 1000 members participate to accelerate the transition to renewable sources. LochemEnergie currently has 250 active members who are both consumers and producers (*prosumers*). Photovoltaic cells are placed on the roofs of 50 houses of participants and on 30 municipal buildings as well. Participants that are not able to have PV on their own roof, can rent PV cells located on these municipal buildings. The total generation capacity of these PV-cells is 1MWp. Their goal is to increase the use of renewable energy sources and reduce the overall consumption to use as much renewable energy as possible.

To help the participants to reach their goals, the IN4Energy program [64] is set up. LochemEnergie works together with the University of Twente, Alliander, Locamation, Eaton and Eneco to exchange experience and test new solutions. For the participants this means that they can use the latest technology and be a front-runner on smart distribution grids. On the other side, companies and the university can test and validate their solutions.

All the participating households (250) have an *Intelligent Home System* to monitor the energy usage [64]. Participants can view their usage and actively take action to lower their energy consumption. The existing LV grid is updated with advanced metering devices to meter the quality of the distributed energy. In addition, *electrical vehicles* (EV) will be available as well which can be used as a storage device. This infrastructure is similar to a possible future residential area. That makes Lochem a good place to test and evaluate solutions for future smart grids.

2.1.3 Power quality

The delivered electrical energy should meet certain quality standards. The term power quality is used to describe the quality of the delivered energy. A lower power quality could lead to a higher failure rate of electronics. Sensitive equipment might even trip due to a small disturbance, which could lead to thousands of euros loss for companies as the production halts. In [9] the factors concerning power quality are described. Power quality exists of many factors and it cannot be expressed in a unit. There are also two different kinds of disturbances: *variations* and *events*. Variations are small deviations that normally occur in the network. Events have more impact and usually occur on failure of a component. Table 2.1 contains the definitions as used by the EN-50160 [44].

<table>
<tr><th></th><th colspan="4">Duration</th></tr>
<tr><th>Magnitude</th><th>.5 cycle</th><th>1 min</th><th>3 min</th><th>> 3 min</th></tr>
<tr><td>> 110%</td><td>Transient Overvoltage</td><td colspan="2">Temporary Overvoltage</td><td>Overvoltage</td></tr>
<tr><td>90% - 110%</td><td rowspan="3"></td><td colspan="3">Normal Operating Voltage</td></tr>
<tr><td>1% - 90%</td><td>Voltage Dip</td><td colspan="2">Undervoltage</td></tr>
<tr><td><1%</td><td colspan="2">Short Interruption</td><td>Long Interruption</td></tr>
</table>

Table 2.1: *Voltage events as described in [44].*

2.1.4 Voltage quality

Voltage quality is concerned with deviations in the sine wave of the voltage. In the ideal case, the measured voltage should be a sine wave at 50 Hz with an amplitude of 325 V between the phase and the neutral, resulting in an effective voltage of 230 V. The voltage level with AC is expressed as the effective voltage, also known as Root Mean Square (RMS) voltage. Deviations can occur in the amplitude, leading to a higher or lower voltage. Variations in the frequency can also occur. These variations could lead to a shorter lifespan for electronics, but are usually not observed by the customer. However, flickering of lights can be observed. The cause for this is voltage fluctuation in which the voltage magnitude varies with a frequency between 1 Hz and 10 Hz.

Variations with a large magnitude or long duration are called events. A possible event is an interruption in which the rms voltage is close to zero. This event interrupts the distribution of electrical energy to the customer and can cause serious damage to equipment. There can also be *over-* or *undervoltage* in which the voltage level is not within 10% of the nominal voltage of 230 V for a longer duration. Short-duration undervoltages are called *voltage sags*. Undervoltages can lead to damaged or tripped equipment. The same holds for overvoltage, in which the voltage level is substantial higher than the nominal voltage. Other possible events are phase-angle jumps and imbalance between the phases.

2.1.5 Harmonics distortion

The sine wave is never exactly a sine wave as well, but consists of multiple frequency waves called harmonics. A harmonic is a component frequency of the fundamental frequency, which in this case is 50 Hz. These harmonics have a frequency which is an integer multiple of the fundamental frequency and have the property to be periodic to the fundamental frequency as shown in Figure 2.4. The order of a harmonic is based on the multiplication factor with respect to the fundamental frequency. For example, with a fundamental frequency of 50 Hz, the second order harmonic is 100 Hz and the third order harmonic 150 Hz. Power is also transported in these harmonics, which is seen as distortion since ideally harmonics should not occur. The amount of distortion is usually given by the *total harmonics distortion* (THD), which is the ratio of power in harmonics to the power in the fundamental frequency.

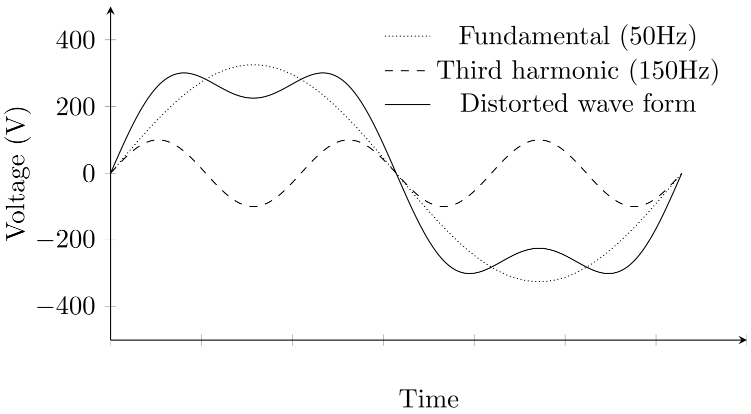

Figure 2.4: *The fundamental frequency and third order harmonic combined.*

Harmonics distortion can be injected by inverters. An example is the inverter used with photovoltaic (PV) panels to transform the direct current (DC) into alternating current (AC) that is necessary to inject the electricity in the grid. The output is not a perfect sine wave and has harmonic distortion. Other phenomenons are voltage notching and voltage noise, which is not harmonic. Voltage notches are spikes in the wave form, whereas the noise results in a not complete perfect wave form. These are shown in Figure 2.5.

Harmonic current flows tend to become a serious issue in LV networks and are one of the main reasons to increase the capacity of cables and transformers. The results of harmonics distortion are different for each situation and need to be tackled independently. Measures to prevent THD might have a positive impact on equipment, but can have negative impact on the grid at the same time according to [66].

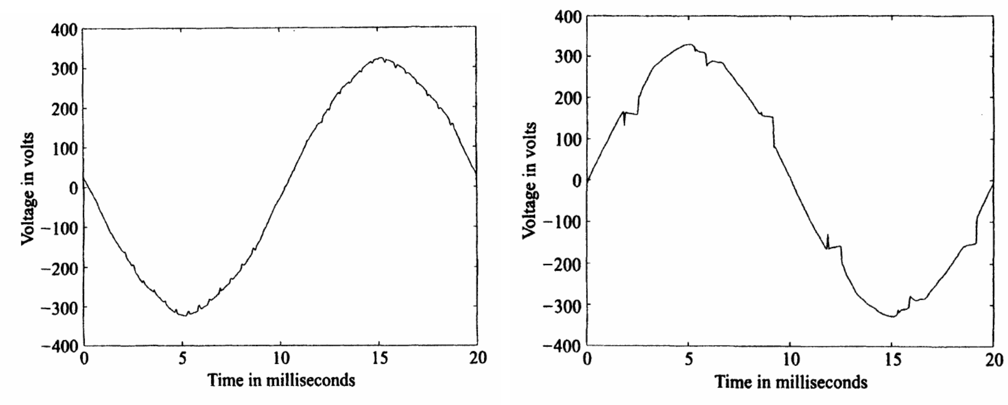

Figure 2.5: *Voltage disturbances due to harmonics (left) and notching (right) [9].*

2.1.6 Power quality regulations

Regulation exists to ensure a certain quality of the delivered electrical energy. The number of disturbances and variations must be kept as small as possible to ensure that equipment will not trip and the lifespan of electronics will be longer. Regulations also ensure that customers will have a stable supply of energy.

The EN-50160 defines the voltage quality character *Distribution System Operators* (DSO) should comply with. This norm is generally adopted through whole Europe and implemented as the NEN-EN-50160 [44] in the Netherlands. The Dutch competition authority (NMa) monitors compliance to a stricter implementation of the NEN-EN-50160, which is specified in the Netcode [43]. The EN-50160 specifies how the voltage should be calculated, usually in ten minute intervals, and limits the allowed fluctuation for these measurements. Equipment can be made capable with this standard in order to ensure correct operation within the allowed voltage variations as described in the standard.

One of the specified limits is the voltage magnitude. This magnitude must be within 10% of the nominal voltage of 230 V for 95% of the 10 minute averages during a week. Limits in magnitude and occurrences concerning rapid voltage changes, supply voltage dips, interruptions of supply and overvoltages are given as well. Limits for the frequency variations are also mentioned. The frequency measured over 10 seconds should be between 49.5 Hz and 50.5 Hz for 99.5% of the week and between 47 Hz and 52 Hz for 100% of the week. Limits to *harmonic voltages* are also provided. An overview of power quality requirements in LV networks by [43] is given in Table 2.2.

Power quality can also be improved on the consumer side. Appliances can contribute to an improved power quality by limiting their harmonics pollution. Furthermore, the allowed pol-

Aspect	Requirement
Frequency	- 50 Hz +/- 1% during 99.9% in a year - 50 Hz + 2% /- 4% during 100% of the time
Slow voltage fluctuations	- U_{nom} +/- 10% for 95% of 10 minute averages during 1 week - U_{nom} +10% / -15% for all 10 minute averages during 1 week
Fast voltage fluctuastions	- $\leq 10\% U_{\text{nom}}$ - $\leq 3\% U_{\text{nom}}$ in situations without interruption of production, large consumers or connections
Asymmetry	- The inverse component of the voltage <2% of the normal component for 95% of 10 minutes measurements during 1 week - The inverse component of the voltage <3% of the normal component for all 10 minutes measurements during 1 week
Harmonics	- The relative voltage per harmonic is smaller than the norm named percentage for 95% of the 10 minute average values. For harmonics not mentioned in the norm, the lowest named value is required - THD $\leq$ 8% for all harmonics up to the 40th, during 95% of the time - The relative voltage per harmonic is smaller than 11/2 times the named norm percentage for 99.9% of the 10 minute average values - THD $\leq$ 12% for all harmonics up to the 40th, during 95% of the time

Table 2.2: *Power quality requirements in LV networks as specified in the Dutch Netcode [43].*

lution could also be increased when appliances are known to be immune. The International Electrotechnical Committee (IEC) develops a framework of standards on *electromagnetic compatibility* (EMC) to decrease the harmonics pollution by appliances. There are two aspects to EMC. The first is that equipment should be able to operate normal within its environment. This means that the equipment should not be sensitive to electromagnetic disturbances. The second aspect is that equipment should not produce to much electromagnetic pollution as well to make sure that the distortions can be kept within certain bounds. The IEC 61000 standard [20] defines limits and test methods.

The IEC 61000-3 series focuses on the limits of emission from equipment for harmonic currents and voltage fluctuation. The IEC 61000-4 focuses on the testing of equipment to be immune for electromagnetic distortions in radio frequencies, transients, harmonics and so on. Testing equipment to be immune is important nowadays. The introduction of microprocessors has made equipment more sensitive to distortions and could show unexpected behaviour when not tested properly. Ensuring that equipment is less sensitive to distortions mitigates the problems of certain disturbances in the power quality.

2.1.7 Summary

This section has shown the topology of transmission and distribution grids. The HV/MV transformers are usually equiped with automatic tap changers and MV/LV transformers are usually fixed, but have different ratios to ensure a correct voltage level. The LV networks are usually operated radially and have NOP points in order to deliver electrical energy during faults via another route. In Lochem, the effects of renewable energy in the distribution networks can be studied with the help of a group prosumers.

There are also regulations concerning power quality. Equipment is designed to work within certain specifications. If these specifications are not met, equipment can damage or trip. This can happen when the voltage level is not within certain boundaries or the frequency of the voltage is not around 50 Hz. Also harmonics distortion could lead to problems. Therefore a certain power quality has to be met as described in the NEN 50160 [44]. On the other side equipment can also be made more resistive to bad power quality. The IEC [20] has defined limits tests to see whether equipment still functions during certain scenarios.

2.2 Distributed generation capacity limitations

The regulations form certain limits to the amount of distributed generation (DG) that can be allowed within the distribution network without breaking the limits set by regulators. This section will cover the expected problems with the power quality when DG is introduced. The rest of the section will cover the factors that limit the amount of DG that can be introduced. First the limits regarding the maximum power that can be supported by the network discussed. Then the transportation losses and voltage level limitation in LV networks are discussed. These limits also include limits caused by other networks that are connected via the MV network. The last part will cover methods to determine how much DG can be allowed in a network.

2.2.1 Power quality and DG

The introduction of *distributed generation* (DG) in a LV network brings both advantages and disadvantages to the network. One of the advantages is that DG can lead to lower losses in the transport over short distances as the energy is more likely to be produced near the consumer. The lowest losses can be achieved when the energy is both produced and consumed in the same premises. Introduction of DG can also have a positive impact on damping voltage dips, variations and harmonics, because of the introduction of one or more voltage sources in the network. However, the introduction of DG can also lead to voltage rises in the network and overloading can occur. There are certain limits to the generation that can be supported by the LV distribution network within a certain power quality. These limits define the hosting capacity for DG in a distribution network. Table 2.3 shows the expected disturbances due to different kinds of equipment.

Equipment	**Voltage variations**	**Over-voltage**	**Harmonics**	**Flicker**	**Asymmetry**
Households, small business			x	x	x
Small business, shops	x		x		
μCHP	x	x			x
PV		x	x		x
Heat pump	x		x	x	x
Wind turbine	x		x	x	

Table 2.3: *Expected disturbances by different kinds of equipment [66].*

2.2.2 Overloading

As energy is generated and transported in the lower voltage networks, the risks of overloading in the HV transmission network decrease. Instead, the risk of overloading in the LV network is increasing. Overload protection of components can trip once they become overloaded or the component will fail and short circuit is the result. The consequence is interruption for consumers. This risk of overloading creates a hard limit for the amount of DG that can be supported within a network.

Formulas to determine the *hosting capacity* in a feeder are given in [10].

Definition 6. *Hosting capacity is the capacity of distributed generation that can be integrated in a certain network. This capacity depends on the layout of the network, the consumption in the network and the limits of network components.*

The power (P) flowing downstream, that is from the transformer to the households, at any point in a feeder depends on the consumption and the generation of power at a certain moment in time. The power flowing at that point can be calculated using:

$$P(t) = P_{\text{cons}}(t) - P_{\text{gen}}(t) \tag{2.1}$$

where $P(t)$ is the power at a given time t, depending on the consumed power $P_{\text{cons}}(t)$ and generated power $P_{\text{gen}}(t)$ at that time. There exists a maximum load in a network at which no overloading occurs. To simplify this introduction, reactive power is left out, but will be introduced later.

Assume that there is no overloading in a network before distributed generation is introduced. As long as the absolute maximum power fed back into the network after connecting generators is equal or lower than the maximum consumption $P_{\text{cons,max}}$ measured before, there is no overloading. There is also a certain minimum consumption $P_{\text{cons,min}}$ within a household. This minimum consumption is at least consumed locally and not fed into the grid. This means that the maximum generated power $P_{\text{gen,max}}$ must be equal or lower than adding minimum and maximum:

$$P_{\text{gen,max}} \leq P_{\text{cons,max}} + P_{\text{cons,min}} \tag{2.2}$$

This condition should be fulfilled for all locations along the feeder to guarantee that no overloading occurs. This is a first approach that can be used as a hosting capacity level. However, this capacity is based on the consumption in a network. The maximum consumption is not necessarily the maximum capacity of a feeder section, the ampacity of a feeder section is the limiting factor. Taking the maximum capacity in the feeder section $P_{\text{max,limit}}$ into account results in the following condition:

$$P_{\text{gen,max}} < P_{\text{max,limit}} + P_{\text{cons,min}} \tag{2.3}$$

This second approach however needs more study according to [10]. Another problem with these approaches is that consumption information is usually not available. Only estimations can be made instead, resulting in underestimation of the hosting capacity.

The maximum transmission of *active power* can only be achieved with a *power factor* of one.

Definition 7. *Power factor is the ratio of real power to apparent power, sometimes also referred to as cos φ-factor. The power factor is said to be leading when the current tops before the voltage tops (current leading voltage) and lagging when the voltage tops before the current (current lags voltage).*

This is the case when the current is in phase with the voltage:

$$\cos\varphi = 1 \tag{2.4}$$

Where φ is the angle between the real and apparent power. However, this power factor is rarely one and *reactive power* has to be transported as well. Reactive power is caused by capacitive or inductive loads. In this case, the *apparent power* S in VA is split up in the useful active power P in W and reactive power Q in var, with:

$$S = \sqrt{P^2 + Q^2} \tag{2.5}$$

$$P = S\,\cos\varphi \tag{2.6}$$

$$Q = S\,\sin\varphi \tag{2.7}$$

Calculations with these powers by using angles and lengths. Complex numbers are used more often to make calculations easier. The active power, which actually transports energy, is in the real axis. In addition, the reactive power does not transfer energy and is in the imaginary part. The apparent power is the sum of the active and reactive power in case of complex values. This is depicted in Figure 2.6. The complex notation is $S = P + jQ$. Note that it is common practice to use j in electrical engineering to denote complex numbers to prevent confusion with i that is used sometimes for current.

With a worse power factor, the power factor being smaller than one, less active power can be transported while the load on the transmission line is equal. The capacity of transformers is given in volt-ampere (VA). A power factor close to one is desirable to transport as much active power as possible. Reactive power is introduced by electronic components such as capacitors

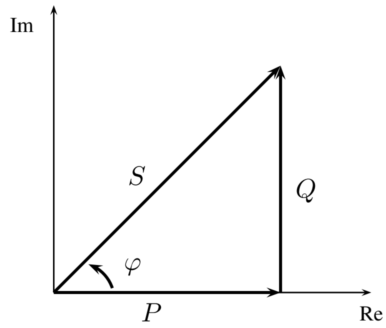

Figure 2.6: *Active (P), reactive (Q) and apparent power (S) in the complex plane.*

and inductors. Capacitors introduce negative reactive power and inductors introduce positive reactive power. These can be used to improve the power factor as well by compensating the effects each other [23]. For cables, the capacity is given in amperes (A). This is the current that can flow constantly through the cable without damaging it. The capacity does not only depend on the used cable, but also on the ground conditions [66]. This also implies that the current flowing through the cables defines whether it is overloaded or not.

Tripplen harmonic currents flow back through the neutral conductor and might form issues regarding capacity as well in LV networks [66]. In some cases, the current flowing back through the neutral can be higher than the current flowing through the phase conductor. These currents also cause additional load on the transformer and additional losses.

2.2.3 Losses in distribution

In [10] the losses during transport as a result of the resistance in the cables are discussed. As mentioned, local production and consumption of energy can lead to lower losses. However, there seems to be a limit. The reduction depends on the load and generation connected to a feeder section. The effects of all feeder sections must be taken into account. The losses are generally reduced as long as the average generation is smaller than twice the average load. As more generation is introduced, the losses will rise again, possibly resulting in more losses than without distributed generation. This is due to the fact that in that case more power is flowing towards the transformer. When the amount of generated energy is twice the load, the power flowing towards the transformer is equal to the power flowing in the opposite direction when no generation was introduced. Therefore the losses will be the same with an equal power factor.

The amount of reactive power also has influence on the losses. With a power factor of one, the losses are reduced most. In [10] a case study is conducted on the losses in the feeder when generation is connected in comparison to the base case where no generation was connected (100%). The results are shown in Figure 2.7. The upper curve has the same amount of reactive as it has active power (power factor of 0.7), the lower curve has only active power (power factor of 1). The intermediate curves have, from top to bottom, a ratio of 0.8, 0.6, 0.4 and 0.2. The graph shows that a good powerfactor is desirable to reduce distribution losses.

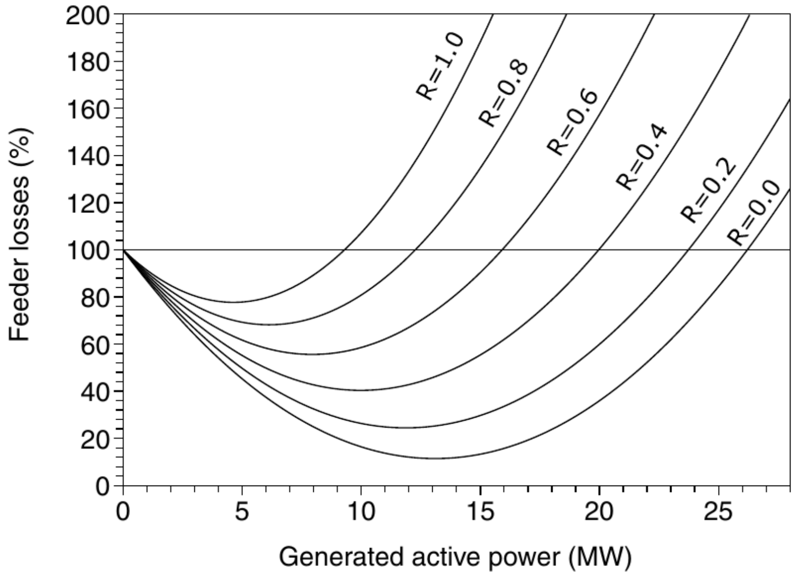

Figure 2.7: *Transport losses depending on the amount of DG and ratio between reactive and active power ($R = Q/P$). The losses are compared to the losses when no DG is connected, which is set at 100% [10].*

In [53] simulations are done on the losses in a network. Simulations using PV, windmills and micro combined heat and power (μCHP) systems are conducted. The outcome of the simulations are depicted in Figure 2.8 and show the same u-curve as described above. Different types of distributed generation show different curves. Wind power has the worst characteristics whereas μCHP shows the best curve. These results are strongly related to the power factor of certain types of distributed generation. Simulations with DG that can control their power factor are also ran. The results of this simulations are positive and show losses can be further reduced by controlling the power factor.

2.2.4 Voltage level

Distribution networks have traditionally been designed to prevent voltage drops only. The introduction of DG has made overvoltages a serious problem for distribution networks as well. The voltage rise due to injection by DG is the main limiting factor for the amount of DG that can be connected. According to [66], the maximum feeder length should be shorter when substantial generation from DG is expected. However, older networks designed without these more recent design practices use longer feeders.

The voltage level in a network depends on the consumption. This voltage level will be highest with minimum consumption and lowest with maximum consumption. The voltage at the connection point depends on the distance from the main substation. The further away, the lower the voltage will be. A high load at the end of a feeder makes the voltage drop even more severe. At the HV/MV transformer, a deadband is usually used on the secondary side in combination with an automatic tap changer to keep the voltage at level. When the voltage level is not within the

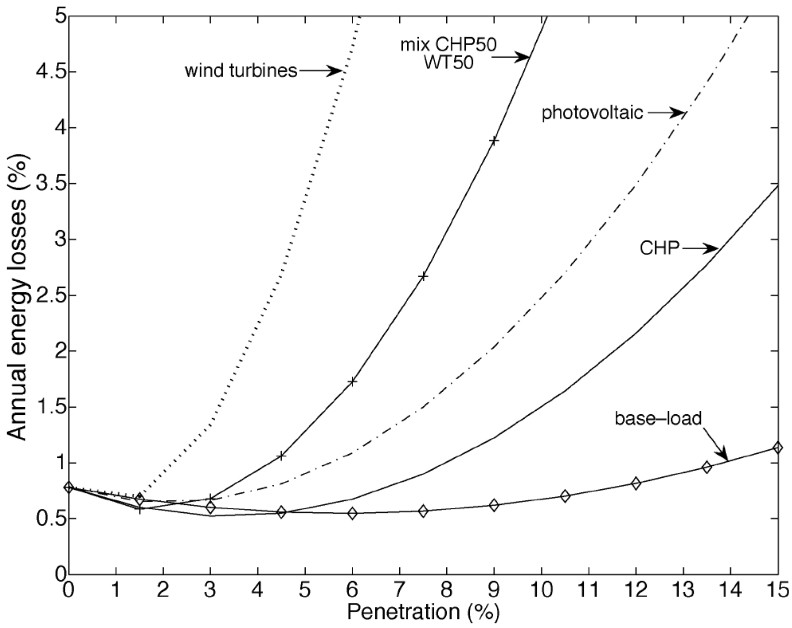

Figure 2.8: *Transport losses depending on the type generator and penetration [53].*

deadband anymore, the tap changer will react by changing the transformer ratio so that the voltage level is within the deadband again. The MV/LV transformers are usually fixed, but use different ratios to ensure that the voltage in each LV network is around 230 V. The deadband and boosting is shown in Figure 2.9. Transformers further away in the MV feeder have smaller ratios to compensate for the voltage drop along the feeder.

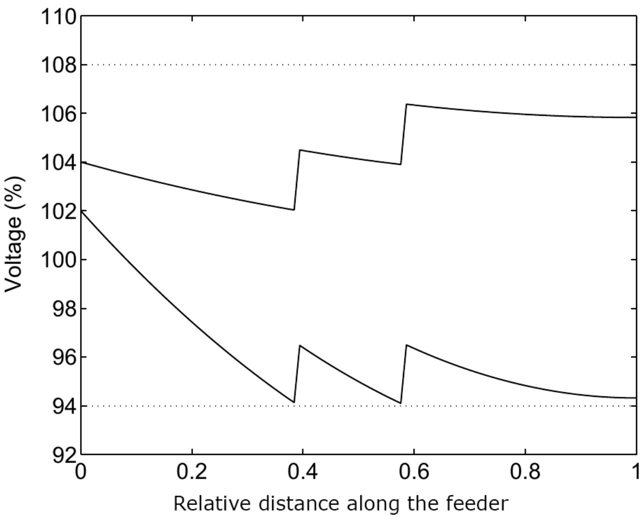

Figure 2.9: *Voltage level without DG and using boosters. The upper curve shows the level with minimum load, the lower curve shows the voltage at maximum load [10].*

The introduction of DG to a distribution network will result in lower voltage drops, resulting in a smaller overvoltage margin which may even be exceeded. An approximation of the relative voltage rise ΔU at the terminal of a generator can be calculated with the source resistance R, the injected active power by the generator P_{gen} and the nominal voltage U_{nom}:

$$\Delta U = \frac{R \times P_{\text{gen}}}{U_{\text{nom}}} \tag{2.8}$$

Reactive power is kept out of the equation here. The relative voltage rise is equal for all locations along the feeder. However, customers have different nominal voltage levels due to their location along the feeder. This results in different overvoltage margins that should not be exceeded due to regulations. For the *hosting capacity* it is thus important what the lowest overvoltage margin is along the feeder. This hosting capacity $P_{\max}$ can be calculated using the absolute voltage margin U_{marg} and the cable resistance R:

$$P_{\max} = \frac{U_{\text{nom}} \times U_{\text{marg}}}{R} \tag{2.9}$$

The cable resistance R is given by the cross section A, length ℓ and the electrical resistivity ρ:

$$R = \frac{\rho \times \ell}{A} \tag{2.10}$$

From the combination of (2.9) and (2.10) the following relations can be obtained [10]:

- The hosting capacity is proportional to the square of the nominal voltage.
- The hosting capacity is linear with the cross section of a cable.
- The hosting capacity is linear with the overvoltage margin.
- The hosting capacity is inversely proportional to the distance between generator and transformer.

Not all generators produce only active power. For instance, most wind turbines use induction generators which produce reactive power. The maximum voltage rise will occur when the highest current is running, which is during maximum production. For the maximum voltage rise $\Delta U_{\text{gen,max}}$ due to the injected power $P_{\text{gen,max}}$ by the generator we find the following formula:

$$\Delta U_{\text{gen,max}} = R(1 - \varphi\frac{X}{R})P_{\text{gen,max}} \tag{2.11}$$

with X being the reactance of the feeder, of which some examples are given in Table 2.4. As a result, the voltage rise can be reduced with a lagging power factor. A leading power factor will result in a higher voltage rise however. Using (2.9) we can find the hosting capacity for generators with reactive power:

$$P_{\max} = \frac{1}{1 - \varphi\frac{X}{R}} \times \frac{U_{nom} \times U_{marg}}{R} \tag{2.12}$$

Type	R (Ω/km)	X(Ω/km)	R/X
50 Al	.64	.085	7.5
150 Al	.21	.079	2.6
50 Cu	.39	.085	4.6
150 Cu	.13	.063	2.0

Table 2.4: *Impedances of different types of cables for LV network feeders [66]. Where the number represents the crosssection surface in square millimeters of one conductor, Al stands for aluminum and Cu stands for copper.*

As as result, by choosing a lagging power factor, the voltage rise will be lower and, at the same time, the hosting capacity will also increase as the term $1-\varphi\frac{X}{R}$ goes toward zero. Disadvantages are that the losses and risks of overloading increase. This does not reduce the amount of DG that can be connected when voltage rise is the limiting factor. A Distributed Automatic Voltage Control (DAVC) system is proposed in [58]. By exploiting the reactive power capabilities of inverters, the voltage level could be lowered. Simulations with a high penetration of DG with inverters using DAVC show that this is indeed the case. The voltage level gets brought back to acceptable levels again. The drawback is that more energy gets lost in the network, however.

Until now the case of a single generator is described. However, DG in the LV network usually exists of multiple generators of different types on different connection locations along the feeder. The hosting capacity must then be shared between multiple generators. However, as showed in (2.9) and (2.12), the hosting capacity depends on the distance between transformer and the generator.

Due to the resistance in the feeder, the hosting capacity is lowest at the end of the feeder ($P_{\text{max,end}}$). The hosting capacity closer to the transformer is higher, however. A sharing rule for DG is proposed in [10]:

$$\sum_i \lambda_{\text{gen},i} P_i \leq P_{\text{max,end}} \tag{2.13}$$

Where $\lambda_{\text{gen},i}$ is the location of generator i and P_i is the generated power by that generator along the feeder. This is a relative location with $\lambda = 0$ being closest to the transformer and $\lambda = 1$ for the end of the feeder:

$$\lambda_{\text{gen},i} = \frac{\ell_{\text{gen}}}{\ell_{\text{feed}}} \tag{2.14}$$

Where ℓ_{feed} is the length of the feeder and ℓ_{gen} the length from transformer to the generator connection. For N generators, an allocation for production can be proposed depending on their location in the feeder:

$$P_i = \frac{P_{\text{max,end}}}{\lambda_i N} \tag{2.15}$$

However, this is only one solution to the planning of DG. If a unit produces less energy than the proposed production limit, not the full hosting capacity along the feeder is exploited. Another generator can exploit this additional headroom and thus produce more than the proposed allocated production. New calculations need to be done to determine how much power this generator can introduce within the hosting capacity.

Since the LV feeders are connected to a shared MV feeder, the length of the MV feeder has to be taken into account as well. As a result, the hosting capacity in a LV feeder at the end of the MV feeder is lower. However, voltage boosters have to be taken into account as well. Figure 2.10 show the hosting capacity in a LV feeder depending on its connection point with the MV feeder.

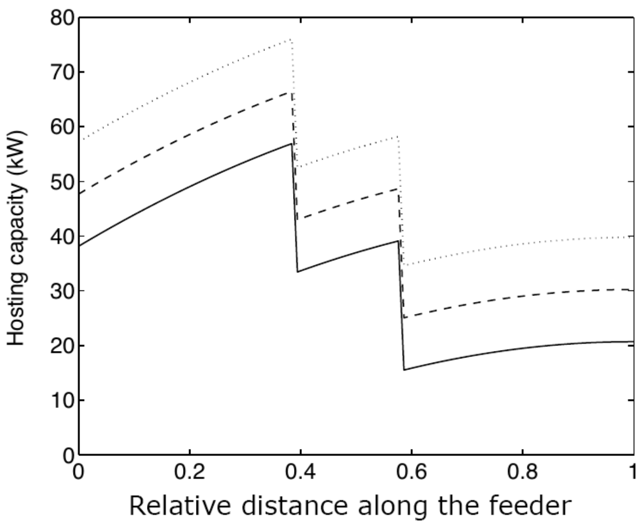

Figure 2.10: *Hosting capacity in a LV feeder as function of its connection point along the MV feeder. The different overvoltage limits are 108% (solid line), 109% (dashed), and 110% (dotted) [10].*

In [54] simulations are done on the voltage rises with the introduction of generation in a distribution network. Generation located far from the transformer shows a more severe voltage rise than near the transformer. However, there is a certain point at which the voltage rise will be equally severe with the same amount of generators connected near the transformer. The introduction of generation in the network also shows that voltage limits get exceeded in certain circumstances. The voltage rise problems get even more severe when normally open points are closed during faults. This is a special case in which it would be desirable to shut down more generators when compared to the normal operation.

2.2.5 Power quality

Hosting capacity is not the only concern with DG. Power quality is also influenced with DG. Fast fluctuations in voltage levels is one of the issues. Fluctuations between 1 Hz and 10 Hz lead to the "flickering light"-effect, which can be observed. These fluctuations can be caused by the generators. A wind turbine will produce more or less energy as the wind speeds change. Clouds temporary blocking the sunlight result in less energy generation from PV as well. With a high penetration of DG, these fluctuations will occur more often and will be pronounced more as well.

Voltage fluctuations can be caused by harmonics distortions as well. Certain harmonics are more influenced than others. *Power electronics converters* are a source for low frequency harmonics. Distributed generation also adds high frequency harmonic distortion, generated by voltage source converters used with PV for example. There are certain limits to the allowed distortions as described in [44]. This can limit the allowed DG within a distribution network as well. However, advanced converters can mitigate the problems.

2.2.6 Network layout limitations

Low voltage feeders are connected with the MV network at the transformers. Usually, multiple LV feeders are connected to one MV feeder. These transformers are fixed at a certain ratio. This makes it impossible, unlike HV/MV transformers, to compensate for voltage variations. This means that a voltage rise in the LV network propagates into the MV feeder. Which in turn will also feed the voltage rise to the other LV feeders. Production in one LV feeder thus affects the hosting capacity in the other LV networks connected to the same MV feeder. In the worst case, the load on a LV feeder is at its minimum, whilst the voltage level on the MV is at its maximum. This will result in the highest voltage level in the LV network without DG and thus the smallest voltage margin.

Most Dutch LV feeders are designed radially. When dealing with a meshed network that is operated radially, another issue has to be taken care of. The NOPs are open during normal operation. However, in case of a fault, the energy supply will be resumed to most end users by closing a NOP. The part from the fault on towards the NOP is then fed via another MV feeder. This has consequences for the hosting capacity. The distance from a connections near the fault to the transformer might be longer, resulting in a different hosting capacity. During normal operation, the hosting capacity is usually much higher. Figure 2.11 shows a LV feeder fed by another transformer, resulting in an increase in distance to the transformer for point A.

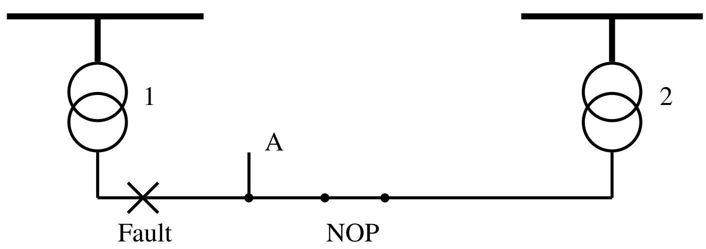

Figure 2.11: *NOP being closed in case of a fault. Point A is fed via transformer 2, which is further away than transformer 1, which feeds the LV feeder during normal operation.*

2.2.7 Determining the hosting capacity

To allow DG in a LV network, the hosting capacity must be determined by the DSO. The overvoltage margin is one of the limiting factors for the hosting capacity. But also the minimum load must be determined. Voltage magnitude variations for a group of customers is considered as the most appropriate method. These can be obtained with metering. These are numbers that are not available when the distribution grid has to be designed, however. Estimates for the consumption and production must be made instead.

To estimate the overvoltage, the following method can be used. The highest voltage at the MV bus, which is the upper limit of the transformer deadband, is chosen as starting point. In addition to this, the lowest load on this MV feeder is estimated. Voltage drops and the effects of voltage boosters at the transformers are taken into account as well. This results in the worst-case voltage on the LV side of the transformer. The overvoltage margin can then be obtained by the difference between this worst-case voltage and the overvoltage limit. This case is shown in Figure 2.12.

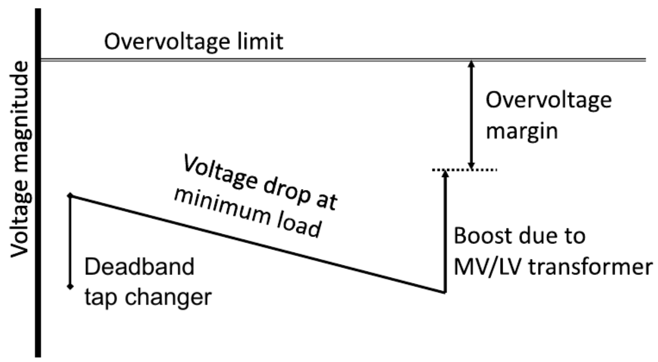

Figure 2.12: *Overvoltage margin in a grid. On the left the worst-case voltage level at the HV/LV transformer is shown. The voltage level drops in the MV feeder, but gets boosted again at the MV/LV transformer [10].*

When designing a distribution grid, a certain planning level has to be determined. This planning level reflects the requirements of the grid to meet the regulation requirements under all expected circumstances. This involves the chosen cable type and transformer capacity. The hosting capacity is affected by the chosen planning level. There are three methods mentioned in [10] when it comes to determining the planning level.

- The first option is to choose the planning level significantly lower than the requirement. The estimated hosting capacity is based on after-diversity maximum production and minimum load. This limits the risks for the network operator.

- As second option, the planning level can be chosen equal to the requirement. In this case a worst-case scenario is used for the hosting capacity. This worst-case scenario could consist of maximum production with zero load.

- Third is a planning slightly lower than the requirement using reasonable estimates. Risk for overvoltages is not carried by network operators due to a regulatory framework.

The first two approaches are used today when planning as the voltage magnitude has to be kept within limits due to regulatory pressure. These two methods are conservative and could limit the allowed DG due to the worst-case scenarios, which won't occur much, if they do. The third approach might be a future solution to remove these barriers due to conservative approaches and allow more DG.

As shown, through the sharing capacity, the distribution of DG along the feeder is also important. A probability approach on DG spreading can help in a risk based approach when dimensioning a feeder. The spreading depends on the design of a neighbourhood. Available information from existing neighbourhoods that are similar to new networks could help to determine the amount of DG that can be expected. In [52] a method to determine the amount of DG in an existing network using measurement data from the transformer. By estimating the penetration of DG in a network, the correct maximum load can be estimated, which is higher than the measured load. The problem for existing networks is that DG is introduced after the network is designed and constructed.

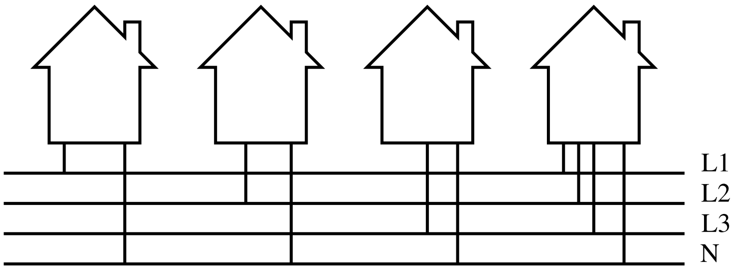

Figure 2.13: *Four houses spread over the phases. The first three houses have one connection to one of the phases, where each next house is connected to the next phase. The fourth house has connections to all three phases. A configuration like this is considered balanced in case the loads are equal.*

To maintain voltage balance between the phases, DG and houses should also be spread equally over the three phases as shown in Figure 2.13. A good spreading would also improve the energy exchange characteristics between houses in a network as transport via the transformer to reach an house on another phase is less likely to happen. The probability that all generators are connected to the same phase will decrease as more DG is introduced. Figure 2.14 shows the distribution probability for six and 30 DG units.

2.2.8 Summary

This section has shown what problems can be expected with certain types of DG with respect to power quality. A practical limitation of the amount of DG that can be allowed in a network is found to be the sum of the minimum and maximum consumption. Furthermore a power factor of one is desirable to use the full potential of the distribution network to distribute active power. However, usually reactive power is transported as well that has impact on the maximum amount of active power that can be exported. The introduction of DG does not always lower the losses in distribution of energy as well. There is a certain limit to reduction of losses, that also depends on the power factor.

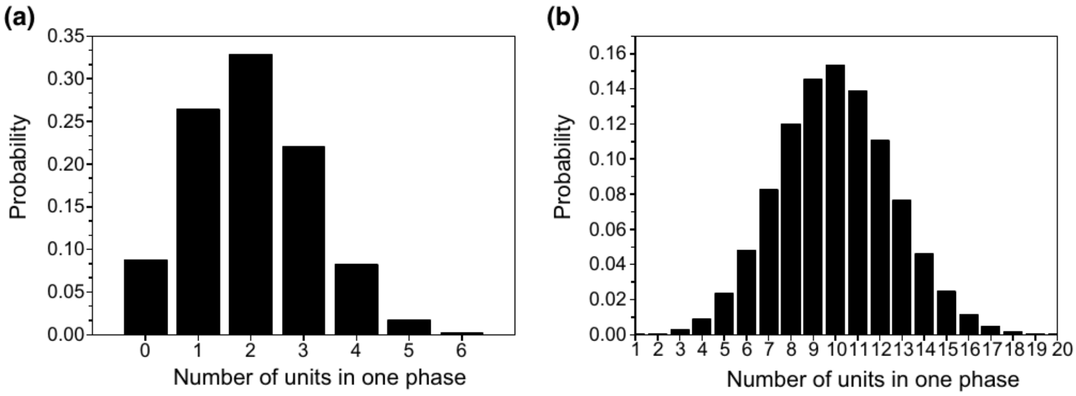

Figure 2.14: *Probability distribution of generators on a phases for 6 units (a) and 30 units (b) [10].*

Another problem to the hosting capacity is the voltage level. Voltage rise is a problem when too much DG is introduced. The location at which DG is located is also important here. The further away from the transformer, the lower the hosting capacity. A sharing rule for DG is proposed in literature which depends on the distance from the transformer and the overvoltage margin. Fluctuation in generation has also impact on the power quality when it comes to flicker.

The hosting capacity is not only limited to the influence in one LV feeder. Introduction of DG in other LV feeders affects the hosting capacity as well due to the fixed ratio in MV/LV transformers. Furthermore, safety issues during faults have to be covered as well since the topology of the network can change during these moments. Limitations in available information during the design of distribution networks make it hard to determine the hosting capacity on beforehand as well.

2.3 Allowing more distributed generation

The previous section has shown what limitations exist in distribution networks that make it impossible to introduce more DG in a network. If the limits are reached, investments are required to introduce more hosting capacity. This section covers the available options to introduce more DG in a network. Both hardware and software solutions are available and will be discussed. Hardware solutions include more cables, the introduction of storage or more advanced equipment that can react to the current situation based on measurements. The software solutions discussed make use of demand shifting to balance load and production better.

2.3.1 Proposed solutions

In [27] various solutions that can contribute to voltage control in a smart grid are discussed. Recommendations for future distribution grids are outlined in [32]. It is suggested to use more metering data to act adequately during faults and exploit the full potential of the LV network with respect to generation capacity. The metering data can be combined with smart transformers that can change its ratio on-line to keep the voltage level within boundaries. Batteries should be added to shave the most severe peaks. Autonomous working intelligent networks that require the introduction of storage and power electronics are proposed in [51]. The focus is to maintain an optimal voltage level for all customers. The most common solutions that are proposed in literature will be discussed here.

2.3.2 Cables

Simply adding more cables is the first solution. A parallel cable to the existing cable results in a higher transport capacity and lower resistance. This is also true for rewiring using larger cross sections. Instead of reinforcing the existing grid, new connections for larger generators can also be created. These dedicated cables could be operated at a different voltage level as well, but a new transformer is required then. These solutions also result in lower losses in transport. The costs of rewiring or adding new cables are high. The Dutch distribution grid consists mainly of underground cables. Adding new cables would require digging in the ground in most cases, usually requiring reconstructing paths or roads as well. However, the costs can be reduced when these reinforcements are done together with other construction work, such as the construction of new sewers.

2.3.3 Power electronics and storage

Using power electronics is another approach to increase the loadability and balance of distribution transformers. Power electronics can redirect a portion of power from one cable to the other. Combining power electronics converters with energy storage will increase the hosting capacity even further. When the generation reaches the maximum hosting capacity, the system can react fast by storing energy. This will increase the load and thus the hosting capacity. The stored energy can be fed back into the grid when the energy generation is lower than the demand. Storage can also contribute to damp the effects of voltage fluctuations to prevent flickering. Voltage dips can be avoided as well using storage. In the event of a dip or fault, the storage can deliver the energy and ride through the dip.

In [35] storage options in combination with PV is proposed. Deployment strategies for both central and distributed storage are presented, together with methods to determine the best locations for storage usage. Results with distributed storage shows that only little storage is required to keep the voltage level within the regulation boundaries in the test case. With centralized storage, storage at the end of the feeder is found to be the best location when optimizing the amount of storage needed. In [34] it is shown that using weather forecasts in combination with storage further enhances the effectiveness of storage by better utilizing the battery capacity in order to waste less energy.

Using EVs to store surplus wind energy is proposed in [38]. The paper shows that the use of storage in a fleet of EVs can increase the integration of surplus wind energy for consumption at later moments. However, not all strategies benefit from more storage. Three methods of charging are applied to a fleet of cars. The first method will charge cars always. The second can either charge or disconnect the whole fleet. With the last method, the cars can be charged independently.

With the two first methods, the amount of surplus wind energy that can be integrated starts to decline again when more storage is introduced. Therefore, good controllability of a storage is required to utilize the full potential of storage.

2.3.4 FACTS

A flexible AC transmission system (FACTS) device can help to improve the power transfer capacity in the grid. A series FACTS device can manipulate the series impedance of the feeder by reactances that can be controlled dynamically. This means that the power factor in a grid can be improved. For radial systems, the tracking mode is used to increase or decrease the power flow through the feeder. This is done by changing the virtual impedance of the dynamic compensator. The change reflects the changes in load and generation. For meshed networks, the regulated mode can be used to keep the power flow constant.

A trend on series compensation is the use of voltage source converters to independently control active and reactive power flow in the AC distribution grid. The DC side utilizes storage and the amount of active and reactive power that can be absorbed or injected depends on the capacity of the storage. Shunt FACTS devices are usually employed to compensate the voltage at a connection point. These compensators inject reactive power and are usually found at the end of a feeder.

2.3.5 Overvoltage protection

Generators can also be equipped with overvoltage protection. This does not improve the hosting capacity itself directly, but does make it possible to add more generators to the grid. In case of an voltage level above a certain threshold, the generator will be tripped to prevent the occurrence of overvoltage. This is most likely to happen when the load is low and the production is high. This is a typical case in which on planning level the amount of DG is limited. When the load is higher, the production can be increased again and the additional generators can be connected. Generators that could not have been permitted otherwise.

As the tripping mechanism can measure and act stand-alone, no additional infrastructure is needed. However, with a high penetration of DG some algorithms must be needed to prevent a lot of generators being tripped at the same time. This leads to a much lower production than necessary. The same is true for reconnecting the generators. This should be done one by one as well to measure the effects and evaluate if another generator can be connected. Other constraints are also applicable to this solution. Some generators cannot be turned off at any time. Generation from μCHP is such an example because it also delivers heat, which might be demanded at the same time. Renewable energy might also be prioritized over other generators to utilize as much renewable energy as possible in favor to the usage of fossil fuel.

2.3.6 Production curtailing

ICT infrastructure enables other solutions that require information about the consumption and production and depend on communication to steer the consumption and production. One of the proposed solutions is to curtail the production when needed instead of tripping the generator. The maximum active power that can be injected is calculated and communicated with the generator. Also the reactive power that should be injected or consumed to compensate for voltage changers are communicated. This is done for all micro generators in a grid. When the total production exceeds the hosting capacity, production needs to be curtailed. This leads to a lower production at that specific moment, possibly including worst-case scenarios. The hosting capacity might be higher at other moments and thus more production can take place. The effects of curtailment on the voltage level are depicted in Figure 2.15. This solution would exploit as much hosting capacity as possible at all times. Estimated hosting capacities, as described, are most likely to be around the same value as the worst-case scenario moments for this curtailment system.

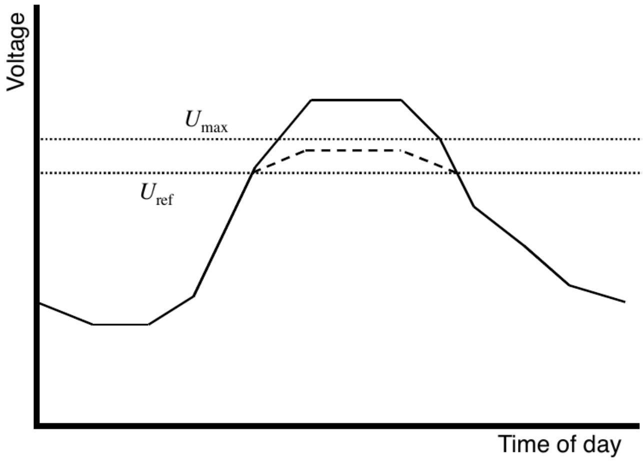

Figure 2.15: *Voltage level without production curtailment (solid line) and with curtailment (dotted line) [10].*

However, not all generators have the ability to curtail their energy production, those might trip while others might curtail their energy production instead. The same constraints as mentioned for overvoltage protection are applicable to this method, although there might be more planning freedom. Research to optimize these control algorithms to transport as much renewable energy is still going on.

In [62] it is shown that the energy production from PV is curtailed is higher towards the end of a feeder when comparing the curtailment to PV installed at houses near the transformer. Therefore a method to share production curtailment more equally over all houses is proposed using different coefficients, based on the location along the feeder. The losses of revenue due to curtailment gets more equally spreaded over the households, however, the total losses due to curtailment increase by 23%.

2.3.7 Demand matching

Demand control is much discussed at the moment. Instead of curtailing the production, the consumption could be matched better with the production to prevent the network from overloading. This can be done using smart appliances that are controllable in a smart grid. Not all production can be controlled such as PV and also μCHP has certain constraints. Nor will all appliances be smart and controllable by the energy system. Consumers demand that certain appliances can be switched on at a certain moment as well. Therefore prediction is required for production and consumption before a planning can be made for appliances.

PowerMatcher [65] is one of the demand matching implementations. PowerMatcher employs an auction system. Devices send bids to an auction agent at which price they will produce or consume energy. The production and consumption have to be matched. The auction agent will determine a market clearing price at which energy will be traded. The communication between different devices and agents on this market is shown in Figure 2.16. This market clearing price is used by the devices on the market to determine their allocation of production or consumption. In [33] field tests in Hoogkerk, the Netherlands, with PowerMatcher are conducted. The results show that it is capable of load shifting in order to shave peaks. For instance, the peak load with electrical vehicles does barely increase with an increased penetration of EV. The hosting capacity within the distribution network can indeed be increased by using PowerMatcher.

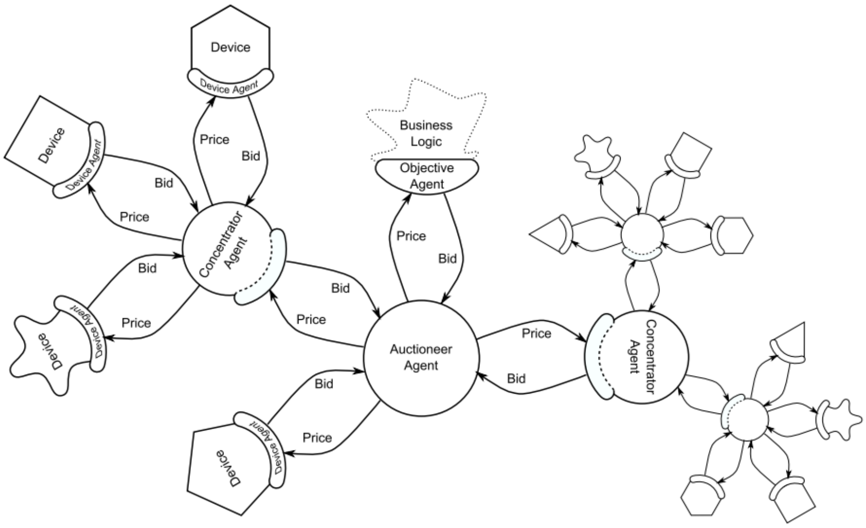

Figure 2.16: *PowerMatcher network. [65]*

TRIANA [39] is a demand and production matching methodology developed at the University of Twente. The main goal is to exploit the optimization potential of domestic technologies to yield a higher efficiency and greater use of renewable energy sources. There are three levels on which optimization can be done: locally, microgrid and a virtual power plant, in which multiple energy sources can be seen as one power plant from the outside world. The control is done using three steps. It starts with predicting the energy consumption and production. These predictions are send upwards, where a global planning is created. Real-time control is used to cope with prediction errors.

In [4] the prediction process for TRIANA is explained using a μCHP fleet. A neural network is used to predict the demand for heat depending on the weather forecast and the heat demand from the previous days. A sliding window is employed as well to cope with seasonal changes in usage. Prediction can also be enhanced by taking future time intervals into account as shown in [40]. The decisions taken in the future are based on possible state transitions. For example,

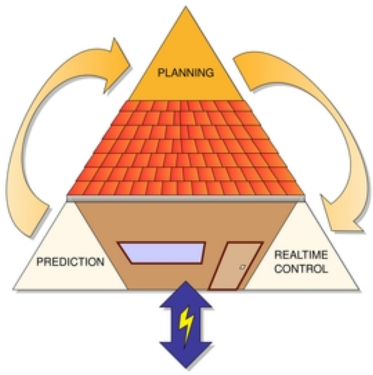

Figure 2.17: *Three step methodology of TRIANA.*

a freezer has the options to be actively cooling or turned off in which it warms up. The chosen state has direct impact on the possible future states when taking temperature constraints into account.

When it comes to planning, there are bounds when planning a fleet of μCHP as a certain comfort level must be satisfied for a household. This is a Multilevel unit commitment problem. A column generation pattern is used in [11] to find a planning for a fleet. The mismatch can be reduced when more iterations are ran.

In [41] a comparison between auction based real-time control, and integer linear programming (ILP) solvers and TRIANA is done. When using planning, TRIANA seems to perform best. However, TRIANA cannot cope with unplanned scenario's, which ILP and auction based control can. Therefore, combining TRIANA and auction based real-time control could be a solution. However, the auction based control has to be altered to optimize as locally as possibly, coping with local grid constraints.

2.3.8 Reducing EMC emission

Emission of harmonics distortion limits the amount of DG that can be connected due to regulations. If each generator and load produces less emission, more generators can be connected. Setting limits doesn't necessary mean that generators and loads have to be smaller. The capacity might be kept at the same level when more expensive components are used to reduce the emissions. For micro generation, the IEC 61000 sets emission limits. These regulations can enforce to limit the emissions so that the hosting capacity increases. The IEC also has guidelines for immunity to emissions. Strengthening devices against electromagnetic emissions could also make it possible to allow more emissions and thus increase the hosting capacity even further.

2.3.9 Tap changer transformers

The HV/MV transformers are usually equipped with automatic tap changers. The fixed MV/LV transformers could also be replaced with automatic tap changer transformers. The advantages is that the voltage in a LV feeder is less influenced by the voltage in other LV feeders. In case of a high voltage, another ratio can be chosen to lower the voltage again. Using automatic tap changer transformers will shift the hosting capacity limits from overvoltage limits to capacity limits. The examples mentioned in [10] show a five times higher hosting capacity. Replacing the transformers is costly and also introduced more maintenance due to aging of mechanical parts that move.

In [31] the use of automatic tap changing MV/LV transformers is simulated in a test case with DG. Three ways of steering the automatic tap changer are proposed. The first strategy is to keep the bus bar voltage constant. The second strategy is to keep the voltage level at the end of the feeder constant. Third, assessing meter data from connection points can be used to keep the average voltage level at connection points constant. Without the automatic tap changer, the voltage level at households is too high in the used test case due to the introduced DG. All three steering strategies show significant improvement in voltage levels. No under- or overvoltage occur after the introduction of an automatic tap changer in the use case.

2.3.10 Summary

This section has shown various solutions that can increase the hosting capacity. The best solution usually depends on the situation and could also be a combination of multiple situations. Adding cables or using automatic tap changer transformers can be done without ICT infrastructure, but are usually costly. Other solutions such as storage could be used without ICT infrastructure as well, but literature has shown that the effectiveness can be enhanced with planning. The same is true for curtailing the energy production by overvoltage protection, which is less efficient and fair then curtailing using communication. Software exists to forecast and plan a smart grid to make it operate more efficient in combination with hardware solutions.

2.4 Simulators

This section covers the external simulation options for the thesis. First some simulations and calculations methods are briefly explained, followed by already available simulators. The load-flow algorithms can be used for an own load-flow implementation in TRIANA. A simulator for the LV distribution grid is needed to evaluate the results of an implemented load-flow algorithm in terms of accuracy. Preferably, the external simulator should provide some sort of API to interface with TRIANA. A list of commercial and non-commercial simulators is given in [45]. A task force by the IEEE Power Engineering Society (PES) [46] also lists simulators. The task force is also standardizing open data formats to store simulator configurations and data. A few simulators are discussed, together with simulators not listed by those pages. As last, an overview on TRIANA is given.

2.4.1 Load-flow calculations

When analyzing distribution networks, *load-flow* calculations are important. These calculations will result in the steady-state of a distribution network. This steady-state can be expressed in the voltage level at certain nodes, the power flowing (both active and reactive) and the phase angle between voltage and current. These calculations are used when planning a new grid or extensions, but can also be used to see the effects of DG on the grid. These calculations are also seen as the base case for a grid. In addition, non-normal operation state calculations are also considered when planning a grid. These include short-circuit analysis and stability analysis. A brief introduction on load-flow calculations is given in this section, more details can be found in the references.

A distribution network can be expressed by a number of nodes connected with cables. An incidence matrix can be obtained from this graphical representation. With a radial distribution network, this will result in a sparse matrix. For AC systems, this involves the use of complex values or the polar form notation. In [69] more details are given on how to model loads and generators with this model. Furthermore, a nodal admittance matrix is used. An admittance matrix expresses how easy current will flow between two nodes. Admittance (Y) is the inverse of impedance and is measured in Siemens (S).

The goal is to determine all voltage levels, angles, and power flows in the network. However, this is a non-linear problem. So numerical methods are used to find a solution to the problem. The most commonly used method is the Newton-Raphson method to find the roots. The Newton-Raphson algorithm is explained in [56]. Initially, values for unknown variables are set to the nominal voltage level. The power balance equations are then solved using this initial value. A certain mismatch is the result. Using linearization and more iterations, the mismatch converges to a solution for the problem. The Gauss-Seidel method is another method to solve non-linear problems, but is used less often. It has as advantage that it uses less memory, but converges slower to a solution and does not scale well with larger networks. Hardware/software co-design is employed in [42] where the Newton-Raphson algorithm is used. The results show up to 10 times faster computation times.

In addition, other algorithms to find the steady state operation in a network are proposed as well in literature. The forward-backward sweep method [55] is well known and suitable for radial networks and weakly meshed networks and makes use of Kirchhoff's voltage and current laws. The forward sweep exists of the node voltage calculation from the sending end to the far end of the feeder (end to end). The backward sweep calculated the currents in the branches from the far end of the feeder towards the sending end of the feeder. Again the mismatch of power or voltage forms the criteria for convergence. Comparison of different forward-backward sweep implementations in [24] show that convergence speed is heavily dependent on the system parameters. Furthermore, the forward-backward sweep method is a solution to inefficient analysis and numerical problems that can occur with Newton-Raphson and Gauss-Seidel algorithms for distribution networks with special features, such as a unbalanced loads. These cases can also lead to ill-conditioned matrices in certain circumstances.

These algorithms are suitable for acceleration using parallelism when real-time simulations are required. In [3] a GPU is used to accelerate the calculation of a three-phase radial network using the forward-backward sweep method. Results show that the performance degrades linearly with the number of nodes in the network. With the used GPU, the computations are executed roughly 30 times faster on the GPU compared to the CPU. However, there is a lot of overhead in transferring the data from and to the GPU, resulting in a total execution time that is only 1.5 times faster on the GPU. Choice of platform depends on requirements with respect to network size and load-flow calculation interval.

Recently, the Holomorphic Embedding Load-Flow method [63] is published. The previous mentioned methods need multiple iterations. This method does not need iterations and is therefore direct. In addition, it also mathematically guarantees the correct solution with the desired accuracy. Otherwise, unambiguously will be signaled when there is no solution, which leads to voltage collapse. The method also performs comparable to optimized Newton-Raphson methods and can be used for reliable real-time applications due to its deterministic behaviour.

2.4.2 Phase To Phase Gaia and Vision

Gaia [47] is a simulation tool for low voltage grids. The software is developed by the Dutch company Phase to Phase B.V. since 1991. The software is used by most of the Dutch utility companies to design and calculate low voltage networks using Newton-Raphson load-flow calculations. It has capabilities to calculate unbalance between the phases as well, which other products from phase to Phase lack. The network in the simulator can be created using a user-friendly GUI as seen in Figure 2.18. The software can calculate and simulate short-circuit currents, voltage levels, earthing safety and load of network components. Considering the safety and network criteria, the software can automatically generate a suitable network.

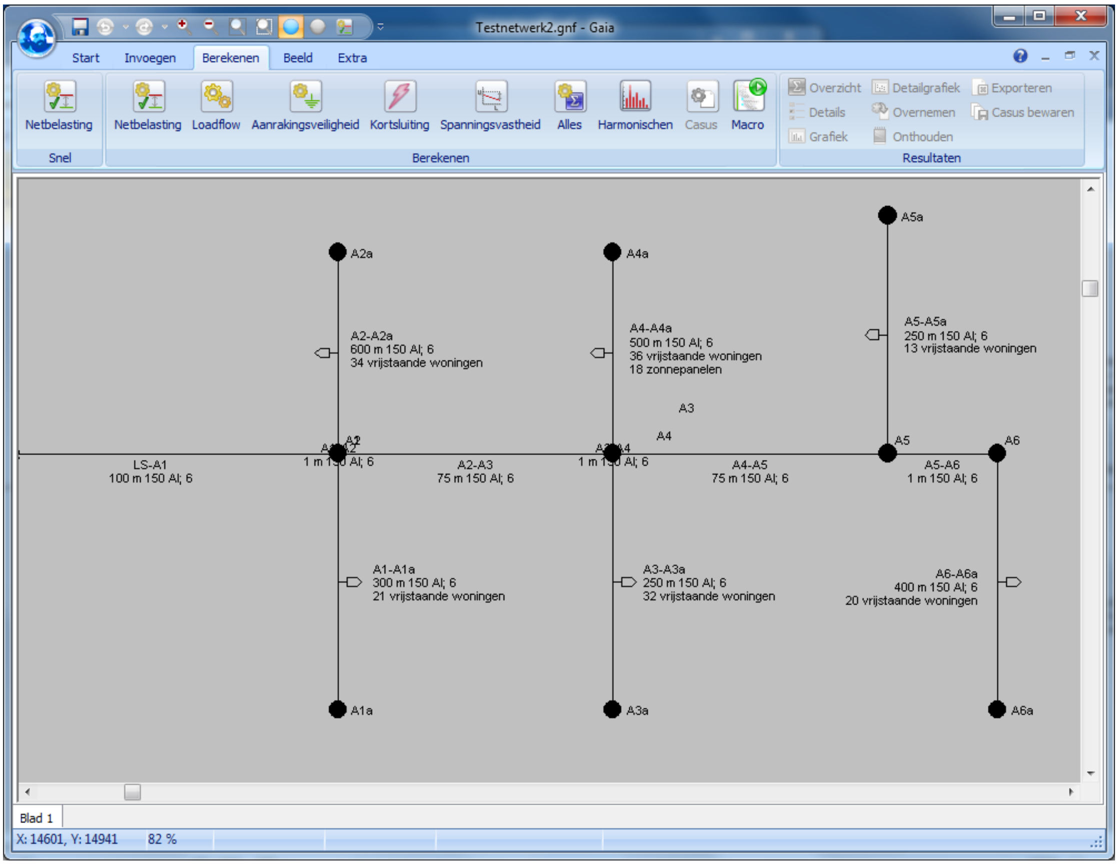

Figure 2.18: Screenshot taken from Gaia.

The software has lots of components to model the network. Several cable types can be selected but also be calculated. Other components such as generators, loads, transformers and supply units can be connected in the network. Most of the components have parameters which makes it possible to model the components as accurate as possible to the real world behaviour. Changes in these components over time can also be added to simulate with expected future changes in the network. Tabs make it possible to keep overview on different parts of the network, whilst all tabs will be used during simulation. It also has a function to dimension a LV network based on economic and technical criteria.

A macro language is also available to automate the simulation process. Data can be exported using the macros into spreadsheet files. This output can be used to feed to the simulator. An import and export function for batch load-flow calculations on a network is being implemented at the moment of writing.

Vision [48] is also a simulation tool for networks by Phase To Phase. It makes use of load-flow calculations. The tool is suitable for different types of networks such as LV networks, MV networks. However, it lacks support for unbalance between phases. Vision is optimized to support very large networks. Vision Network Analysis is a tool to plan and design networks. Analysis can be done on faults and reliability of the network. Vision also lacks an API, but uses the same macro structure as Gaia. In comparison to Gaia, some parameters are slightly different as well. Gaia is specifically aimed for LV networks with high detail modeling, where Vision is aimed for larger LV and MV netorks combined.

2.4.3 DIgSILENT PowerFactory

PowerFactory [21] is a simulation tool developed by the German firm DIgSILENT. The software package is comparable to Gaia and Vision. Load-flow calculations are also done using the Raphson-Newton method. The software can simulate different types of grids from HV to LV. For LV, it has options to simulate residential areas or industrial areas. Loads can be edited and also generators such as wind turbines and PV can be added to the simulation model. Everything can be modeled using an graphical user interface.

The software offers also options to analyze and optimalize distribution networks. One of the options is to calculate what reinforcements are needed in the grid to host certain amounts of DG. Furthermore analysis can be done on power quality, voltage drops and so on. Optimizations on losses are also possible with the software. DIgSILENT PowerFactory has a lot of options when it comes to importing and exporting files. It has tools to be integrated with GIS (Geographical Information System) and SCADA. Data can also be exchanged using text files, spreadsheets or databases such as MS-SQL. An own object-oriented programming language is also included, which can also do Dynamic Link Library calls to other software.

2.4.4 Matlab

Matlab by MathWorks is a flexible program with many plugins for all kinds of calculations. Simulink, also by MathWorks, is aimed at simulations and is extensible as well. For simulations on distribution grids, several plugins are written for both programs.

SimPowerSystems [36] is the first one. It is a commercial addition to Simulink to simulate distribution networks. It consists of multiple models for components such as PV and wind turbines. The analysis include only load-flow analysis, steady state voltage and current values. Harmonics analysis and total harmonic distortion calculations can also be done. An user interface is available to enter the network, connect all the components and change parameters.

Free Matlab toolboxes also exist, maintained by several researchers. The Power System Analysis Toolbox (PSAT) [26] is such a toolbox. The package is distributed under GPL. However, the documentation for PSAT is not available for free anymore. PSAT features a GUI for all operations, but the commandline can also be used, which is also compatible with Octave, an open source high level programming language. The toolbox can handle power flow calculations and has models for wind turbines, fuel cells and others available. User defined modules can be added to the software. Results can be exported in plain text and Microsoft Excel files, along other options. Details about the implementation and used formulas are given in [37]. PSAT exploits vectorized computations and sparse matrix functions from Matlab and uses the Newton-Raphson method.

MatPower [68] is another open source package for Matlab. It is distributed under the GPL license as well. M-files are provided for solving power flow and optimal power flow problems. In [69], the implementation details are given. MatPower uses branch admittance matrices for the network. These matrices are sparse and this is exploited. Four algorithms are implemented for solving. These are the Newton-Raphson method, two Fast-Decoupled methods and the Gauss-Seidel method. The package comes without a GUI. However, the package is very well documented in [68], where all options and used formulas and algorithms are described. MatPower can be extended with several other packages to provide additional options.

MatDyn [18] is a Matlab package that relies on MatPower. The package is developed by ESAT-ELECTA of the Catholic University of Leuven. Instead of the steady-state analysis in MatPower, MatDyn focuses on dynamic analysis, such as transient stability and time domain simulations of power systems. The implementation and used algorithms are also well documented in [18] and [19]. The power system is represented by algebraic differential equations. To simplify the solving algorithm, partitioning is used. The package focuses on education and research and is therefore simplified in comparison to more accurate commercial software. Simulation results are also compared to PSAT and the commercial PSS/E simulator by Siemens. The results show that MatDyn is accurate, despite some parameters are not taken into account in comparison to PSS/E.

2.4.5 InterPSS

When it comes to open source simulators, InterPSS [30] is one of the options. InterPSS uses the open data format that is maintained by the IEEE [46]. The software is written in Java and is modular. Several modules exist such as a user interface. All modules can be connected to the core system of InterPSS using an API. This core software is able to do load-flow calculations, distribution system, transient stability and short circuit analysis. The algorithms used are Newton-Raphson, Fast-Decoupled and Gauss-Seidel.

2.4.6 OpenDSS

OpenDSS [29] is an open source simulation tool by the Electric Power Research Institute (EPRI). The software is available under a BSD license. There is both a Windows executable available as a dynamic link library for integration. The software has an user interface, but not an user friendly method to design networks. These have to be entered using code. OpenDSS can do analysis and calculations that are commonly used, such as power flow calculations, harmonic analysis and fault current calculations.

More details on the software and used algorithms are given in [22]. The software aims to support research on smart grids. As DG has its effects on the load shape of a distribution network. Tools are available to simulate the impact of DG on the network as well as analysis where DG can be integrated best. The calculations are not based on the commonly used forward-backward sweep methods. Instead, the modeling is done using the primitive admittance matrix approach. The cause for this is that the software is evolved from harmonic distortion flow analysis software.

2.4.7 TRIANA

For the planning of a smart grid, a simulator also exists. The TRIANA simulator developed at the University of Twente is able to simulate the effects of planning within smart grids using the three step method of forecasting, planning and real-time control. In [5] the implementation of the TRIANA simulator is described. The simulator is written in the C++ language and uses the QT-libraries [50]. Four different types of devices are created for the simulator, which also makes it easy to implement new devices in the future. These devices are: buffering-, consuming-, producing- and converting devices. These devices are limited to their natural limits when it comes to usage and states. Energy between devices is transferred using pools. These pools must be balanced, i.e. the energy that flows in is equal to the energy that flows out of the pool. The use of devices that are connected via pools is visualized in Figure 2.19.

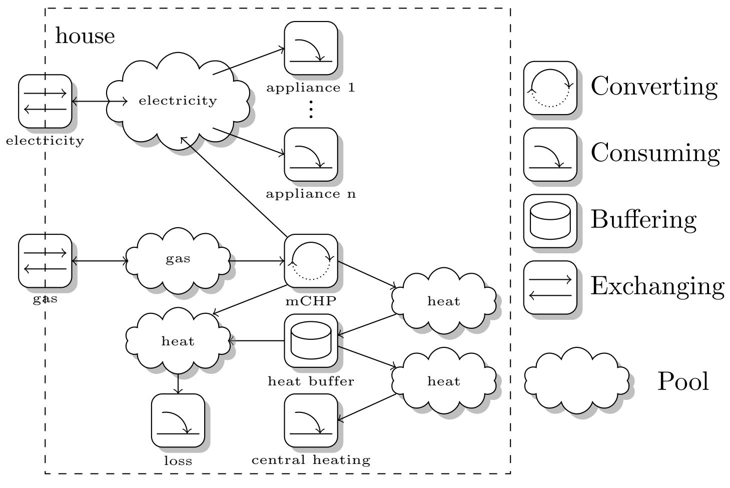

Figure 2.19: *A house modeled in the TRIANA simulator using devices and pools [5].*

The simulator is distributed to enhance the performance. Configuration files are used to load in new simulation setups, keeping the software flexible. A protocol between the different instances (that can be ran on different computers) is explained. The most common setup is to have a global controller, then a grid controller for each grid and a house controller for all individual houses. A selection of devices is implemented to test the performance of the simulator and the efficiency of the distribution. A small overhead from the communication is observed, but the simulator clearly benefits in terms of performance when more computers are added.

2.4.8 Summary

This section has outlined different power flow calculation algorithms. Power flow calculations give insight in voltage levels, active and reactive power flow and phase angles. Today, mathematical tricks are used to find the steady-state of a network.

Different software solutions are available to simulate a distribution network. These include commercial packages such as Gaia, Vision and DIgSILENT. The possibilities to communicate with other software are limited, however. Open source simulators also exist, both stand-alone and as Matlab plugins. These are usually developed at academic institutes and provide good documentation on the used algorithms. TRIANA is a simulator to test the effectiveness of planning between loads and generators. One of the grid simulators should be combined with TRIANA to study the effects of the planning on the distribution grid. This will be the topic of the remaining part of this thesis.

3 Requirements and choices

This section will discuss the requirements regarding the simulation. The first part will detail the factors that will be taken into account with simulation. This choice for factors depends on required computational power, relevance and availability of required data. The second part will cover the requirements of the network, including households. These requirements will lead to a use-case that will be used to verify the simulation results in the other chapters.

3.1 Power quality factors

There are several factors regarding power quality, which are discussed in the previous chapter of this thesis. A choice must be made to take certain factors into account, whilst others will be omitted. These factors are the voltage levels in a network, voltage balance between the phases, voltage variations, THD and frequency.

Selecting certain power quality features depend on the relevance and availability of required parameters. Also implementation time and required computational power is considered. A tradeoff must be made between accuracy and feasibility, considering time, computational power and relevance. To make a choice, results from the literature study will be used, in combination with some relevant simulations.

The planning of consumption and production in TRIANA is done using time intervals. For each time interval, the state of a device will be determined. The smaller the interval size, the more computational time will be required. For a large network with more accurate modeling, this can become an issue when grid optimizations are required. For each time interval, it is important to determine the steady-state operation of the network as exact details about transitions between states are unknown. The time interval size used in TRIANA will directly impact the detail level of grid simulations as well. This also limits the factors that can be simulated to evaluate the power quality in the grid.

3.1.1 Voltage level

The voltage level is one of the most important issues with DG. Most existing LV networks are not designed with generation in the network in mind. Literature has shown that voltage rises due to DG can become an issue with a high penetration of DG. Furthermore, the location in the grid is also important. Generation without load has more severe issues towards the end of a feeder.

To evaluate voltage level issues with spreading of load and generation, a simple simulation model is created in network simulator Gaia. It consists of a 400 kVA transformer and a 1000 meters long 150mm aluminum cable. A generator is connected at the end of the feeder with a symmetric connection. The generator injects a current of 50 A into the grid (11.5 kW at 230 V) and is connected symmetric, which means that the injected current is balanced over the phases. This network is depicted in Figure 3.1. Some tests are done by changing the load in the network.

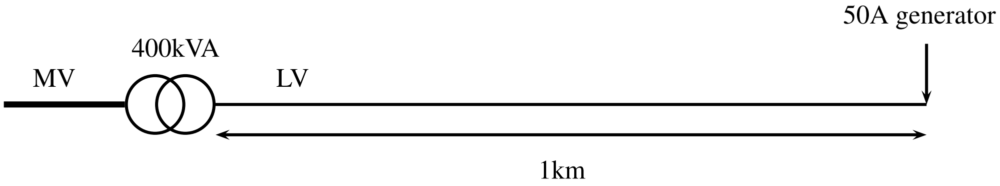

Figure 3.1: *Test network used for simulation to evaluate the effects of the location and amount of load in a network with DG.*

In the first test the load, which is also 50 A, is shifted in position in steps of 100 meters, starting at the transformer and moving towards the end of the feeder. The voltage level on all phases at the end of the feeder is simulated using load-flow calculations. In the worst case, the load is at the transformer which results in a voltage level of 242 V at the end of the feeder. When the load moves towards the generation, the voltage level at the end of the feeder improves to a level of 231 V. This is also the expected behaviour due to the effect in resistance in cables, which increases with longer distances. The voltage levels on the three phases at the end are plotted in Figure 3.2. Similar figures are obtained when an increasing load, ranging from 0 A to 50 A, is introduced at the generator.

Thus it is important to utilize knowledge of the network when planning the grid. Matching the amount of generation and consumption is not only important to improve the power quality, the location of both is also important. To cancel out voltage rises and drops. By using load-flow calculations, the voltage level in the network can be determined. It is then possible to see whether the voltage level stays within the boundaries as stated by the Netcode [43].

With load-flow calculations, information about the power factor and losses in the network can be obtained as well. This information can be exploited to further optimize the location of production and consumption of energy to reduce the waste of energy during transport. Load-flow calculations can also be done by various simulators.

The data needed to do load-flow calculations is also available. The active and reactive power consumed or produced by the different devices or households are required. These are available in measurements and models of different generators and appliances. Furthermore, the topology of the network is required. This information is documented when the network is designed. The

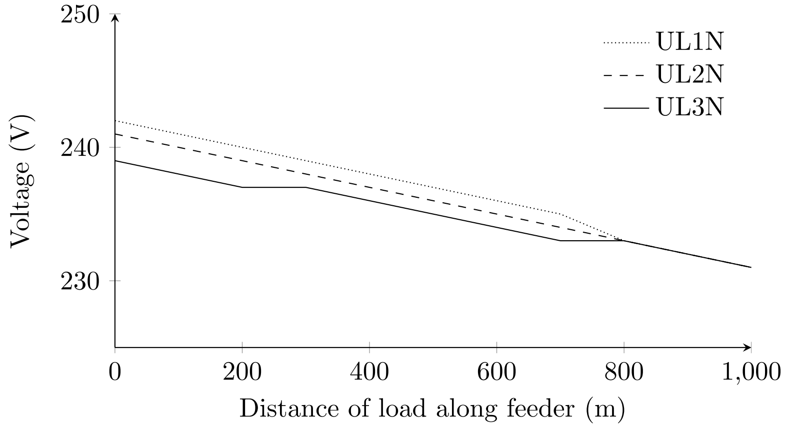

Figure 3.2: *Voltage level at the end of the feeder in a test simulation model. The generator (50A) is located at the end of the feeder and the load (50A) is moved from a position at the transformer towards the load.*

distances and properties of cables are required to determine the voltage levels. The consumption level, production level or the infrastructure could be altered and simulated again to verify whether the regulation criteria is still met.

The computation time depends on the network and used algorithm for load-flow calculations. These calculations are considered to be the most important when it comes to power quality and hosting capacity within LV networks and cannot be omitted. Due to the importance of the overvoltage problems with distributed generation, the load-flow calculations will be a requirement for the simulations. The data required is available and different simulators, open and closed are available to use for this.

3.1.2 Voltage asymmetry

More detail to the load-flow analysis can be added by differentiating between the phases. Asymmetry is an aspect that can be expected with DG in a LV network. If consumption and production are not equally spread over the phases, different voltage levels can occur and will also lead to increased losses in transportation of electric energy.

To evaluate the effects of unbalanced loads and DG in a LV network, the same network as the previous subsection is used. Two simulations are done. In the first simulation, the same 50 A generator is connected to phase L1. In addition, the load of 50 A is also connected at phase L1. Just as in the previous simulation, the location of the load is changed from near the transformer to the generator. The voltage levels on the phases are shown in Figure 3.3. On the L1 phase we see the same behaviour as in the previous simulation. However, the voltage levels have become worse as only one of the three conductors in the cable is used.

When the load and generator are connected to different phases, one would expect that the voltage levels get worse as the load moves to the generator. Since the load and generator are not on the same phase, distribution of energy can only happen via the transformer, resulting in a voltage

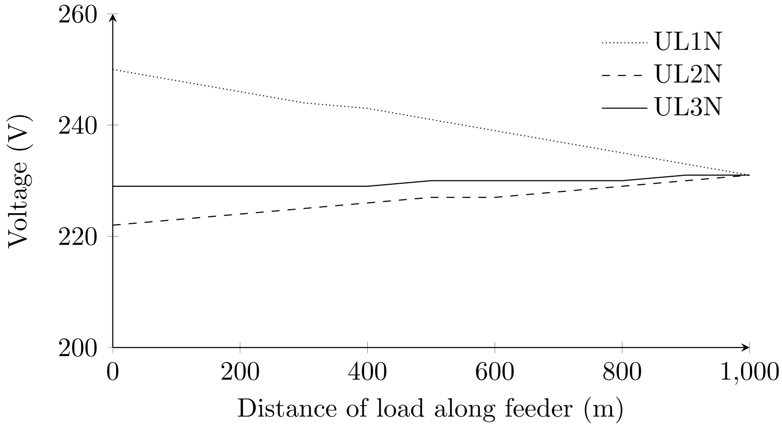

Figure 3.3: *Voltage level at the end of the feeder in a test simulation model. The generator (50A) is located at the end of the feeder on phase L1 and the load (50A) is also connected to phase L1 and is moved from a position at the transformer towards the load.*

drop due to the load in the first phase and an voltage rise in the other due to the generator. Simulation shows that this is indeed the case when we connect the generator to phase L2 instead of phase L1 and the load is once again moved. The voltage levels at the end of the feeder are shown in Figure 3.4. From these simulations it is clear that it does matter that load and generation are not only balanced over feeder distance, but also in all three phases.

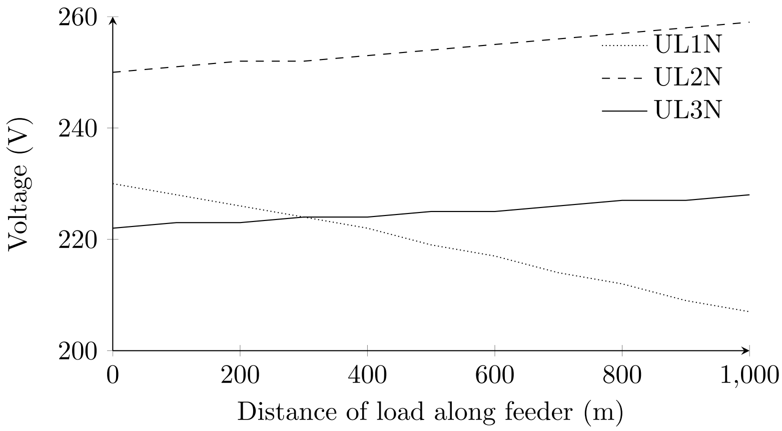

Figure 3.4: *Voltage level at the end of the feeder in a test simulation model. The generator (50A) is located at the end of the feeder on phase L2 and the load (50A) is connected to phase L1 and is moved from a position at the transformer towards the load.*

The same load-flow calculations can be used for a three phase system, the computational time required will be increased by a factor four (for the three phases and the neutral conductor). In addition, knowledge on which phase or phases a household is connected must be known. This data is not always available or accurate. However, equipment exists to determine the connected phase. When information is not available, normal distribution can be assumed as the preferred method to connect houses is to balance the load on all three phases. Connecting a household to another phase is also not a huge issue since the cables are already available at the houses. The option to switch phases can also be exploited to find a better balance for the amount of connected DG and therefore improving the voltage level in the phases.

Voltage unbalance can lead to overvoltages and undervoltages on different phases, whilst the average voltage level might be within the limits. Adding a three phase unbalanced model is thus an important factor to investigate these unbalance problems. Some simulators offer the option to calculate the voltage levels in the different phase. Since asymmetry can be a problem with DG, this is a significant addition to the load-flow simulation as well.

3.1.3 Total harmonics distortion

Another problem concerning power quality with household appliances and inverters used with PV cells is harmonics distortion. To simulate THD effects, a lot of data has to be added to device models. In [7] individual and combinations of devices are measured to obtain a fingerprint of the harmonics distortion. The interaction between multiple devices is also simulated in [28], which shows that the THD might be lower when installing more inverters. The results also show that phase angle and the load connected to an inverter can make a huge difference to attenuate each others harmonic pollution emission. The measures to that need to be taken to reduce harmonics distortion also depend on the situation. Passive and active filters can be used to reduce THD [66]. Injection of harmonic currents with DG can even cancel out harmonics resulting from load according to research in [6].

For simulations, adding THD means adding fingerprints for all devices. The simulations will also lead to a significantly increased time required for computations to determine the interaction between multiple devices. Strict regulations on EMC emission of appliances is encouraged by [7] and [28] to improve the power quality instead. With a high penetration of PV, inverters might trip due to violation of regulations, as shown in [25]. However, it is hard to say when these regulations will be violated.

Most of the evaluated simulators in the literature study do not offer THD simulations options as well. As a result, THD will not be considered in the simulations. Obtaining THD data for all devices and simulate the effects will take a lot of time. Stricter regulations will likely have more positive impact on THD than planning can achieve. Major sources of harmonic currents are PV inverters, compact fluorescent lamps and electronics such as a computer. Measurement results of these and other residential appliances can be found in [7, 8, 59]. Most of these loads have little planning freedom. Peak-shaving might reduce the absolute amount of harmonics as less polluting devices might be turned on simultaneously. On the other side, the percentual THD might increase. However, THD currents cause additional currents and heating of components and might be considered for future work.

3.1.4 Frequency

For the power quality, it is also important that the frequency is stable around 50 Hz. However, inverters used with DG have to synchronize to the frequency of the network. There are also certain regulation requirements to enforce a certain synchronization. In case that certain requirements regarding the frequency are not met, the inverter has to disconnect. For generators with rotating parts, such as diesel generators, the rpm must be stable enough to ensure a correct frequency.

Frequency synchronization is done on-line using controllers. Most analysis on frequency issues is done using simulations with small time steps to simulate the effects of starting generators. In case of frequency problems, generators are disconnected from the grid. The effects this has on the voltage level can be simulated. However, as it is an on-line control at the equipment, it is hard to predict when this happens. To simulate this, all models have to be rewritten to incorporate frequency variations, which will require too much time within this master's thesis. Furthermore, none of the discussed available network simulators do frequency calculations either.

3.2 Use-case requirements

A use-case is required to evaluate the effects of planning on a network. The requirements for use-case consists of two parts. The first is the topology of the network that will be used. It defines the relation between connections and the used cables. This also yields cable parameters which will be required for calculations. The second is the modeling of the households. This is the part where differences can be made using smart grid planning. It is essential to create a balanced setup of houses with enough planning freedom. On the other side, the chosen configuration must be an acceptable estimation of a (future) household in order to obtain realistic results.

Simulations will be executed on a LV network. Individual consumption and production of devices within a household will be simplified to a single house with a load and generator. The aim is to do simulations and analysis on a LV network. Higher voltage level networks are part of future work.

Furthermore, distribution networks are normally operated radially. Meshed structures are very rare and not used in todays design of networks. For most typical Dutch LV networks the network can thus be seen as a tree without cycles. Models and calculations can make use of the properties of such tree structures in order to simplify calculations and reduce the load that a certain implementation would have on an embedded system.

The network of Lochem is chosen as the network topology for the use-case. Within the experimental environment in Lochem, additional measurements are done in the network. A detailed network model for Gaia also exist. One of the residential areas in Lochem with such a model and additional measurements is the at the Kopermolenring transformer. This 400kVA transformer feeds 232 households in a residential area from the mid nineties. Half of the residential area is detailed in Gaia. For these houses, the exact distance to the transformer is known, as well as the used cables.

The part that is modeled in detail has 121 households, which can be considered a fair amount. It ensures that simulations don't need too much time, but there is enough planning freedom to study the effects. Furthermore, it is a considerable amount that allows a good evaluation of the performance.

These households will be modeled after futuristic scenarios by [17]. This model contains households with both controllable and uncontrollable loads and generation. Energy consumption patterns of devices and production patterns for photovoltaic cells for uncontrollable devices are generated. The controllable devices are dish washers, dryers, washing machines, hot plug electrical vehicles, heat pump and batteries in various penetrations. This results in a different configuration for each house for each day for a complete year.

3.3 Simulator

A simulator is required for the load-flow calculations to evaluate whether limits regarding power quality are met. In addition, internal quick power quality calculations should be implemented in TRIANA. These quick network calculations need to give insight that it is most likely that a network does not show power quality issues. When certain thresholds are violated, the external simulator should be accessed to see whether power quality issues are indeed violated, or that it is still within boundaries set by regulations. Various available network simulators are mentioned in the literature and will be discussed in this section.

3.3.1 Simulator

From the previous subsections a list of requirements for the simulator can be composed. Regarding the previous discussed requirements, a load-flow simulator is required. As a LV network will be used as test case, the simulator should be suitable for this purpose. An additional feature is the ability to simulate a three phase grid with unbalanced loads. Simulation of THD would be another feature to consider for possible future research, but is not taken into account at this moment. Obviously, the simulator should have options to exchange data with TRIANA.

A comparison of simulators on these criteria is shown in Table 3.1. The network simulators from the literature are compared, except for MatDyn, which uses MatPower for voltage level calculations and would not add anything new for voltage calculations. Each simulator is awarded with either a -, +/- or +. The criteria are as follows: Integration reflects the possibilities for integration based on APIs and documentation. Voltage reflects the possibilities to calculate voltage levels in a three phase unbalanced system (+), only balanced voltage levels over three phases combined (+/-), or no possibilities (-). For eventual future implementations, possibilities to calculate THD levels are also reviewed. Documentation reflects the amount of documentation available and other knowledge sources about the simulator. The open column reflects the openness of the software for implementation options directly in the code. An asterisk at the name marks that it is a free open source simulator.

Considering the requirements, Gaia is the best suitable simulator. It is specifically written to simulate LV networks with unbalanced phases. Simulations regarding THD can also be executed in the future. Gaia is the simulator that is used within Alliander as well and various networks are modeled using Gaia. Using Gaia would make it more convenient to import and export network models between both simulators without the need to convert them to a third software tool. The strong relation between Alliander and Phase to Phase also leads to new implementations in Gaia on request, such as an import and export function. This softens the weak point that the simulator is not open source. The documentation of Gaia is good and gives insight in implementation of certain algorithms and modeling of components. As Alliander uses Gaia, a lot knowledge about the software is available too. All this makes Gaia the best choice for load-flow calculations on the network.

	Integration	Voltage	THD	Documentation	Open
Gaia	+/-	+	+	+	+/-
Vision	+/-	+/-	+	+	+/-
PowerFactory	+/-	+	+	+/-	-
PSAT*	+	+/-	-	-	+
MatPower*	+	+/-	-	+	+
InterPSS*	+	+/-	-	+/-	+
OpenDSS*	+/-	+	+	+/-	+
SimPowerSystems	+	+	-	+/-	+

Table 3.1: *Different simulators compared on their features and possibilities for integration.*

3.3.2 Calculations

Calculations on the network have to be implemented in TRIANA as well. These calculations do not need to be as detailed as load-flow calculations. However, they should be suitable to get a good insight whether power quality regulations are met or violated. Discarding details will make the calculations faster, which is of importance when multiple scenarios need to be calculated. This will make the simulations also suitable for less powerful embedded systems. The TRIANA approach is to use distributed control with embedded systems. These same embedded systems might be the target to run load-flow calculations on. However, embedded systems have only limited performance. This limitation has to be taken into account to make sure that calculations can be performed in time.

A threshold must be taken into account to compensate for the discarded details of the calculation. When the calculated values do exceed this threshold, the external simulator can be used to verify whether power quality limits are indeed violated. The next chapter will give details on the modeling of components that can be used for an own implementation for load-flow calculations.

3.4 Summary

To summarize this chapter, the power quality aspects that will be taken into account are the aspects that are related to the voltage level. This includes the voltage level on various positions in the network. But also the balance in voltage level between the three different phases. This can be done with load-flow calculations. Load-flow calculations will not only give insight in voltage levels, but also in power flowing, the power factor and phase angles, as the voltage level depends on these values. Aspects that will not be taken into account are THD and frequency related aspects.

When it comes to a use case, a LV network will be used. More specific, the Kopermolenring in Lochem, where additional measurements will be done. A model of this residential area is also available for modeling. For simulation, Gaia is chosen as the simulator. It has all the features for load-flow calculations, offers good documentation and has options for customization to our needs.

4
Modeling

This section will cover the required parameters for different aspects of the simulation to model the grid and individual components. Input parameters from the Phase to Phase Gaia and Matpower simulators are studied to see what parameters will be required. Furthermore, theory from [66] is used as well to determine parameters. Advanced modeling of components and formulas given in [61] are also used.

The second part of this chapter details how these parameters can be used in models of components and networks. Load-flow algorithms and the formulas required to obtain load-flow data are also given. The main target is to keep the required computational time limited, whilst the accuracy of the results should still be acceptable for planning usage.

There are mainly two modeling parts. The first is the layout of the network itself to identify how components are connected. The second part are the components itself. The network itself can be seen as a tree with branches that connect different nodes. These branches represent the cables and have certain parameters. Instead of cables, branches can also be fuses or transformers. Buses can be connected to the nodes. These buses can be a load, generator or a reference slack bus. Figure 4.1 gives an overview a network topology and all components. The parameters and models of all these components will be discussed in the rest of the chapter.

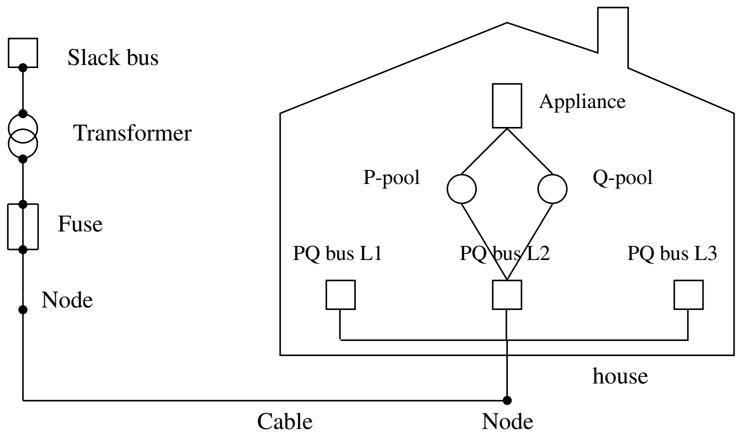

Figure 4.1: *Overview of a LV network structure with all components connected to it.*

4.1 Bus types

Specifying loads and generation is done using buses. There are three types of buses in load-flow calculations: loads, generators and slack buses. For each of these buses, certain parameters are known whilst other are unknown. The unknown parameters have to be obtained by load-flow calculations. The parameters that are generally assumed known and unknown are shown in Table 4.1.

Bus	Type	P	Q	U	Phase φ
Load	PQ	Known	Known	Unknown	Unknown
Generator	PU	Known	Unknown	Known	Unknown
Slack	UT	Unknown	Unknown	Known	Known

Table 4.1: *Bus types with known and unknown parameters according to [66].*

For load buses, the energy consumption is known through the load that is connected. These buses require the amount of active and reactive power. For the constant power consumption model as used in TRIANA, these parameters can be filled in directly and have a constant power consumption. However, the consumption of certain loads depends on the voltage level. There are two other classes of loads. One with constant current and one constant impedance. To determine the power consumption of these loads, the voltage level must be known. This means that there are dependencies in the equations that have to be solved.

For generators, the produced active power and voltage level is known. The reactive power depends on the load, but could be specified with certain limits. This applies to generators that are voltage regulated. There are also generators with phase angle compensation of which active and reactive power are known. These can be modeled as a negative load.

A slack bus is required to balance the active and reactive power flowing through a system. It has the reference angle and voltage level and is therefore also called the reference bus. The bus is used to emit or absorb active and reactive power to or from the system. All other voltage levels and phase angles in the system are relative to this slack bus.

4.1.1 Load bus

Loads within a household can be modeled using active power (P) and reactive power (Q) parameters. For each appliance i within a household this will result in a complex number:

$$S_i = P_i + jQ_i \tag{4.1}$$

where S_i is the apparent power in VA for appliance i. For N appliances, the complex values can be added, resulting in a complex load value that represents the total load of a household h:

$$P_h = \sum_{i=0}^{N-1} P_{i,h} \tag{4.2}$$

$$Q_h = \sum_{i=0}^{N-1} Q_{i,h} \tag{4.3}$$

$$S_h = P_h + jQ_h \tag{4.4}$$

For a range of appliances, the active power consumption can be obtained quite easily. Obtaining the reactive power consumption usually involves measurements as these are not usually specified. However, this assumes that the load has a constant power consumption profile, which is not always the case. There are also appliances with a constant impedance instead, such as light bulbs and water boilers. The power consumption depends on the voltage level for this type of devices. Some devices have a constant power consumption part and a constant impedance part.

The voltage level is not known on beforehand. A nominal voltage level of 230 V could be assumed to simplify the model. This would also be a logical choice from a planning point of view. Furthermore, the voltage cannot fluctuate too much considering the enforced regulation, so the error introduced by this assumption is limited.

With distributed generation, the generators can also be modeled as a negative load. In LV networks, DG should not regulate the voltage level. By regulations [43, 2] it is enforced that generators in the LV network synchronize their current sine wave and voltage magnitude. Therefore their active and reactive power production is known whereas the voltage level is not. These can than be modeled as a negative load bus (PQ bus).

Since load and generators in a LV network can be modeled using a PQ bus, a household can be simplified by subtracting the generation from the load. The result is a single PQ bus which represents the complete load of a house. Of course this load can be negative which means that the household feeds in energy.

The parameters for this bus are:

- P - Active power consumption of the load in Watts (W)
- Q - Reactive power consumption of the load in volt-ampere reactive (var)

4.1.2 Generator bus

As generators in the LV network can be modeled using a PQ bus, the generator PV bus is not required. However, for larger generators connected to the MV network this type of bus might be required.

The parameters for this bus are:

- P - Active power production of the generator in Watts (W)
- U - Voltage level of the slack bus in volts (V)

4.1.3 Slack bus

The slack bus sets the base voltage level and phase angle in the distribution network. Only one slack bus should be modeled in a separate network to prevent problems with load-flow calculations. Networks with multiple slack buses usually result in current values that do not correspond with the reality [66]. Note that the slack bus is not the replacement of a transformer.

The parameters for this bus are:

- U - Voltage level of the slack bus in volts (V)
- φ - Phase angle of the slack bus in degrees

4.1.4 Household buses

Households are connected to nodes using these buses. For a LV network, it is sufficient to model a complete household as one PQ bus. This PQ bus contains the aggregated energy consumption or production of a household. Production and consumption is determined by the devices in each household and their state. Households are modeled after futuristic scenarios by [17].

This model contains 400 households with both controllable and uncontrollable loads and generators. Energy consumption patterns of devices and production patterns for photovoltaic cells for uncontrollable devices are generated. The controllable devices are dish washers, dryers, washing machines, hot plug electrical vehicles, heat pump and batteries in various penetrations. This results in a different configuration for each house for each day for a complete year.

Multiple scenarios are available for this model with different penetrations of these devices. The optimistic scenario contains the highest penetration of PV, batteries and large loads such as electric vehicles. In total, 90% of the houses have an electrical vehicle, 30% is equipped with a PV installation and 20% of the households has a battery. All houses are equipped with smart dish washers, washing machines, heat pumps and resistive heaters. For the other loads, a consumption profile is generated.

The energy production of a PV installation can be as much as 3.9 kW. The capacity of the batteries is 8.5kWh. Almost all houses have an electrical vehicle with a mean demand of 6.3kWh, with certain cars requiring a 12kWh charge. The heat pumps can draw 2kW from the grid, the resistive heaters are rated 10kW. The average consumption of uncontrollable loads is 8.9kWh per day.

4.2 Network model

The total network can be modeled using branches and nodes. For each branch the starting and end node must be known. The result is a tree which represents the LV network. Search algorithms can be used to find the shortest route between two buses.

From the geographical information, the length of each cable can be determined. Cables themselves are modeled with the so called *pi-model*. It consists of a certain impedance from node to node of which the resistance and reactance can be obtained from the cable type used, combined with the length of the cable. A cable also has a certain capacitance to ground which causes additional reactive power. The losses can be obtained using the current running throught the cable and impedance of the cable. Phase angle deviations can be given as well as properties of cables.

For LV networks, Alliander uses the program Gaia from Phase to Phase. Models of networks exists in this program for several networks. They include the lengths and cable types between different nodes. Figure 4.2 shows an example of a LV network in a residential area of Lochem. The network topology including cable types can also be obtained from WebGIS, an web application containing geographical data of network components.

Figure 4.2: *A network model of a residential area in Lochem from Gaia projected on the satellite images from Google Maps.*

4.2.1 Network topology modeling

As a network can be seen as a tree structure, the structure of the network must be described as such as well. The topology exists of nodes that are connected with each other via branches. Load buses can also be connected to these nodes. A connection between two nodes represents a cable, transformer or fuse. This connection can be modeled using a pair of nodes. These connections can be described in various forms.

Such a topology is often modeled using a matrix. For N nodes, a $N \times N$ matrix $\mathbf{A}$ is required to specify all connections. A connection between two nodes can be denoted with a non-zero element. A three dimensional matrix can be used when more parameters must be specified such as cable type and length. Although the entry in the topology matrix can also refer to an identification number for more parameters in another data source.

Due to the layout of LV networks, most of the nodes are only connected directly to two or three other nodes via branches. This results in a sparse matrix. Properties of sparse matrices can be used to reduce the memory usage of the topology model. Furthermore, to import a network, tuples can be used. These tuples represent branches, the two nodes it connects and some additional parameters.

Network topologies models in Gaia and MatPower are also entered using tuples. In addition to the from and to locations, they also specify the length and cable specific parameters. The latter is done directly in MatPower, whereas Gaia references only to a cable type which contains these parameters as well. Since there are only few cable types used in a network, the latter option seems to be the best solution. By only specifying the length and cable type, less data needs to be entered and cable properties can be changed easier.

General routing algorithms can be used to determine a shortest path to another node and more importantly to the transformer. These analyzes are valuable to locate the connections that are far from the transformer that are most likely to cause problems. The shortest path to another connection to exchange energy can also be found with these algorithms.

The parameters for a branch are:

- Node A - Connection from this node
- Node B - Connection to this node
- ℓ - Length in meters (m)
- Cabletype identifier
- Name - Unique identifier name for the connection to link data with Gaia

The parameters for a node are:

- Name - Unique identifier name for the house to link data with Gaia
- House number - Optional parameter to link a household in TRIANA to a specific node.

4.2.2 Cable properties

Cables are usually modeled using the *pi-model*, see Figure 4.3. This pi-model is a replacement scheme with an series impedance and a parallel capacitor, which represents the cable properties. These parameters can be obtained from the Types.xls file that is provided with Gaia. Each cable type has its own parameters per kilometer cable for each conductor in the cable. There is also a nominal current for which the cable is designed for. This forms a limit for the grid when planning. This nominal current level should not be exceeded for a too long period. A typical three-phase LV cable consists of four conductors, those for lines L1, L2, L3 and the neutral.

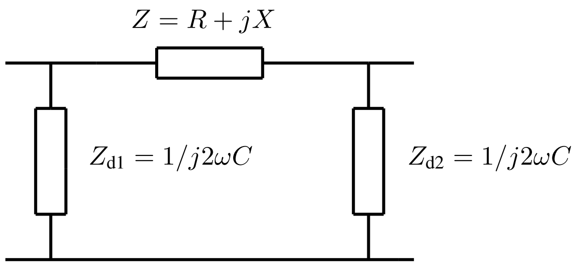

Figure 4.3: *Replacement pi model of a cable for electronic network schemes.*

More detailed models for three-phase systems also include inductive coupling effects in the cable itself. But also the type of ground has influence on heating of the cable, again resulting in different parameters. These advanced models are described in [66] and [61]. For distribution networks, the effects of capacitance to ground is so small compared to the series impedance that it can be neglected. For transmission lines, the capacitance to ground can have significant effects and is therefore usually used in load-flow calculations on these transmission networks.

What is left is the series impedance Z for each conductor in the cable. This impedance is then given by:

$$Z = R + jX \tag{4.5}$$

Using this impedenace, power losses and voltage drops can be obtained as well as phase angle changes.

The parameters for modeling cables:

- R - Resistance of a conductor in ohms (Ω) per kilometer cable
- X - Reactance of a conductor in ohms (Ω) per kilometer cable
- C (Optional) - Capacitance in micro Farads (μF) to ground per kilometer cable
- I_{nom} - Nominal current of a conductor in amperes (A)

Section 4.3 gives formulas on how to use these parameters to obtain voltage drops and distribution losses.

4.2.3 Transformer

A transformer alters the voltage level between two nodes with a certain ratio τ and phase shift φ_{shift}. However, the focus is on the LV network. It is the slack bus that sets the reference voltage level for this LV network. A real transformer model is not required in these calculations.

The effects of a lower voltage level in the MV network cannot be omitted. As the slack bus sets the reference voltage level, this reference voltage level can be increased or decreased to simulate the effects of a different MV voltage level. Usually this level is around 10.5 kV. The shift from delta configuration on the primary (MV) side to a wye configuration on the secondary (LV) side results in an additional 30° phase shift. In a delta configuration, the coils are connected to two phase, whereas in a wye configuration the coils are connected between the phase and neutral.

To transform this voltage level from the primary MV network U_{primary} to the secondary LV network $U_{\text{secondary}}$, the following formula can be used:

$$U_{\text{secondary}} = U_{\text{primary}} \times \tau + \angle\varphi_{\text{shift}} \tag{4.6}$$

To test whether the transformer capacity is enough for the demand, the folowing parameter is required:

- S_{capacity} - Transformer capacity (VA)

4.2.4 Fuses

Fuses define the maximum current that can flow through a particular branch. It can be seen as a second limit in maximum current that can flow through cables that has to be met. The limit in fuses can be lower than the actual capacity of a cable and has to be taken into account when planning as this limit should not be broken during normal operation. However, a short time of violation will not cause the fuse to melt and can be permitted.

The parameter for a fuse is:

- I_{max} - Maximum current before fuse breaks in ampere (A).

4.3 Calculations

For load-flow calculations integration in TRIANA it is important to keep the required computational power limited as multiple load-flow calculations might be required during planning. A simplified model which sacrifices accuracy in order to lower the computational time is the key aspect here. The accuracy of the calculations must be acceptable however such that a decision can be made whether the planning will certainly not violate regulations.

Accuracy must be evaluated in a comparison with a more sophisticated load-flow simulator such as Gaia. This results in a threshold at which the simplified calculations are not accurate enough to be certain that the regulations are met. In that case, Gaia can be used to give more confidence whether the planning does violate regulations or not.

The error in calculations should not be too large. As regulations [43] require that the voltage level must be within +10% / -10% of the nominal voltage level of 230 V for 95% of the ten minute averages, a difference of about 2V between our implementation and Gaia can be considered acceptable. Simulations with external software shouldn't be required too often to validate a planning for network feasibility or not. The algorithms described in this section are implemented as described in chapter 5 and evaluated in chapter 6.

4.3.1 Algorithms

Multiple algorithms for load-flow calculations exists. Well known algorithms are Newton-Raphson, Gauss-Seidel, Fast Decoupled and Forward-Backward Sweep [67]. The Newton-Raphson method uses a power mismatch function with an initial solution guess. Then the root of this function is approximated using tangent lines in an iterative process to find the solution. With Gauss-Seidel, the power system must constantly satisfy Kirchhoff's Current Law (KCL). Each iteration, the voltage levels are updated and the power system function is evaluated to satisfy KCL. Both Newton-Raphson and Gauss-Seidel are applicable to meshed network structures.

The fast-decoupled method is based on the Newton-Raphson method. However, this method exploits some numerical properties of power flow formulations to make simplifying assumptions. These assumptions result in dramatic savings in required computations.

The forward-backward Sweep method is used a lot in load-flow calculations and described in [67, 66, 14, 15, 13, 16, 12]. This algorithm makes use of KCL and Kirchhoff's Voltage Law (KVL) and is suitable for radial networks. Meshed networks are not supported with this method. The algorithm works by walking through the tree, starting from the slack bus, towards the end of each branch. This is the forward sweep in which the voltages get updated at each node. Then in the backwards sweep towards the slack bus, the currents running through each branch are updated.

In [67] benchmarks are ran to evaluate the performance of these algorithms and their variations with various networks. The standard backward-forward sweep algorithm performed best in terms of required computations. Variations of the forward-backward sweep show small increases in required computations as do the fast-decoupled algorithms. The Gauss-Seidel algorithm takes about 3.5 times as much floating point calculations compared to the standard forward-backward sweep algorithm. The amount of floating point operations required by the Newton-Raphson algorithm are approximately one order larger on average.

From these results the forward-backward sweep algorithm is the most suitable for embedded systems. It requires the least amount of floating point operations in comparison to other options. The drawback for this algorithm is mainly in the fact that it is only suitable for radial networks. For LV distribution networks this is not really an issue since these are designed radially nowadays. For meshed networks, which can be found in MV networks, it is not suitable. However, most of these MV networks contain NOPs, resulting in a suitable radial operated MV network.

In the basis, the forward-backward sweep works as follows. The slack bus forms the starting point of this tree for calculations and sets the reference for the rest of the network. During the forward sweep, the voltage levels at the nodes are updated. The algorithm walks through the tree to set the voltage levels at the nodes based on the voltage drop along a branch. The voltage drop is a result of the current running through the cable and its impedance.

Once all voltage levels are updated along a path, the algorithm walks back towards the slack bus through the tree. During this backwards sweep, the currents running through the cables are updated. For all nodes, the currents running to and from the node are calculated. These are slightly different due to the updated voltage level. This process of forward and backward calculations continuous until convergence criteria is met. This is when the difference in voltage between this and the previous iteration is lower then a certain threshold. More details on the algorithm are given in the next subsections.

4.3.2 Network initialization

Before a load-flow calculation can be executed, the initial voltage levels U^0 must be set at each node for each phase. For a typical LV network the nominal voltage level between line and neutral is 230 V. There is a 120 degrees phase shift between the line voltage levels. Furthermore, a 150 degrees phase shift is introduced by the delta-wye MV/LV transformer usually used. This results in the following initial values that are generally applicable to a Dutch LV network:

For U_{L1N}, the phase voltage level between line one (L1) and the neutral (N) this value is 230 V $\angle -150°$. For U_{L2N} it is 230 V $\angle 90°$ and U_{L3N} is 230 V $\angle -30°$. In this case the line voltage levels (L1, L2 and L3) are equal to the phase voltage level. The neutral has to be initialized as well, in the common case this is 0 V $\angle 0°$.

4.3.3 Forward-backward algorithm

The forward-backward sweep is mainly a depth first search algorithm through a tree without cycles. The forward sweep starts at the node n that is connected to the slack bus. From this point, the algorithm walks over the first branch b that is connected to the node. The reached node m is than flagged as visited. It is a depth search first algorithm, such it goes one node deeper until a node is found that is only connected via the branch the algorithm just came from. As long as the algorithm gets further from the slack bus, the forward sweep is applied. That is when the number of branches between the current location and slack bus is larger than the number of branches between the previous node and the slack bus.

When the current node is only connected to the node the algorithm just came from, the backward sweep is applied. This backward sweep goes on until a node is reached that still has branches that lead to unvisited nodes. Then the forward sweep is again applied until all nodes are visited and the current node is connected to the slack bus again. This is one iteration of the forward-backward sweep. The forward sweep calculations are omitted in the first iteration as the currents are still unknown. However, the path finding is still used during the first iteration as the end of each branch has to be located for the backward sweep.

Consider the example network depicted in Figure 4.4. Using the depth-first search, the algorithm will walk the branches in the tree in the following order after it arrives at node n_1 it will walk along b_1 towards n_2. Then b_2 towards n_4 etc. During the backward sweep the same order is applied, but then in reverse.

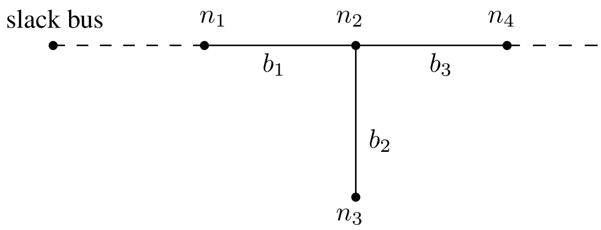

Figure 4.4: *Part of an example network.*

4.3.4 Forward sweep calculations

During the forward sweep the voltage at the nodes is updated using KVL. The voltage for each conductor at a node can be calculated using the voltage level of the previous node and the voltage drop over the cable. The voltage drop over the cable is the result of the current running through the cable and the impedance of the cable. Depending on the direction of the current, the voltage level at the current node is lower or higher than the voltage level of the previous node.

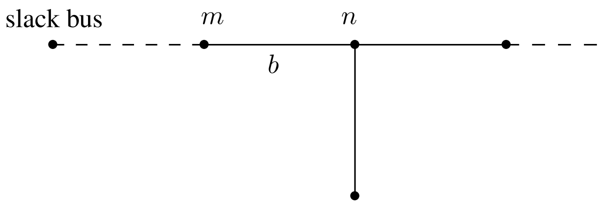

Figure 4.5: *Part of an example network.*

Consider the example network in Figure 4.5 A three-phase cable in typical LV networks consists of four conductors. The three conductors c for line L1, L2 and L3 combined with one for the neutral. If n is the current visited node and m the previous node that is connected to n via branch b, the voltage level $U^k_{c,n}$ at node n for iteration k for conductor c can be calculated as follows:

$$U^k_{c,n} = U^k_{c,m} - U^k_{\mathrm{drop},c,b} \tag{4.7}$$

where $U^k_{\mathrm{drop},c,b}$ is the voltage drop for conductor c over branch b for iteration k. This value can be calculated as follows:

$$U^k_{\mathrm{drop},c,b} = I^{k-1}_{c,b} \times Z_b \tag{4.8}$$

where $I^{k-1}_{c,b}$ is the current running through branch b in conductor c in the previous iteration and Z_b is the impedance of the branch, based on the branch length and the cable properties. The voltage measurement locations are depicted in Figure 4.6. All numbers are complex numbers in these calculations. These calculations have to be done for the three lines (L1, L2 and L3) and the neutral (N) conductors to obtain the voltage levels at the next node. Unless specified differently,

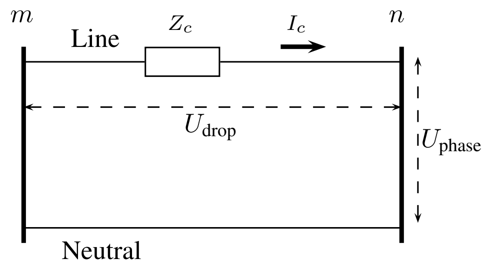

Figure 4.6: *Voltage level measurement to find the voltage drop and the phase voltage.*

the voltage level is measured between the indicated point and ground level of 0 V. The phase voltage level at the node is given by measuring between the L1, L2 or L3 conductor and the neutral conductor at the node itself. The formula for the phase voltage (or line-to-neutral) is then given by:

$$U^k_{\text{phase},n} = U^k_{\text{line},n} - U^k_{\text{neutral},n} \tag{4.9}$$

where $U^k_{\text{line},n}$ and $U^k_{\text{neutral},n}$ are the voltage levels with respect to neutral level at the slack bus.

4.3.5 Backward sweep calculations

The backward sweep calculations update the current flowing through the conductors using KCL. The basic rule is that the sum of all currents at a node equals zero. These are the currents that flow through the branches as well as the currents flowing towards the connected buses.

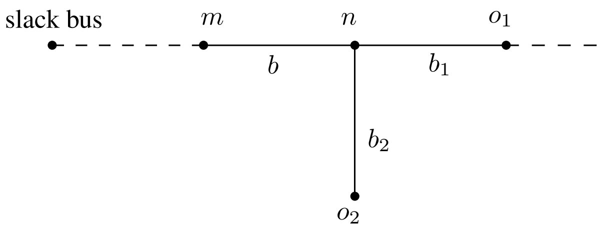

Figure 4.7: *Part of an example network.*

Consider the example network depicted in Figure 4.7. Let d be a vector of all branches connected to node n and a node further away from the slack bus (being b_1, b_2 in the example). And let e be a vector with all PQ buses connected to node n. For the currents running through branch b from node m to n, the currents running through the conductors of the branches that are connected to a node further way from the slack bus must be known. The same is true for the currents running towards the buses I_{bus} connected to the node at a phase. The latter one can be calculated by converting the power consumed by PQ bus p at node n connected to a phase and the phase voltage level obtained in the forward sweep:

$$I^{(k)}_{\text{bus, p}} = \frac{S_{\text{phase},p}}{U^{(k)}_{\text{phase},n}} \tag{4.10}$$

The line (either L1, L2 or L3) current of branch b from node m towards node n (see Figure 4.8) can than be calculated using the following formula:

$$I^{(k)}_{\text{line},b} = \sum I^{(k)}_{\text{line},\forall b \in d} + \sum I^{(k)}_{\text{bus},\forall p \in e} \tag{4.11}$$

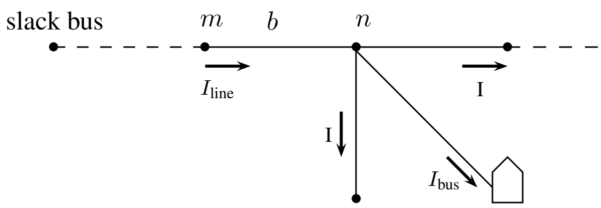

Figure 4.8: *Part of an example network with current flows.*

The current flowing through the neutral of branch b from node n towards node m is equal to the sum of the three line currents:

$$I^{(k)}_{\text{neutral},b} = -(I^{(k)}_{\text{L1},b} + I^{(k)}_{\text{L2},b} + I^{(k)}_{\text{L3},b}) \tag{4.12}$$

Note the negative sign as the current in the neutral conductor flows back.

4.3.6 Convergence criteria

The forward-backward sweep algorithm needs convergence criteria as a stopping condition. In literature, the convergence criteria is usually evaluated on the voltage levels, but current levels could be used as well. To meet the convergence criteria, the phase voltage level on all three phases for all nodes must be stable. This can be done by comparing the phase voltage level U_{phase} at each node n for the current iteration k and the previous iteration $k-1$. The difference must be smaller than a certain error ε:

$$\left| U^{(k)}_{\text{phase},n} - U^{(k-1)}_{\text{phase},n} \right| < \varepsilon, \forall n, \forall \text{phase} \tag{4.13}$$

4.3.7 Cable losses and utilization

To find the total losses, the losses in each cable must be calculated. These losses can be calculated using the current running through the four conductors c of a branch b.

$$P_{\text{loss},c,b} = I_{c,b}^2 \times Z_b \tag{4.14}$$

The total network losses can be calculated by adding all losses for all branches for all conductors. The utilization of a cable can also be calculated to determine the headroom that is left. The nominal current I_{nom} level for a cable is the current that can flow through each conductor.

The utilization η_c of a conductor can then be determined using the current I_c through the conductors:

$$\eta_c = \frac{I_c}{I_{\text{nom},c}} \tag{4.15}$$

The total branch utilization is determined by the maximum utilization value of all conductors in a cable. For the standard model of three phase four conductor cables these are the utilization of the three lines and the neutral:

$$\eta_{\text{cable}} = \max(\eta_{\text{L1}}, \eta_{\text{L2}}, \eta_{\text{L3}}, \eta_{\text{neutral}}) \tag{4.16}$$

4.3.8 Feasibility criteria

To verify whether a planning is supported by the network or not, the load on all network components must be within the limits of those components. The limits set by the regulations also have to be met. Formulas in this section can be used to verify whether limits are violated or not.

First, the line voltage level at all nodes must be within the error margin ζ set by EN 50160, which means a ζ of 23 V for Dutch networks:

$$U_{\text{nom}} - \zeta < U_{\text{phase},n}^{(k)} < U_{\text{nom}} + \zeta, \forall n, \forall \text{phase} \tag{4.17}$$

The current $I_{b,c}$ running through a conductor must be smaller than the maximum current $I_{\max}$ that can run through a conductor. This has to hold for all conductors c for all branches b in iteration k and $k-1$.

$$|I_{b,c}| \leq I_{\max,c}, \forall c, \forall b \tag{4.18}$$

The same is true for the current through all fuses f:

$$|I_{f,c}| \leq I_{\max,f}, \forall c, \forall f \tag{4.19}$$

For transformers, replaced by the slack bus in this model, the power running through each of the three inductive coupling phase windings should be within limits. These loads can be obtained using the currents flowing through the branches connected to the slack bus as given in Equation 4.11 using a virtual branch connected to the slack bus. Using the three obtained currents for the three phase windings, the power can be calculated as follows:

$$S_{\text{phase}} = |I_{\text{phase}} \times U_{\text{phase}}| \tag{4.20}$$

As the transformer is rated for a balanced three phase load, the highest load on one of the windings is the limiting factor that defines the transformer capacity required. Hence we need to find the maximum power consumption:

$$S_{\max} = \max(S_1, S_3, S_3) \tag{4.21}$$

The following condition must then be met to verify that the transformer limit $S_{\text{transformer,limit}}$ is sufficient:

$$|S_{\max}| \times 3 \leq S_{\text{transformer,limit}} \tag{4.22}$$

Keep in mind that components usually do not break after a short period of overloading. However, the consumption levels with the simulations result in average consumption levels for the simulated discrete time interval. Overloading might occur during this time interval as well. This averaging over time intervals cancels out the need for advanced models of effects of short term component overloading.

4.4 Summary

This chapter has shown how a typical Dutch LV network can be modeled. These networks are often designed, or at least operated, radially. This allows to model the network using a tree structure where the branches represent the cables and the nodes represent intersections where loads and generators can be connected. For the network components, such as cables and transformers, the required parameters are given and details on how these can be modeled.

The second part of the chapter has shown how load-flow calculations can be implemented to calculate the voltage levels, currents and cable usage within the network. From the algorithms found in literature, the forward-backward sweep algorithm is described. This algorithm is suitable for the described radial networks and has a low complexity. The basics of the algorithm for a three phase four wire system is given, together with methods to determine whether the network limits are violated or not. The next chapter describes how these algorithms are implemented in the TRIANA simulator.

5 Implementation

To evaluate the effects of demand side management (DSM) in the network, an implementation of the models and the load-flow calculations should be added to an exiting simulator. The modeling parameters and load-flow details as given in the previous section are implemented in the TRIANA simulator. This chapter gives a broad overview of the classes and functions implemented in TRIANA. Details on how to describe a network using configuration files are also given. A stand-alone tool to convert network files from Gaia into a TRIANA network configuration is also written to allow co-simulating the same network with the same energy consumption and production values in both TRIANA and Gaia.

5.1 Implementation in TRIANA

The network models and load-flow calculations are implemented directly into the TRIANA simulator. Just like TRIANA, the implementation is done in the C++ language and makes use of the Qt-library [50]. New classes are created specifically for the network models, calculations in the complex plane and the load-flow calculation. The implemented models and algorithms follow the descriptions presented in the previous section. This section gives a broad overview of these new classes, their purpose and the most important functions.

From the algorithm described in chapter 4 it is easy to create flowchart of this load-flow algorithm. For the software, some additional procedures are added such as a maximum amount of iterations and the storage results. Figure 5.1 shows a flowchart of the fundamentals of the implementation. An UNL diagram of the implemented classes with the most notable functions and their relations is depicted in Figure 5.2. The general data structure follows the tree structure described in the previous chapter. Nodes reference to their childs and branches that connect each other using a list (`QList<QPair<EnergyNode*, Cable*> > nextNodes`). An example of this structure is given in Figure 5.3. The next sections will give more details on the implementation, how the classes interact and what the use is of the most important functions.

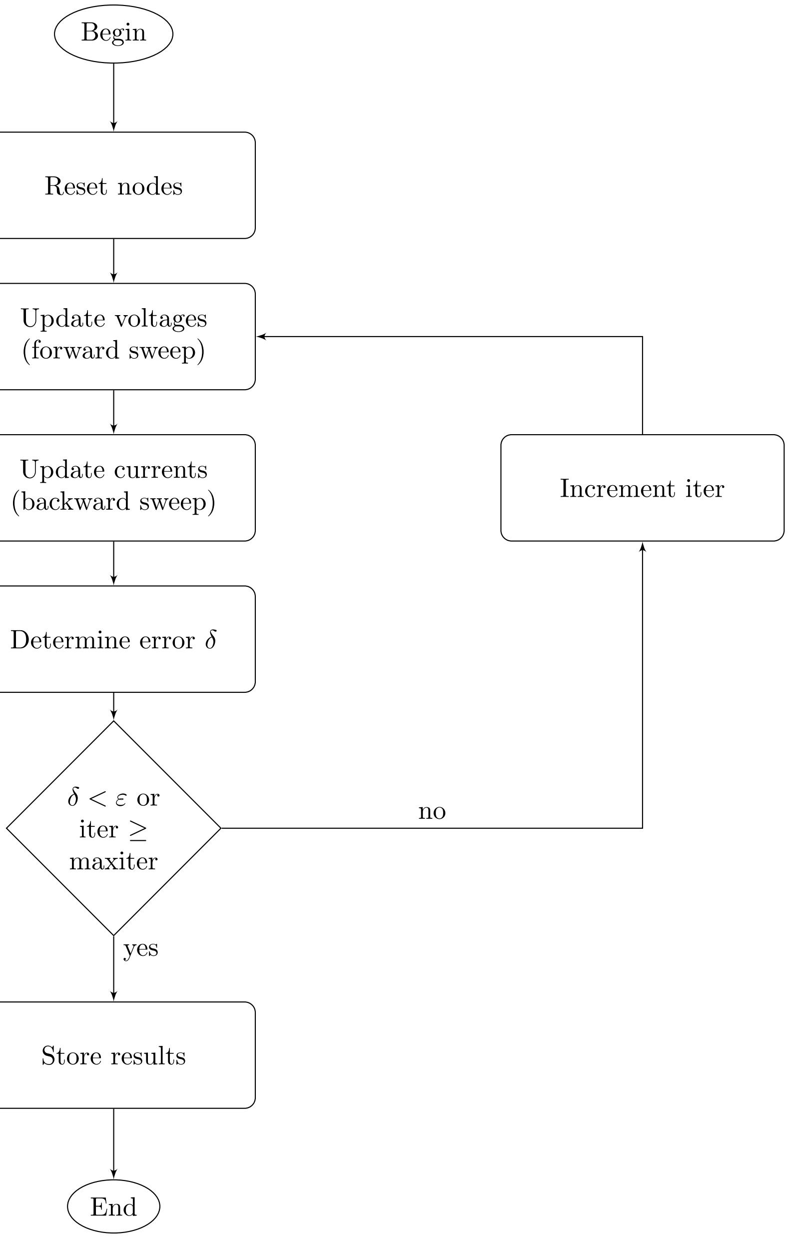

Figure 5.1: *Flowchart of the implemented algorithm.*

5.1.1 Class Loadflow

The `Loadflow` class is the core class for the load-flow calculations. It contains the load-flow algorithm implementation and provides functions to obtain network data resulting from load-flow calculations such as voltage levels, cable usage and violations. Houses in the TRIANA simulator can be mapped to certain nodes in the network.

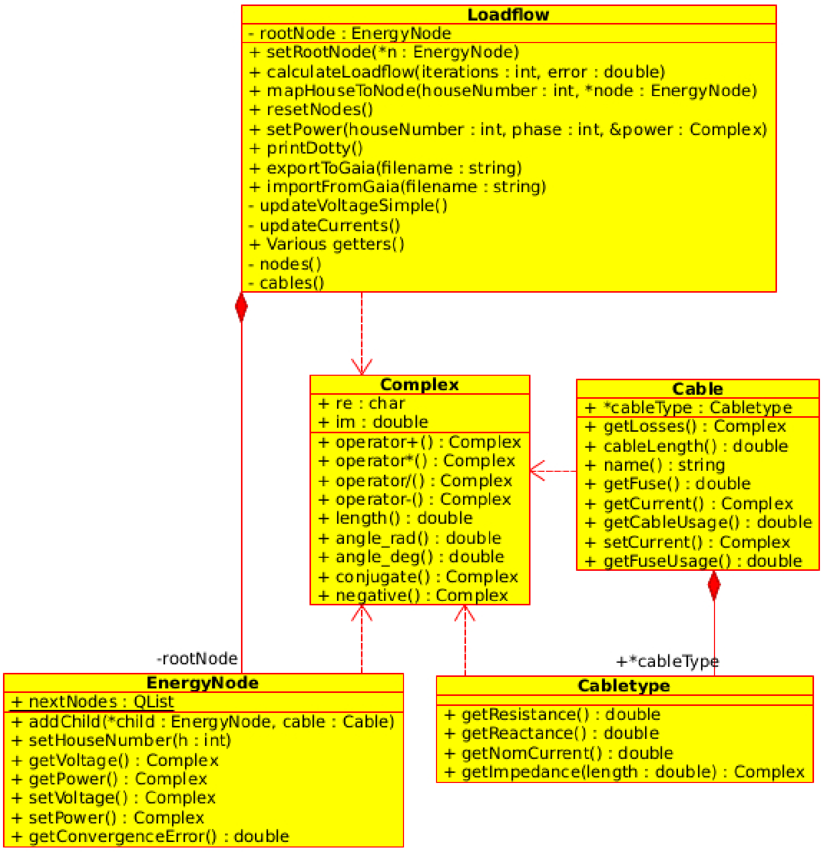

Figure 5.2: *UML diagram of the implemented classes with the most notable functions.*

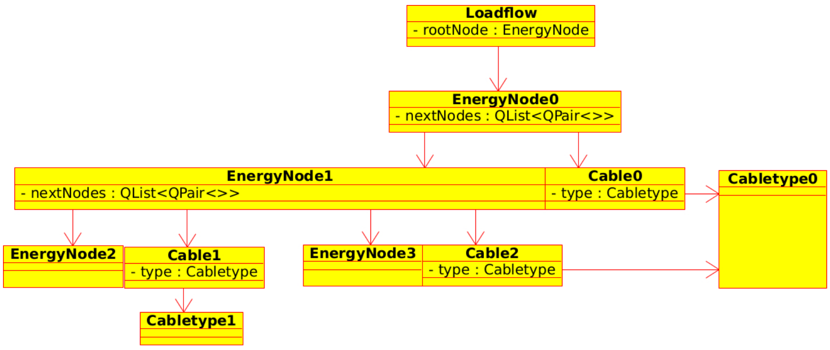

Figure 5.3: *Diagram of the data structure where EnergyNodes reference to their childs using a list.*

Before a load-flow calculation is executed, the consumption or production of all buses in the network must be set using the `setPower(int houseNumber, int phase, Complex & power)` function. After the all consumption and production levels are set in the load-flow class, the calculations can be started using the `calculateLoadflow(int iterations, double error)` function. The maximum number of calculation iterations has to be specified to guarantee that the calculations will stop at a certain moment in case the convergence criteria are not met within reasonable time. The convergence criteria can be set by the error parameter, which represents the error in voltage level between the iterations at each node as stopping criteria.

First a `resetNodes` will be executed to reset all nodes to their respective initial state. During the load-flow calculations the functions `updateVoltageSimple()` and `updateCurrents()` are called respectively for the forward- and backward-sweep. After each forward-backward sweep iteration `checkConvergence()` is called to test for the stopping criteria.

After a load-flow calculation, the data is available via the various public getters. These functions are used in the `Grid` class of TRIANA to create several graphs in the simulation results window. More details on the available data will be given in Section 5.2.2. The instances of nodes and cables of the network can be obtained via the `nodes()` and `cables()` functions.

The `Loadflow` class also provides functions to import and export data to Gaia for comparison. Phase to Phase has provided an application called GaiaCalc to execute load-flow calculations using an input file. More about this GaiaCalc application is given in Section 5.3.6. The function `exportTo-Gaia(QString filename)` can be used to create a file with loads at each household that can be read by GaiaCalc to execute a load-flow calculation. The `importFromGaia(QString filename)` function can be called to obtain the results from the load-flow calculation from GaiaCalc. This function waits until the file is available.

5.1.2 Class EnergyNode

One of the two basic components of the network-structure is the node. This `EnergyNode` class stores the information of voltage levels and production or consumption rates at the node. It also stores information about the voltage level in the previous iteration to test for the convergence criteria.

Also notable is the `QList< QPair<EnergyNode*, Cable*> > nextnodes` list that contains all nodes connected to this node via the listed cable. As the name suggests, these are the next nodes, which are the nodes one branch further away from the slack bus. This can be seen as a linked list and can be exploited to walk quickly through the network for the load-flow calculations.

5.1.3 Class Cable and Cabletype

The branches between the nodes represent the cables which are modeled in the `Cable` and `Cabletype` class. The `Cable` class represents the actual link and holds information about the current running through a branch and the length of the cable. Furthermore, the maximum current that is allowed to run through the branch can be limited further using an optional value for the fuse.

The cable properties are given via the `Cabletype` class, which contains the impedance and capacitance of the cable, together with the nominal current of the cable. There are often only a few types of cables used. The data stored in both classes can be used to determine limits in the links of the network. Currently only a three phase four conductor model is included, but this can be extended with a three phase three conductor model for MV networks.

5.1.4 Class Complex

To do calculations in the complex plane, the class `Complex` is written. It contains the complex operations required for the load-flow calculations and makes use of the operator overloading ability of C++.

5.2 Integration within TRIANA

The implementation of the load-flow calculations and network models does not depend on TRIANA and could be used stand alone. However to evaluate the effects of Demand Side Management (DSM) on the network data has to be exchanged. Steering of devices in TRIANA is done using cost functions where the devices react to the energy price. This results in an aggregated energy consumption level for all devices per house which can be obtained via the energy exchanger. These exchangers correspond with a connection to one of the three phases to the LV network. Therefore there is a mapping with houses and nodes to map all these grid exchangers to the corresponding node in the LV network model. For the load-flow calculations the consumption patterns for each house from the TRIANA planning are set using the `setPower()`. This can be done in both the planning and realtime control phase.

In the current approach, all electrical energy consumption is aggregated to one single consumption value during the planning stage. Therefore, a normal distribution over the three phases is applied where the connected phase is determined using $3 - (n \mod 3)$, with n being the house number. This forms a problem when more steering of devices for specific phases is required. A workaround at this moment might be to map three houses to one node to represent the three phases of one household. This will also allow pricing per phase rather than household, leading to more flexibility to improve power quality and imbalance locally. For the realtime control it is possible to assign the phase(s) to which a household is connected to by using three exchangers.

5.2.1 Feedback to DSM algorithm

After all consumption patterns are set, a load-flow calculation is performed. The resulting voltage level at each house is send as feedback to tweak energy price and give incentives to improve the voltage level. Price based steering is only done when the voltage level is not within 5V of the nominal voltage level of 230V. A random number between zero and one (p) is generated to decide whether the price has to be changed or not. This prevents that prices for all houses are increased which can cause overshoots in the steering and oscillating behaviour. The chance that prices change and the amount with which the price changes depends on the deviation from the nominal voltage level and increases with a larger deviation. The following formula is used to calculate with which amount the price will be changed c_{change}:

$$c_{\text{change}} = k * \left(\frac{230 - U}{20}\right) * \left\lceil \left|\frac{230 - U}{20}\right| - p \right\rceil \tag{5.1}$$

with k being a constant multiplier which is set to 75 units in the simulations. The initial price level is 1000 units. This integration is found in the `sendPrices(const QList<QList<int> > &prices)` function in `FleetController.cpp`. The load-flow feedback is used during each planning iteration.

5.2.2 Graphs and data

To evaluate the power quality of a planning on the simulated network, graphs and statistics are provided within TRIANA. The statistics provide information about the number of violations, minimum, maximum and mean voltage levels of the network. It also provides information about worst-case cable usage and network transportation losses.

Various graphs are also provided. Voltage levels, currents flowing and cable usage graphs are available for each individual node and cable. Summarizing graphs are also available to view minimum, maximum and mean voltage levels per interval and in sorted form. The same type of graphs are available for currents and cable usage. Additional information about energy import or export per phase is also available. Performance in number of forward-backward sweep iterations required to achieve convergence is also given.

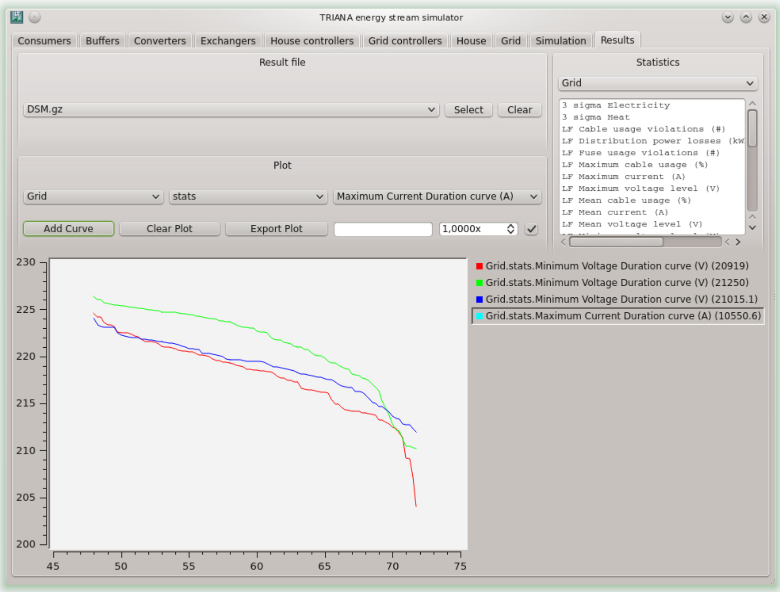

Figure 5.4: *New graphs in the TRIANA result view.*

Information for the graphs is stored in the `Loadflow` class and added to the existing `StorageManager` in `Grid.cpp` after each simulation interval and simulation day. Simulation results are kept over multiple planning intervals and only discarded after a complete day is simulated using the `resetStatistics()` function.

5.3 Network configuration file and tools

Before a network can be simulated, its layout and properties have to be supplied. Means to supply network configurations are made available by using ini configuration files. This type of configuration files is already used within TRIANA for all other configurations. This section details how to insert a network using these configuration files. Tools are made available as well to generate TRIANA network configuration files from Gaia network files.

The configuration structure shows similarities to the structure of classes. Nodes, cables and cabletypes are specified individually in the configuration file. Additionally there is a general section to indicate how much nodes, cables and cabletypes are specified. Examples of these configuration sections are given in the following subsections. A valid network configuration has to be provided. This means unique names for components, no loops and no unused or unconnected components.

5.3.1 Cabletypes

The cabletype section defines the cable properties for the used cables. The parameters are grouped in a section, denoted by square brackets. Each section should start with "Cabletype", followed by a number without a space. Numbering must start with zero, the second must be one, and so on. So defining "Cabletype0" and "Cabletype1" will be valid. Cable properties such as resistance, reactance, capacitance and nominal current must be specified. A name has to be given as well. An example is given in code snippet 5.1.

```
[Cabletype0]
name=4*150 Al + As5
resistance=0.235
reactance=0.079
capacitor=0.72
nomCurrent=225
```

Code 5.1: *Cabletype section configuration snippet*

In the configuration, the parameters are given in the following units:

- Resistance in Ω per kilometer cable
- Reactance in Ω per kilometer cable
- Capacitance in μF per kilometer cable
- nominal current in A

5.3.2 Nodes

Nodes are created using the "Node" section. Numbering of the section is done in the same way as for the Cabletypes. A name has to be specified. Optional are the house numbers to map houses to nodes. The first node "Node0" will be the root node of the network and be considered as the slack bus of the network. A configuration snippet is found in snippet 5.2.

```
[Node0]
name=transformer

[Node1]
name=node1
connectedHouse=1
```

Code 5.2: *Node section configuration snippet*

Note that the `connectedHouse` field can only contain a numerical value no less than one.

5.3.3 Cables

Cables are created using the "Cable" section. The same numbering requirements apply here. Again a name has to be specified for a cable. Obviously, a cable connects two nodes, a `nodeFrom` and a `nodeTo` are required together with the length of the cable. A reference to the cabletype for cable properties has to be made as well. An example is given in code snippet 5.3

```
[Cable0]
name=cable0
cableType=0
nodeFrom=0
nodeTo=1
length=10
fuse=250
```

Code 5.3: *Cable section configuration snippet*

Where the length is given in meters. Ofcourse the `nodeFrom` and `nodeTo` fields must reference to existing nodes and the `cableType` field must reference to an existing cabletype in the configuration.

The fuse is an optional limit to the current that can flow through a branch. If a fuse is specified, the maximum allowed current will be equal to the lowest allowed current, which is either the fuse limitation or the cable ampacity.

5.3.4 General

The general section is required to give the amount of nodes, cables and cabletypes in the configuration. This is information that cannot be easily extracted from the ini file by the parser and thus has to be supplied. An example is shown in code snippet 5.4

```
[General]
numCableTypes=1
numNodes=2
numCables=1
```

Code 5.4: *General section configuration snippet*

5.3.5 Parser

The parser reads the configuration file and creates all objects in the software that represent the network. The parser checks for various errors in the configuration file including unused cables and nodes. Invalid configuration files will be rejected to avoid simulations which may contain a structure that was not intended. Cables with a reversed `nodeFrom` and `nodeTo` fields are fixed automatically. Checks are also build in for components with duplicate names and undefined elements. The parser is found in the `createEnergyFlowModel()` function in `Grid.cpp`.

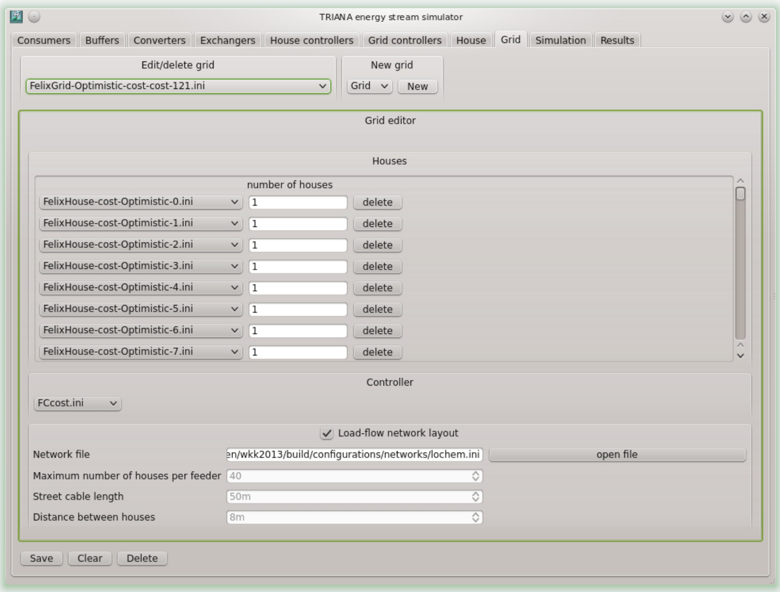

Figure 5.5: *TRIANA configuration with addition of load-flow settings.*

A way to generate a synthetic network based on standard network design practices is also available in this function. This will give insight in effects of certain planning strategies on a typical residential network. The code uses the number of houses as a parameters and will divide these houses over several feeders, with each containing about 40 households. The number of houses per feeder can also be overruled by the settings. Furthermore, the distance between the houses can be set, just like the distance between the first house of a feeder and the transformer.

New user interface objects are added to enable the use of load-flow calculations by providing either a configuration file or defining a synthetic network.

5.3.6 Gaia integration

To enable co-simulation with the implementation in TRIANA and Phase to Phase Gaia, a tool called Gaia2Triana (see Figure 5.6) is written to convert configuration files. This makes importing an existing network easier and also prevents errors in converting network structures. The tool allows to convert a complete network with all cable properties using four comma separated value (csv) files exported by Gaia. The names of all cables and nodes are also preserved. The same is true for names of household connections, which makes it easy to map each house to a model of that house in TRIANA.

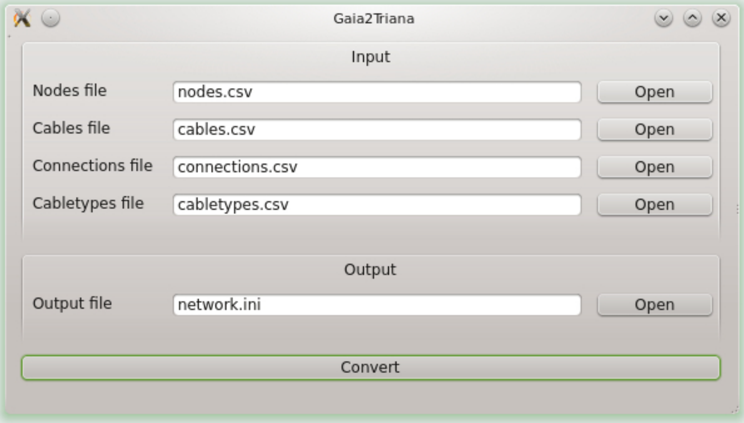

Figure 5.6: *Gaia2Triana conversion tool.*

However, there are some limitations when converting a network:

- Unique names for all cables, connection and nodes.
- No unused nodes
- No unused cables
- No loops
- Start of the network must be called "transformer"
- House numbering must start at one and may not skip a number
- House numbering must be in the format "house1"
- Only one household per node

These requirements are needed to create a valid network in TRIANA. The parser will check for these requirements and give errors when needed. These errors must be resolved in Gaia or the configuration file. The former method is adviced to allow correct co-simulation.

Since the native Gaia network configuration files are hard to understand, the tool works with comma separated files using semicolons. The network structure can be exported to Excel. Three comma separated files need to be saved: the list of connections, list of cables and list of nodes. A file with all cable properties is also extracted from Gaia and provided as default database. A new list with updated cabletypes can be imported by saving a comma separated file of the cable tab in the Types.xls file of Gaia.

For co-simulation, Phase to Phase has provided a program called `GaiaCalc.exe`. It can be used to simulate the same network with the same loads as in TRIANA. Before co-simulation can be executed, the network file has to be opened and the software must be set to "waiting for file" state. The software will execute a load-flow calculation when a file called `belastingen.txt` is written in the same folder as the executable. After calculations are done, a file `loadflow.txt` is saved in the same folder, containing a space separated file with the voltage levels and currents.

Functions in TRIANA are written to create the `belastingen.txt` file. This is the `exportTo-Gaia(QString filename)` function. Directly after exporting, the `importFromGaia(QString filename)` function can be called which waits until the results from GaiaCalc are available. The results are parsed and stored in TRIANA. The results of GaiaCalc contain the voltage levels and currents only. Information about phase angles is not available. The information is thus limited, but can be used to verify whether voltage levels and cable usage are indeed violated or not. It also allows to compare both results. All the values are given per node and cable using the unique names, hence the requirement to use unique names for each cable, node and household.

5.3.7 Tools

The `mkResults.py` script has been extended to export all new data graphs resulting from load-flow calculations as comma seperated files. To support simulations with the Felix-case [17] better, additions to alter connection of devices per phase have been made easier. These tools are available for use with simulations.

5.4 Summary

This chapter has given a brief overview about how the models and load-flow algorithm presented in the previous chapter are implemented and incorporated TRIANA and Gaia. Data is exchanged via various set and get functions that make it possible to pass through energy consumption values to simulate the effects of the network. The load-flow information is used as feedback to improve voltage levels in the network.

A way to provide a network structure is offered in the form of ini-files, just like the rest of TRIANA. The structure of these network configuration files show similarities to those of other simulators to make conversion easier. A tool to convert files from Gaia is already available. The parser checks various structure problems such as loops and unused cables and nodes. The next chapter will show how the implementation performs.

6 Simulations

This chapter covers analysis of simulation results for analysis on the performance of the load-flow calculations and the integration of load-flow feedback into DSM. The first section contains simulations to evaluate the performance and accuracy of the load-flow implementation follows. Two use cases are used to compare the implemented load-flow algorithm with results from Gaia. Timing measurements are also given to evaluate the performance in computational time required. This chapter ends with the conclusions that can be drawn from these simulations.

The second section will outline the different networks and models that were used for the simulations. To networks, a synthetic network and an existing networks in Lochem are used. These networks all use the optimistic Felix-case [17] models for the houses as given in chapter 4. One day during the winter is simulated using three settings: no control, DSM and DSM with load-flow feedback (DSM+LF).. Resulting voltage levels, cable usage and electricity import figures and numbers are presented and discussed in these sections.

For the simulations, a modified version of the Felix use-case with 400 houses is used [17]. This use case has different penetrations of smart appliances, DG, electric vehicles and heat pumps as presented in section 4.1.4. Each household is connected to one phase of the grid via one grid exchanger. A normal distribution of houses over the phases is applied. Since the model has no data about reactive power, a power factor of 0.9 is used.

6.1 Implementation performance evaluation

This part consists of two use-cases. The first is a synthetic setup to evaluate the accuracy of the initial implementation. Additionally a Raspberry Pi is used to evaluate the performance on an embedded platform. The second evaluation is done on the Lochem use-case where a complete day is co-simulated with Gaia.

6.1.1 Performance evaluation

A comparison with load-flow results between the implementation presented and LV network simulator Gaia is conducted using a test case with 40 households. These 40 households are connected to one feeder and is a commonly found number of households connected to a feeder. A residential area might have multiple of these feeders originating from the MV/LV transformer.

The distribution of the households over the three phases is normally using $((n) \mod 3)+1$, where n is the housenumber, ranging from 0 to 39. For each household the production or consumption level is set. These levels range from -3000W (indicating production) to 4000W. This model is entered in both the implemented load-flow algorithm and the LV grid simulator Gaia.

The values converge after three iterations for this case. The error ζ is set to 0.001. The calculated values by the implementation show a standard deviation of 0.52V and a mean deviation of 0.08V compared to the values obtained from Gaia. The maximum voltage deviation compared to Gaia is 1.19V. The mean deviation of the current is 0.02A with a standard deviation of 0.09A. These results show that the implemented load-flow calculations are accurate enough for integration into DSM during the planning stage, where prediction errors in load profiles can also occur.

A Raspberry Pi is used to perform analysis on the required computation time of the implemented load-flow algorithm. The same network structure of 40 houses was used. Then the number of houses is increased in steps of 40 by adding more of these feeders. Since these are independent of each other, it is expected that the number of iterations required do not increase and the computation time does increase linearly. Simulation show that this is indeed the case. For a load-flow calculation with 400 households, the Raspberry Pi took 69ms.

A second performance evaluation is done using the Lochem network with the same configuration as used for the other Lochem simulations. The convergence error ϵ is set to 0.00001. The voltage levels converge within ten iterations for all 96 intervals and take 1.3ms on one processor core of an Intel Core i5 430M processor running at 2.26GHz. The calculated values by the implementation show a standard deviation of 0.50V and a mean deviation of 0.12V compared to the values obtained from Gaia. The maximum voltage deviation compared to Gaia was 1.31V. The results from co-simulation with DSM+LF settings are shown in Figure 6.1. The mean deviation of the current is 0.00A with a standard deviation of 0.10A in this case. These results are shown in Figure 6.2..

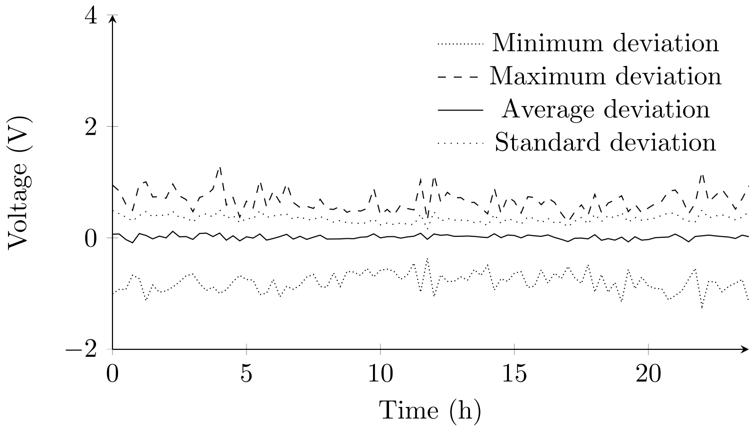

Figure 6.1: *Comparison of voltage level results from the TRIANA implementation with results from Gaia.*

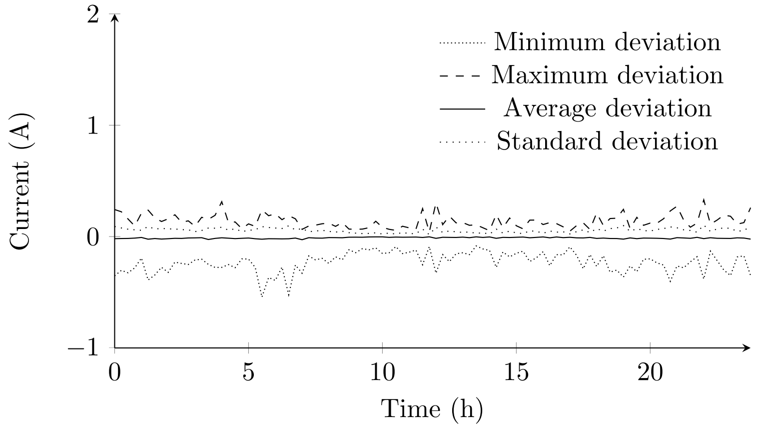

Figure 6.2: *Comparison of resulting currents from the TRIANA implementation with results from Gaia.*

These results show that the implemented load-flow calculations are accurate enough for integration into DSM. Other parameters not taken into account in both load-flow algorithms, such as the ground temperature, can also lead to errors of this magnitude. A different temperature results in slightly changed parameters, which can result in a 2 V higher or lower voltage level according to [60].

6.2 Synthetic network use-case

The LV network consists of ten feeders with 40 houses connected to each feeder. The distance between the households is 12m and the distance from the slack-bus to the first house of a feeder is 87m. The cross-section of the feeder cable decreases along the feeder distance in the network. The feeder at the first 20 households is an aluminum (Al) cable with a cross-section of 150mm (Al150). For the next ten houses this is 95mm (Al95) and the last ten houses 50mm (Al50). The properties of these cables are given in Table 6.1. The network is depicted in Figure 6.3. This is a general network structure for a residential area.

Cable type	**A (mm^2)**	**R (Ω/km)**	**X (Ω/km)**	$I_{\mathbf{nom}}$ (A)
Al150	150	0.206	0.079	230
Al95	95	0.320	0.082	175
Al50	50	0.641	0.085	115

Table 6.1: *Cable properties*

Figure 6.4 shows the worst-case voltage levels for every time interval, ordered from high to low. DSM+LF improves the worst-case voltage levels, but still violates the EN 50160 in one interval. Only one interval violated the EN 50160, in which enough room was left to plan differently to avoid these problems with more sophisticated implementations. This problem occurred with too much devices activated in one time interval, whereas the time interval before and after show a lower load. A better spreading of activations over these time intervals could have solved this

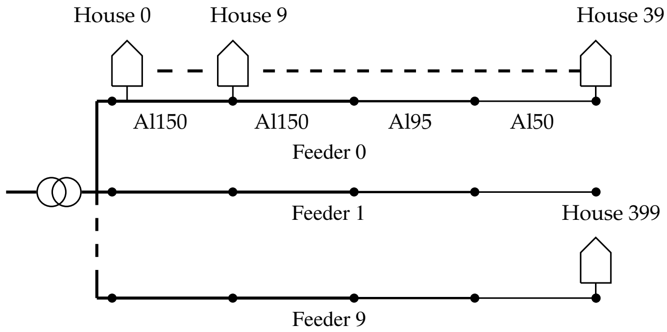

Figure 6.3: *Use-case network with 400 houses over ten feeders to evaluate the performance of DSM+LF.*

issue. Using higher prices was not a solution, however. Too high prices lead to postponing too much devices until they cannot postpone any longer due to deadline constraints. This limits the planning freedom in later intervals in which the devices switch on regardless of the price, leading to more severe voltage problems.

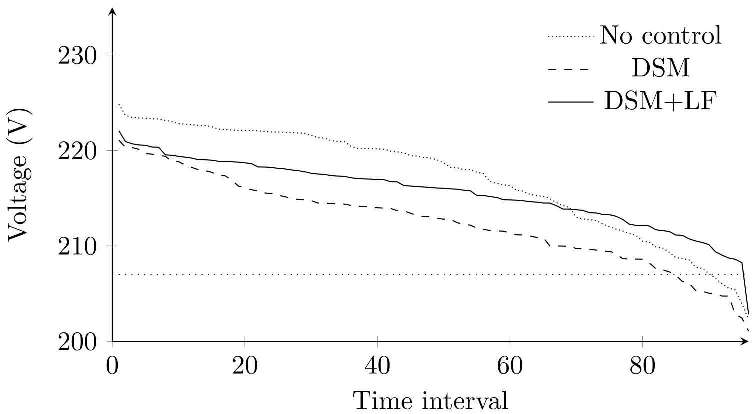

Figure 6.4: *Voltage level duration curve of the worst-case voltage levels in the simulated network. The dotted line at* 207 V *shows the minimum level allowed by the EN 50160.*

The mean voltage level (U_{mean} and U_{stdev}) are comparable with all three settings. Figure 6.5 shows the mean voltage of all nodes for every time interval as a duration curve. Peak-shaving strategies distribute the mean voltage level more evenly over the whole day, where no control shows more diversity. The simulation without control shows the worst results with a mean voltage level of 219.9V in one inter. Using DSM results in an mean voltage level of 224.1V whereas DSM+LF achieves an mean voltage level of 224.4V (see Table 6.2).

Also the worst-case cable usage shows large improvements as shown in Fig. 6.6. Without planning, one cable got overloaded slightly, whilst DSM reduces the worst-case usage to 85% due to peak-shaving. Adding load-flow information reduces the worst-case cable usage to 69%.

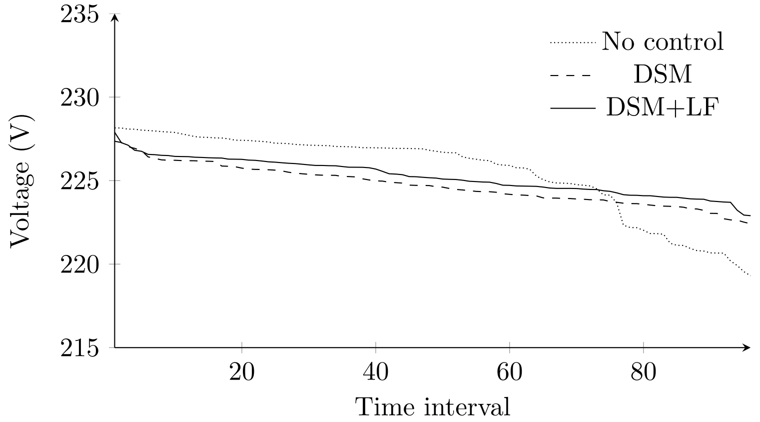

Figure 6.5: *Mean voltage level duration curve of the worst-case voltage levels in the simulated network.*

	$U_{\mathbf{mean}}$	$U_{\mathbf{stdev}}$	$U_{\mathbf{mean,wc}}$	$U_{\mathbf{stdev,wc}}$	$\mathbf{3}\sigma$ (W)
None	225.5	2.66	219.9	3.58	676407
DSM	224.7	2.54	224.1	2.66	216217
DSM+LF	225.2	2.18	224.4	2.55	217068

Table 6.2: *Simulated voltage (in V) levels and consumption flattening results*

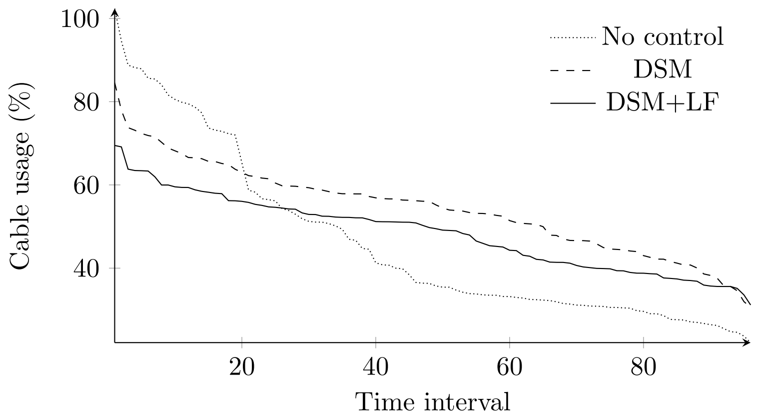

Figure 6.6: *Cable usage duration curve of the worst-case cable usage.*

Next to these improvements, the addition of load-flow calculation feedback does not significantly affect peak-shaving performance. This performance is shown in Figure 6.7 using an electricity load duration curve. The difference in the 3σ values is only 149 W.

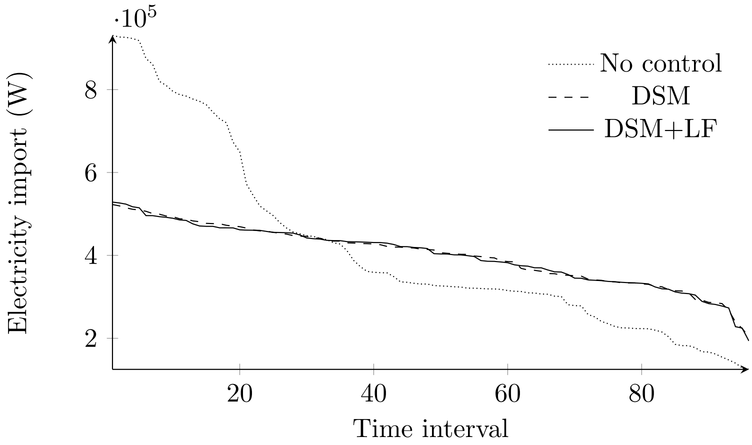

Figure 6.7: *Electricity duration curve.*

The results show that flattening the consumption pattern using DSM without load-flow information does not lead to significant savings in required network capacity or improved voltage levels. Instead, the voltage levels get worse. Using the load-flow feedback removes most of these severe issues, resulting in a better voltage level during most intervals and also lowers the maximum cable load significantly. As the DSM planning is taken as a starting point, the peak-shaving performance is comparable to that without load-flow feedback.

6.3 Lochem

Next an actual network is simulated, the network of Lochem. As this network contains 121 households, the number of modeled houses is reduced to this number. The network used for the simulations is a part of an existing Dutch LV network in the town of Lochem (see Figure 6.8). The network files are provided by Dutch distribution system operator Alliander and consists of three feeders with a total of 121 households. The length of the feeders is approximately 400m and the feeder thickness decreases over the feeder length. Aluminum cables with cross sections (A) of 150mm^2 (AL150), 95mm^2 (Al95) and 50mm^2 (Al50) are used for the feeder. Each feeder contains about 40 households connected using thinner aluminum cables with a cross section of 16mm^2 (Al16). The properties of these cables are given in table 6.3.

Cable type	**A (mm²)**	**R (Ω/km)**	**X (Ω/km)**	$I_{\mathbf{nom}}$ (A)
Al150	150	0.206	0.079	230
Al95	95	0.320	0.082	175
Al50	50	0.641	0.085	115
Al16	16	1.91	0.096	60

Table 6.3: *Cable properties*

Figure 6.8: *A network model of a residential area in Lochem from Gaia projected on the satellite images from Google Maps.*

The simulation shows comparable results to the synthetic network. The worst-case voltage levels U_{wc} become worse with DSM compared to simulations without control as shown in Figure 6.9. Eight voltage level violations were reported with DSM, where no control resulted in zero violations. DSM+LF improves the voltage levels and resolves the violations introduced with DSM. The mean voltage level of all nodes during the worst-case time interval also shows improvements. Without control a mean voltage level of 223.9V is obtained. Using DSM results in a mean voltage level of 226.0V whereas DSM+LF achieves an mean voltage level of 226.3V.

	$U_{\mathbf{mean}}$ **(V)**	$U_{\mathbf{wc}}$ **(V)**	$\eta_{\mathbf{wc}}$ **(%)**	$\mathbf{3}\sigma$ (W)
No control	227.3	210	93.3	203640
DSM	227.2	204	88.5	66111
DSM+LF	227.2	212	66.3	68179

Table 6.4: *Simulated voltage levels and consumption flattening results*

Using three dimensional plots, the voltage level over the whole network can be evaluated. To obtain such a plot, the voltage levels for each household and each time interval are stored in a matrix, with households being the columns and the time intervals in the rows. Then the voltage levels are first sorted from high to low per column. Then this dataset is sorted from high to low using the complete rows. This results in a sorted surface of the network.

Figure 6.10 shows the voltage levels in the network during the simulated day. It is clear that the peak consumption results in a lower voltage in the whole network. With DSM, some households get a significant lower voltage level as shown in Figure 6.11. The DSM+LF method in Figure 6.12 shows a more evenly distributed voltage level over all houses for all time intervals resulting in an overall flatter surface.

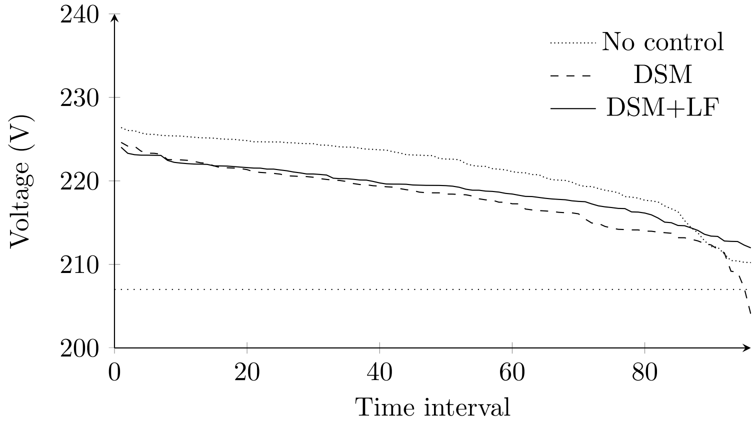

Figure 6.9: *Voltage level duration curve of the worst-case voltage levels in the simulated network. The dotted line at 207 V shows the minimum level allowed by the EN 50160.*

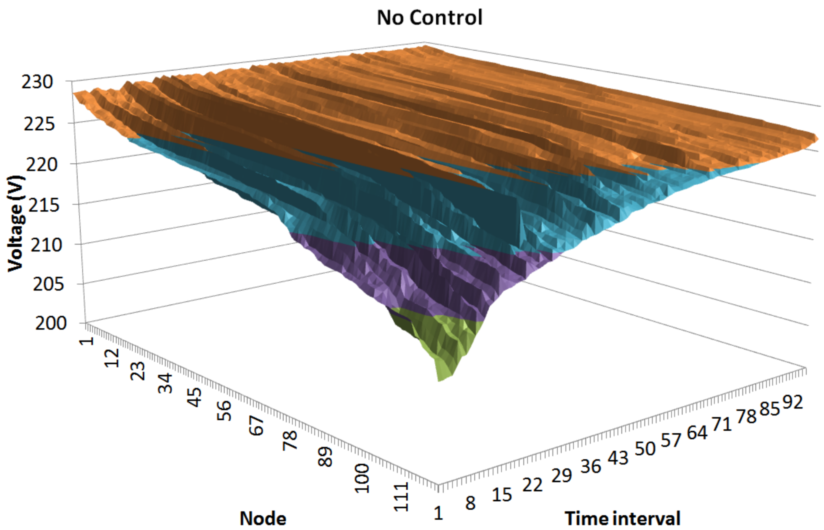

Figure 6.10: *Surface plot of voltage levels at the houses for all time intervals without control.*

Also the worst-case cable usage (η_{wc}) shows large improvements as shown in Figure 6.13. Without planning, the currents in one cable reached 93.3% of the capacity, whilst DSM reduces the worst-case usage to 88.5% due to peak-shaving. Adding load-flow information reduces the worst-case cable usage to 66.3%.

Next to these improvements, the addition of load-flow calculation feedback does not significantly affect peak shaving performance. This performance is measured in 3σ load deviation from the average energy consumption over all simulation intervals (see Table 6.4 and Figure 6.14).

These results do not mean that transformers could be dimensioned based on the highest electricity import values. The transformer capacity is given for a balanced load on all three phases. This is not necessarily the case for unbalanced loads that can occur in LV networks. When comparing

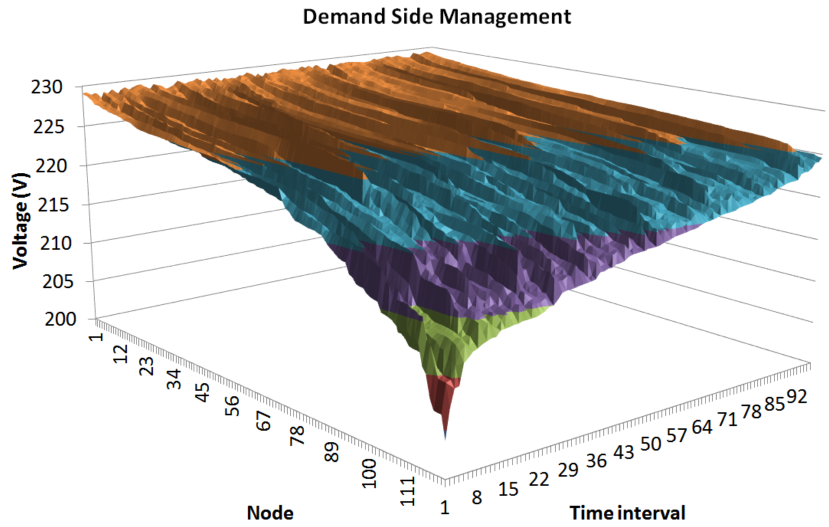

Figure 6.11: *Surface plot of voltage levels at the houses for all time intervals with DSM*

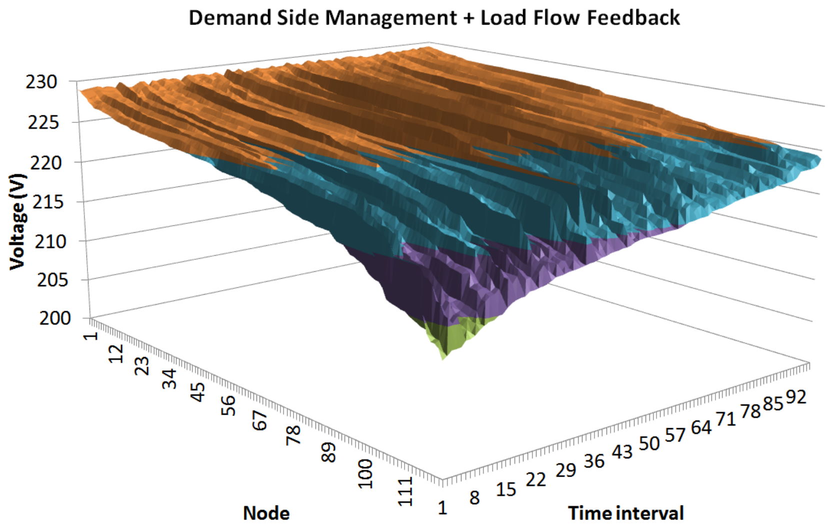

Figure 6.12: *Surface plot of voltage levels at the houses for all time intervals with DSM+LF.*

the difference in power between the phase with the highest load and the lowest load at the transformer, the simulation results show that the balance is best without control (see Figure 6.15). In the worst-case, DSM shows an imbalance that is twice as much, while the energy imported by the network is much lower. Using DSM+LF improves this figure slightly.

The main cause for this problem is that the DSM method does not take the network structure into account during planning, resulting in an unbalanced distribution of active and inactive devices over the physical network. The current load-flow feedback method seems to have only limited effect to improve this balance. The next chapter covers more analysis on this problem and does

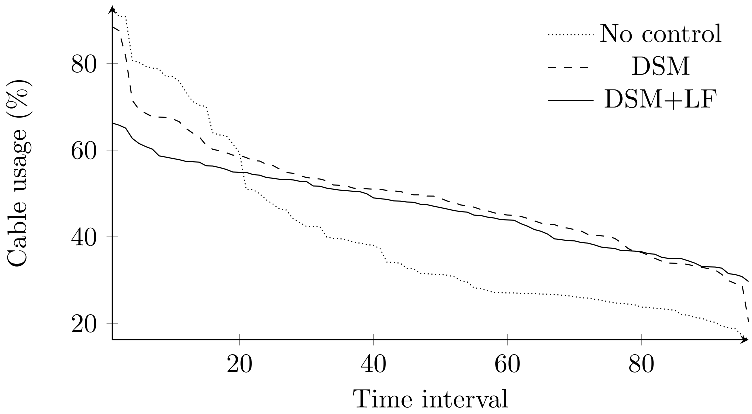

Figure 6.13: *Cable usage duration curve of the worst-case cable usage.*

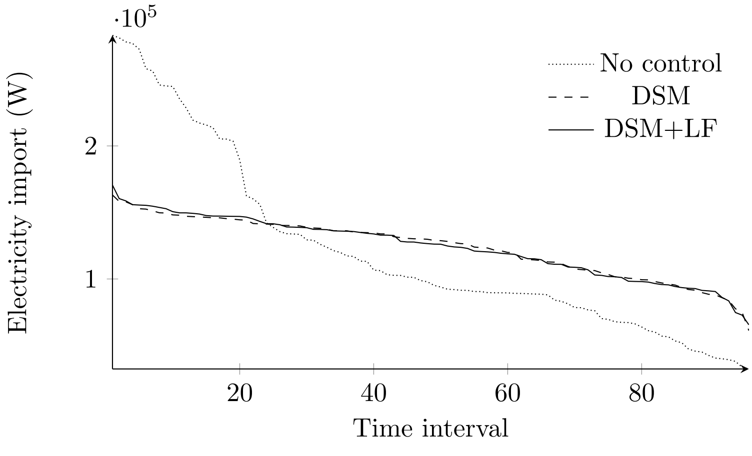

Figure 6.14: *Electricity duration curve.*

suggestions on future work that might be able to solve this balancing problem.

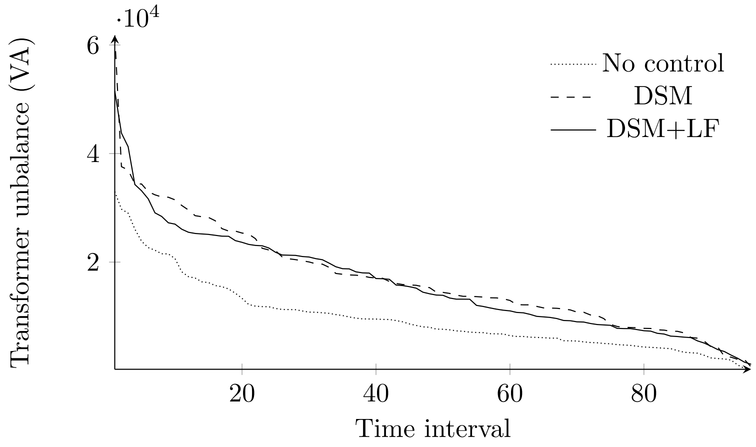

Figure 6.15: *Transformer inbalance duration curve.*

With DSM, one of the feeders originating from the transformer shows a current of 198A on phase one, where the third phase shows a current of 48A. Further analysis on this imbalance problem problem and its consequences are done in the next chapter.

Overall the Lochem case shows the same results as the synthetic simulation. This is no surprise since the basic network properties are equal. Both contain around 40 households per feeder and have a decreasing conductor cross section over the feeder length. For future generic simulations to evaluate DSM performance, the synthetic network can be used to simulate a realistic network. Both simulations show that there is room for improvement in the voltage levels and reduction of component usage when using network information in DSM. It remains the question how much more improvement is possible without sacrificing peak-shaving performance, which is left for future work.

6.3.1 Simulations with more photovoltaic cells

The Felix-case is altered a little bit to simulate the effects with a larger penetration of photovoltaic cells in the residential area of Lochem. Instead of a penetration of 30%, a simulations with 50% penetration of photovoltaic cells is used. For this simulation, a day during the summer is simulated to see the effects of a large feed-in by PV in the area.

The simulation results are summarized in Table 6.5. As could be expected, the energy production by PV, which peaked at an average of 2.9kW per household in the afternoon, leads to voltage rises. For all three strategies, no network violations occur. This time, DSM+LF performs worst of the three on the voltage levels, having both the lowest and highest voltage level reported, whilst the best voltage levels are achieved without control. Figure 6.16 shows the duration curve of worst-case minimum voltage levels. From this curve it is clear that the DSM+LF method improves the voltage levels over DSM during most time intervals. Only in the worst-case interval the minimum voltage level drops rapidly, resulting in the worse minimum voltage level obtained.

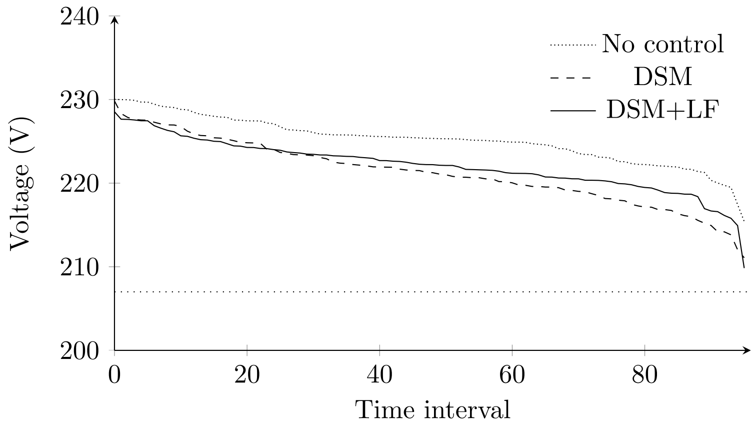

Figure 6.16: *Voltage level duration curve of the worst-case voltage levels in the simulated network with PV. The dotted line at* 207 *V shows the minimum level allowed by the EN 50160.*

The lowest worst-case cable usage values are also found without control. Notably is also the peak-shaving performance where DSM+LF outperforms DSM in this simulation. This result is caused by one peak in the consumption pattern. This peak of 214kW even exceeds the peak energy import of 146kW achieved without control.

	$U_{\mathbf{min}}$ (V)	$U_{\mathbf{max}}$ (V)	$\eta_{\mathbf{wc}}$ (%)	3σ (W)
No Control	215.4	238.2	55.2	255402
DSM	211.1	244.5	72.71	195277
DSM+LF	209.8	244.6	60.6	186496

Table 6.5: *Simulation results with 50% penetration of PV during the summer.*

The results show again that DSM does not necessarily lead to reduction in cable capacity and voltage levels. The implemented load-flow information feedback is not performing better in all cases as well. Except for the peak-shaving performance, the DSM strategies are significantly outperformed by no control.

6.4 Conclusions

These results show that DSM decreases the worst-case voltage level and introduces voltage violations due to the lack of network information. The DSM+LF implementation shows a significant improvement in both voltage levels and cable usage compared to DSM and no control, without significantly reducing the peak-shaving performance. Enough flexibility is found in the networks to achieve this result.

However, these results are achieved by applying feedback after the device planning is already made. The planning does not use any network information. Therefore planning limits the freedom left for the load-flow feedback to improve the power quality in the network. This is also visible in the transformer unbalance. Reducing the overall load peaks does not necessarily mean a better power quality in the network as shown in the simulations. Overall DSM does improve the average values for each interval, but at the cost of worse worst-case values. The DSM+LF method tries to reduce these worst-case peaks.

From these results it also seems that thinner cables could be used when using DSM+LF. This is only partly true. Thinner cross-sections also mean a higher resistance and thus larger voltage drops or increases in the network. The minimum voltage level shown in DSM+LF does not leave much room for further voltage drops when applying a safety margin. Therefore it would not be advisable to use thinner conductors.

The performance analysis show that the algorithm is accurate enough for DSM practices as it is always good to keep a margin to compensate for forecasting and planning errors. Cable properties are also not completely exact due wearing or the temperature. The implementation is also fast, which makes it applicable for use over multiple iterations.

6.5 Summary

This chapter has presented the results from load-flow simulations in three use-cases. The results show that voltage levels are increased with load-flow feedback and that cable usage is improved. However, not all figures are improved with the implemented solution, but room for improvement is left. The imbalance in load on the transformer is increased. The accurateness of the load-flow algorithm is good enough for DSM, considering error margins and incompleteness of information. The implementation is also very fast, which makes it useful for on-line simulations.

7

Analysis

This chapter does further analysis on the simulation results from the Lochem use-case network to see how voltage levels could be improved even further. Some other planning and steering solutions are also briefly evaluated. Short comings in the current implementations of TRIANA and the load-flow implementation and discussion how these possibly could be tackled in future work are also given. The same holds for available data of networks. This results in recommendations for future implementations of TRIANA and network design and documentation practices.

7.1 Network balance analysis

The simulations from the Lochem use-case show significant improvement in voltage levels when using-load-flow feedback. But, as seen, the unbalance on the transformer increases. Results also show high currents running through the neutral line, which also indicate unbalance. When a network is in balance, the current through the neutral line is zero. For the simulations with DSM, a maximum of 146 A is measured in the neutral line. For DSM+LF this is 108 A and no control performs even better with 85 A. These results are shown in Figure 7.1.

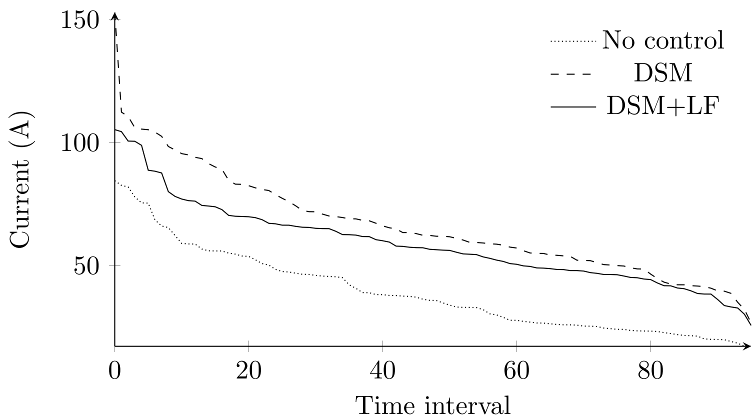

Figure 7.1: *Current duration curve for currents in the neutral conductor.*

A high current through the neutral line means both additional energy losses and an additional voltage drop. The additional voltage drop over the neutral line causes lower voltage levels in one phase whilst other phases will see an increase in voltage. However, the voltage drop will appear in the phase with the highest load, worsening the minimum voltage level seen over the three phases. With better balance, smaller transformers can be used as well as these are rated for a balanced load. The resulting unbalance between the phase with the highest load and the one lowest load using DSM is 60kVA. When looking at the maximum load on one of the three phases, a load of 90kVA is found, meaning that a transformer with a rating of at least 270kVA. However, the maximum combined load is only 182kVA, which would require a 182kVA rated transformer for these 121 houses for the simulated day with perfect balance.

Simulations without control show a maximum load of 121kVA on one phase, resulting in a required transformer rating of 363kVA. Note that these are the ratings only based on the power consumption figures, discarding problems related to harmonics. These would still require a higher transformer rating. Furthermore, complete balance in the LV network will hardly occur in real life. In the end, DSM still performs better on this point. However, due to the imbalance, the reduction in load on one of the transformer coils is only 26% compared to no control, whereas the peak consumption was reduced by 42% as seen in Chapter 6.

The scatter plot in Figure 7.2 shows the relation between maximum current flowing in the neutral lines and minimum voltage level during the simulation intervals. The current flowing in the neutral line seems to correlate quite well with the voltage level. The scatter plot shown in Figure 7.3 shows the relation between the minimum voltage level and the electricity consumption. Note that the minimum voltage levels without control are similar to the DSM methods, despite the much higher load. This is the result of the imbalance in the network.

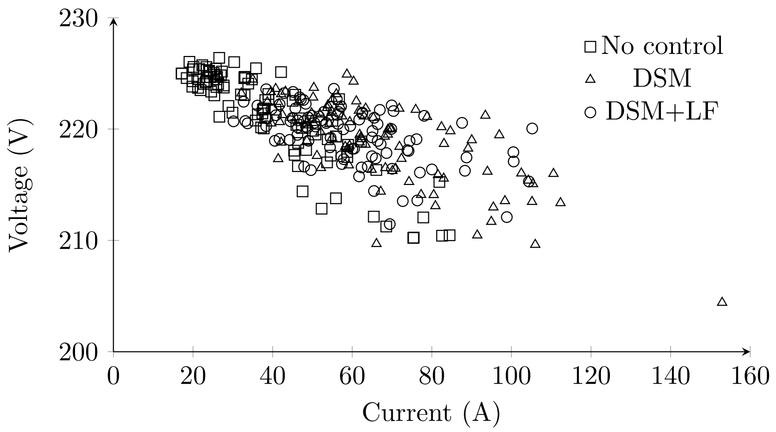

Figure 7.2: *Scatter plot with the relation between the minimum voltage level in an interval and the currents running through the neutral.*

Currents running through the feeders cause voltage drops or rises. The longer the distance over a feeder, the larger the total impedance towards the connection. This larger impedance will cause larger voltage drops or rises at the point of connection. These problems get more severe with higher currents.. When a lot of large loads are enabled at the end of a feeder, the combined load of these devices cause a large current to flow through the whole feeder, resulting in large voltage drops and low voltage levels in the end of the feeder. Balancing active loads over the feeder

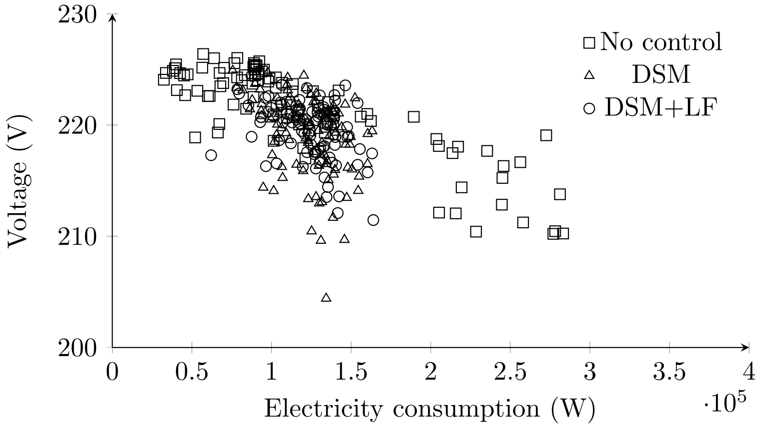

Figure 7.3: *Scatter plot with the relation between the minimum voltage level in an interval and the energy imported by the network.*

length will result in less current flowing in the end of the feeder, leading to a smaller voltage drop and thus higher voltages at connections at the end of a feeder.

These results show the issues with unbalance in the network as seen in chapter 3. Solving the unbalance issue is likely to have a great impact on improving the voltage levels, cable usage, and perhaps reduce distribution losses in future planning strategies.

7.2 Other planning strategies

These imbalance results also show that the problem of not incorporating network structure in the first planning stage, leading to large imbalance on the physical grid. The DSM+LF approach tries to improve the levels by altering the prices from the original planning. This results in limited freedom for better solutions in the solution space. Adding network information to the planning step could possibly lead to other solutions with less or without network violations by balancing the loads better over the network and phases.

Other solutions which are easy to implement have also been briefly looked at. One implementation used feedback during the planning stage to evaluate the performance of each iteration. Planning iterations with bad voltage levels are given a penalty, such that these iterations are less preferable. This also means that the iterations with the best peak-shaving performance can become less interesting due to higher penalties. A brief look at this method indeed shows that voltage levels are improved compared to DSM, but that the peak shaving performance decreases significantly.

Another method divides the fleet of houses in multiple fleets. An implementation with nine fleets, one feeder and phase per fleet, was used to test this method. This method results in less planning freedom but not in significant reduced peak shaving performance. All the nine fleets try to balance their load, which should result in a better balance. Results show that the balance between the phases indeed decreases. The distribution losses are reduced as well. Except for one odd worst-case voltage drop to 200 V, the results are quite comparable to DSM+LF.

7.3 Future work

Adding the LV network models and load-flow calculations adds a lot of interesting data to TRIANA. It adds network properties to test whether a planning is supported by a network. Feedback from load-flow calculations also adds potential to improve the power quality in the network. The massive amount of data resulting from the simulations also leads to new insights and new research questions.

There seems to be potential to improve voltage levels and reduce network usage by better balancing loads and generators. Looking into solutions proposed on optimal power flow in literature is left for future work. It is good to look for a good trade-off between peak-shaving performance, power quality, minimizing network costs and residential comfort level. The TRIANA approach tries to keep the imported electricity as stable as possibly without affecting comfort level for residents of the houses. The challenge is to find solutions to improve the power quality and mitigate network investments without significantly affecting peak-shaving performance and comfort degradation.

The current implementation covers a LV network. Adding more models such as NOPs and transformers is left for future work. This is also true for adding MV networks. These models would further improve the accuracy of the values since voltage levels at the transformer are not always around 230 V, but depend on the voltage level in the MV network. It will also allow to connect larger generators in a network such as wind turbines. The implementation will require extension of the current model and additional parameters.

It is valuable to keep the separation between the physical grid, which has been added with this work, and the virtual grids which were already implemented. An exchanger of a house that belongs to a certain virtual grid could be connected to a phase of a node of the physical network. This makes it possible to simulate the effects of certain planning partitions, but also the effects of multiple corporations, with different goals, on the same physical network.

A new pool to represent devices with constant current electricity consumption should also be added in the future to the house model of TRIANA. During the planning stage, a voltage level of 230V could be assumed to determine the power consumption, but with load-flow simulations the actual power consumption depends on the resulting voltage level. This makes the results from load-flow calculations more accurate with large loads such as resistive heaters.

Simulations on the effects of introducing more three-phase connected loads and generators, such as heat pumps and PV panels, could be considered in the future as well to improve balance. Such large loads and generators increase chances of an imbalanced network due to their impact on the network. Adding more three-phase connected devices will most likely improve the balance.

A graphical representation of the network is also left for future work. The current graphs provide access to data, but it is hard to find where problems occur in the network. Usually multiple violations are found in the same part of the network due to the dependencies in the network. With a graphical representation it will be easier to see where the problems occur and possibly how these can be solved.

Enhancement on the robustness of the network control can also be added in the future. The current steering does not give guarantee grid stability as devices can be active regardless high prices. To give these kind of guarantees, limits to consumption or production must be enforced. These limits can be lower than the installed fuses in households during certain intervals and depend on local grid states. These dynamic limits are possible with smart meters.

Another issue is the stability and safety in the grid when communication fails. The control methodology can fallback to the original internal planning and forecasting. However, when networks rely on planning and communication to operate stable, it is harder to guarantee stability when communication fails. Research could be done on exploiting the availability of the network structure information in combination with voltage level measurements by smart meters to determine how much energy could be consumed without causing network problems in the event of long term communication failure.

Total harmonics distortion becomes a bigger issue as well and new design practices use larger transformers to cope with the problems related to THD. Future models could add THD values for devices to get a static analysis. These would however require a lot of new measurements for devices.

7.4 Recommendations

For most households it is not documented which phase they are connected to. This information is required for a good modeling of the network and right steering if the houses. For new residential areas where planning strategies such as TRIANA are tested and evaluated, it is advised to document phase information for each household. This allows faster and more accurate modeling and steering for the planning methodology. To improve balance in networks, it might be good practice as well to connect quite large residential consumers and producers to all three phases.

It is also shown that DSM alone does not improve the worst-case voltage levels and power quality, but decreases it. Therefore it is advised to enable load-flow simulations in future research, even if the network is not used in the planning. Adding load-flow simulations gives insight in how a network might behave and whether the results seem to be feasible in realistic existing networks or not.

7.5 Summary

This chapter has shown where room for improvement is left. Load-flow calculations and network models have added a lot of valuable data to TRIANA to test its performance in realistic LV networks. Still there are issues to tackle with respect to balance in the network. Pointers to further improvement for unbalance are given. Other issues and improvements for future work are presented such as additional network models and robustness of network operation. In the future it is also encouraged to enable these load-flow simulations to give more details on the impact of a planning. Documentation about which house is connected to which phase is encouraged for future residential areas with smart grid testing.

8
Conclusions

This chapter will give answers to the research questions as stated in chapter 1. Findings in literature and the simulation results will be used to answer the questions.

The first main research question is formulated as:

> *"What is the impact of high penetration distributed generation on correct functioning of the low voltage network?"*

To answer this main question, the following sub-questions are answered first:

> *"What are the important factors that define whether a network is functioning correctly?"*

The answer to the first sub-question can be found in chapter 2. First of all, the individual network components should not fail, such as fuses, cables and transformers. These set physical limits to the maximum capacity in the network. The second important factor sets stricter limits on voltage levels, frequency and harmonics. These are mentioned in the EN 50160 [44, 43], and must be met by distribution system operators. For a network to function correctly, both physical limitations by components and requirements by the EN 50160, must be met.

> *"In which way does distributed generation influence these factors?"*

Literature discussed in chapter 2 shows that generation of energy in the network leads to voltage rises whereas traditionally only voltage drops were expected in networks due to connected loads. Uncertainty of production might also lead to flicker in the network. Another issue with certain types of DG using power electronics is the injection of harmonics, resulting from DC to AC conversion.

> *"How can these components be modeled and factors be simulated?"*

Chapter 4 has given parameters and models for network structures an components. The structure for common radial LV networks can be modeled using nodes and branches. Loads and generators can be connected to the nodes. Branches represent the cables, transformers and fuses. Load-flow calculations are used to obtain voltage levels and currents flowing through the network. Components such as batteries are available in TRIANA and can be added as loads or generators connected to nodes. Other components such as cables and transformers can be modeled as different type of branches. Models for these components are presented in [68]. Harmonics and frequency problems were out of the scope for this thesis. Static analysis of harmonic distortion and frequency problems might be possible in the future, however.

To answer the main question, the second sub-question already uncovers a lot of details regarding voltage rises with DG. The simulations in chapter 6 show these voltage rises. Unbalanced spreading of DG over the three phases and feeder can also cause unbalance. But, not only DG can cause problems, large loads such as heat pumps and electrical vehicles can also lead to problems as simulations have shown. Other effects that can affect grid stability are frequency variations and injected harmonics. The latter one is also caused by electronic loads. The injected currents and resulting voltage rises might require more capacity in the network to operate stable.

The second research question covers the smart grid part.

> *"Can smart grids help to lower the minimum required capacity in the low voltage network?"*

To answer this main question, the following sub-questions are answered first:

> *"What would a typical low voltage network and residential area look like?"*

In chapter 4 the network of Lochem is shown. This is a network that can be considered typical. It consists of multiple feeders originating from the transformer and is operated radially. The thickness of the feeders decrease over the distance. Modern network design practices use the same thick cable for the whole feeder to cope with uncertainties in the future. The households for a futuristic setting contain smart appliances, energy storage solutions, DG such as PV and large loads such as heat pumps. These models are given in [17].

> *"What would be the required capacity in the low voltage network with high penetration of distributed generation without planning?"*

The network of Lochem is used for simulations. From the simulation results in 6 it seems that the cables are just sufficient for both large loads and a high penetration of DG. However, not much room is left at this point. The same holds for the worst-case voltage levels which are close to the limits set by the EN 50160. The effects of harmonics are not taken into account here as well, which might require additional capacity. The peak consumption or production by the network is to be found around 300kW for the 121 houses. Considering balances and harmonics, a typical transformer rated at 400kVA would be advisable for this part of the network.

> *"Which components can have a positive effect on the required network capacity?"*

To improve voltage levels and reduce cable usage, consumption and production can be matched to reduce the currents running through the network over a longer distance. This will also reduce the total energy imported or exported by a network, reducing the load on the transformer. This however requires planning freedom of devices and steering of these devices. When not enough freedom is available, storage can be used as additional load or generator. Furthermore, smart transformers can be used to keep the voltage level around an optimal value, depending on the consumption or generation of the network.

To answer the main research question, we need to consider the simulation results in chapter 6 and the analysis in chapter 7. The results of the simulations with the Felix-case [17] on the Lochem network show that the energy imported by the network is more constant over the day using DSM. However, this does not guarantee grid stability. The worst-case voltage levels are worse and cable usage is not improved by much. Imbalance is becoming an even bigger issue with DSM. The lower voltage level would suggest that even thicker or shorter feeders are required with DSM compared to simulations without control. In other simulations with a high penetration of PV, a transformer with higher capacity would be required as well due to the imbalance caused. Simulations with the load-flow information feedback show improvements in several simulations. Worst-case voltage levels improve and cable usage decreases without significant effects on the peak-shaving performance.

So the answer to the question whether smart grid technology can lower the required network capacity is both yes and no. The current solutions that do not take the network topology and properties into account clearly do not improve the required capacity and even lead to worse performance in certain circumstances. Adding network models to the planning step and optimize location of consumption and generation using this information is most likely able to solve the balance problems and improve voltage levels. When a good tradeoff between peak-shaving performance and balancing can be found, smart grids might indeed be able to lower the required network capacity or improve the power quality.

8.1 Contributions

The main contribution of this work is the addition of network models to the TRIANA simulator in combination with load-flow calculations. The implemented structure as discussed in Chapter 5 forms a basis for further extension with additional models. With the addition of load-flow calculations, a planning can be checked for feasibility on a physical network and future scenarios simulated. This can be used for more robust operation of smart grids.

The integration of these models and simulations in TRIANA instead of using an external tool makes it possible to fully exploit the properties of the model for future improvements in the planning step of TRIANA. Especially more integration and optimization on location of generation and consumption will be required to improve power quality in the network with DSM. The used algorithm is also shown to be fast and accurate at the same time. This makes it possible to execute multiple load-flow calculations during planning without significantly affecting computation time of the planning step.

Acronyms

AC Asynchronous Current

CHP Combined Heat and Power

DC Direct Current

DG distributed generation

DSM Demand Side Management

DSO Distribution System Operator

EMC electromachnetical compability

EN European Norm

EV electrical vehicle

FACTS flexible AC transmission system

HV high voltage

IEC International Electrotechnical Committee

KCL Kirchhoff's Current Law

KVL Kirchhoff's Voltage Law

LV low voltage

MV medium voltage

NOP Normally Open Point

PV photovoltaic

RMS Root Mean Square

THD Total Harmonic Distortion

TSO Transmission System Operator

Glossary

Distributed generation Decentralized production of energy using multiple small energy sources.

Demand Side Management Control of demand for energy using incentives such as different pricing during the day, usually with the goal to reduce the need in network investments by reducing peak consumption.

Hosting capacity The amount of distributed generation that can be allowed in the network to ensure a correct functioning network

Load-flow calculations Calculations on network models to obtain voltage levels, distribution losses and other network information for a certain scenario. These calculations are used in network design to validate that the required capacity will be realized.

Power Factor Power factor is the ratio of real power to apparent power, sometimes also referred to as cos φ-factor. The power factor is said to be leading when the current tops before the voltage tops (current leading voltage) and lagging when the voltage tops before the current (current lags voltage).

Power Quality The quality of the delivered energy to the customer, depending on voltage characteristics, frequency and harmonic distortion.

Smart grid A Smart grid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies [49].

List of used units

Symbol	**Unit**	**Description**
A	m	Cross section in square metres
f	Hz	Frequency in hertz
I	A	Current in ampere. RMS current given in case of AC
ℓ	m	Length in metres
P	W	Active (useful) power in watt
Q	var	Reactive power given in volt-ampere reactive
R	Ω	Resistance in ohm
S	VA	Apparent power given in volt-ampere
t	s	Time in seconds
U	V	Voltage in volts. RMS voltage given in case of AC
X	Ω	Reactance in ohm
Y	S	Admittance in Siemens
Z	Ω	Impedance in ohm
ρ		Resisitivity, unitless
φ		Phase angle in degrees
ω	rad/s	Angular velocity in radians per second

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Use-case de Teuge

Use-case De Teuge

Gerwin Hoogsteen

June 23, 2013

1 Introduction

De Teuge is a residential area in Zutphen (see figure 1), consisting of 184 households equipped with heat pumps. A lot of issues regarding power quality arose in the beginning. The capacity of the network was not sufficient, but the households also lack buffers to store heat. The document is best read in combination with the full thesis [1] for more in depth details.

Figure 1: De Teuge residential area (image from Google Maps)

Measurements after the network was reinforced were conducted by Liandon [2, 3]. These results show a good power supply, but that is with a strong network. Notable is that of ten measured households, five heat pumps were active during the complete day, indicating that they were not or barely capable of heating the house during a very cold winter day. It is doubtful whether a heat buffer would make a difference here. When the heat pump is barely able to fulfill the heat demand by residents, there is no room left to fill the heat buffer.

This report will show the results of simulations on the original network with no control and the DSM+LF control to evaluate the impact of the latter control strategy on the heat pumps.

2 Test setup

Measurements are done on the newer network instead of the original situation. This makes it impossible to compare the results of the simulation model used. The measurements also lack detailed information of the consumption pattern of the other devices. Only in depth measurements of the heat pumps are considered.

Due to the limited data and time, the Felix-case is used for the modeling of other devices in the households. The electric vehicles, batteries and PV are removed from this model to make it more realistic. This results in a consumption pattern for non controllable devices. The heat pumps and additional resistive heating are modeled after the datasheet of the Energion 6kW heat pump that is installed most households. Other heat pumps do not differ too much. The 8kWh heat buffer from the Felix model is kept to model the heat capacity in the house itself.

The maximum consumption is set to 1.8kW for the heat pump with a multiplication factor of 3.0. This results in a maximum output of 5.4kW of heat. The sixth day of the Felix case is used for these simulations. This is a cold winter day in the weekend where there is a demand for heating during the whole day. This results in a behaviour of the heat pumps that is comparable to the behaviour measured in both consumption level and frequency of turning on and off (see figures 2 and 3). Some heat pumps turn on and off often, whilst others are turned on for hours during the day. This will result in a comparable worst-case situation during the day.

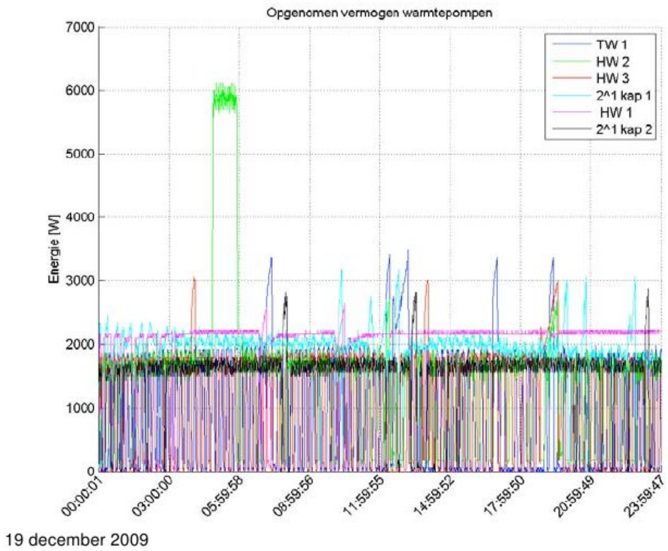

Figure 2: Behaviour of 6 heat pumps as measured by Liandon [2].

The network is modeled in TRIANA using the data available from the original network in de Teuge in WebGIS and Gaia network files. The cable properties are obtained from the Gaia modeling parameters. The voltage level at the transformer is set to 233V, equal to the lower voltage levels measured at the newer

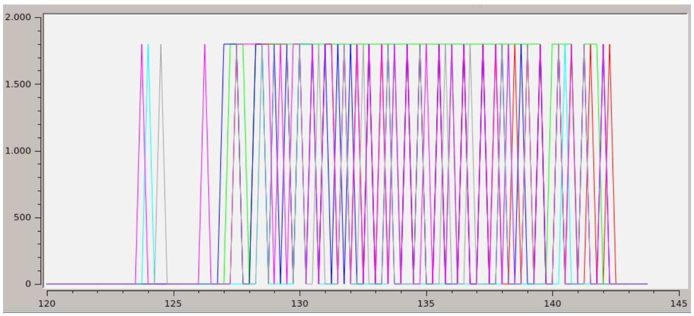

Figure 3: Behaviour of 6 heat pumps as simulated in TRIANA without control. X-axis show the time in hours, Y-axis the consumption in watts.

Barmels MV/LV transformer.

With the worst-case scenario, two networks are simulated: the original one and one with an additional feeder to the second part of the residential area. This additional feeder is connects the network at the intersection of Nieuwe Weide and Kanon to split up the east half of the residential area. In the original network, one feeder feeds the whole east half of the area with approximately 90 houses. The additional feeder doubles the distribution capacity to this part. Simulations have to show whether this additional cable would have been enough to solve problems.

The same two networks are used in a second simulation where the parameters of the heat pump are improved to a 1.5kW electricity consumption and a multiplication factor of 4, resulting in a heating capacity of 6kW. These are similar to the specifications of the heat pumps used and show how the network will behave during less extreme days. Perhaps this would require a warmer source temperature.

Expectations for the simulations are that the DSM+LF strategy can't make a significant difference in this use-case due to a very limited planning freedom. Especially in the worst-case scenario where heat pumps can barely fulfill the heat demand.

3 Results worst-case

Without the additional cable, both simulations (see figure4) show a voltage level that is just under the allowed $207V$. More importantly is that the limiting cable has a peak-load that is far over its designed usage in both no control as DSM+LF. Furthermore, a high load is seen during the complete day as a lot heat pumps are active simultaneously. This also translates to a high load on the cables in figure 5.

With the additional cable, the voltage drops improve significantly and prevent that too low voltage levels occur. However, without control, the cable is still pushed over its limits.

As expected, the DSM+LF strategy does not help a lot here to improve the voltage levels or cable usage without the additional cable. As the heat pumps have barely enough capacity to fulfill the heat demand, there is very limited room left to plan alternatively. Especially considering that comfort has a higher

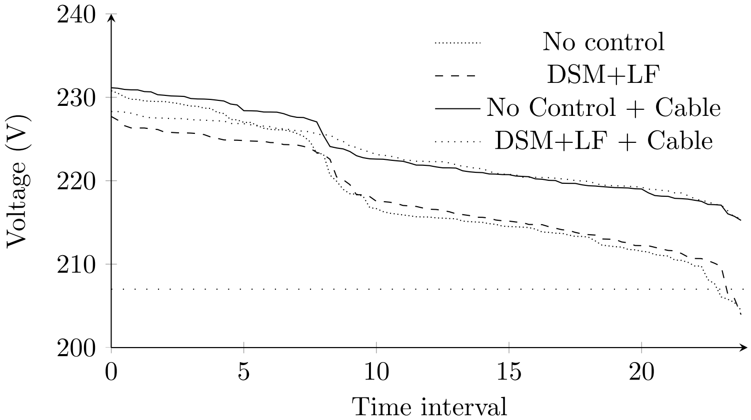

Figure 4: Voltage level duration curve of the worst-case voltage levels in the simulated network. The dotted line at 207V shows the minimum level allowed by the EN 50160. The "+ Cable" denotes the results with an additional feeder.

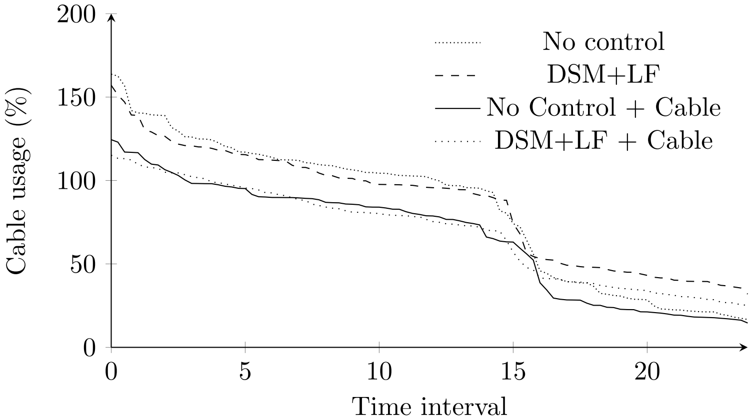

Figure 5: Worst-case calbe usage duration curve. The "+ Cable" denotes the results with an additional feeder.

priority then a stable grid. These limits in planning freedom lead to a limited win in voltage levels and cable usage.

Inspection of detailed graphs in the simulator show that the heat pumps indeed show the same behaviour as the measurements. A lot heat pumps are turned on simultaneously, whereas some are turned on for hours during the day. Also the maximum load of 587kVA on the transformer as measured. Our results show a combined load of 543kVA, so these figures are comparable between the measured data and the simulated data.

4 Results better heat pump performance

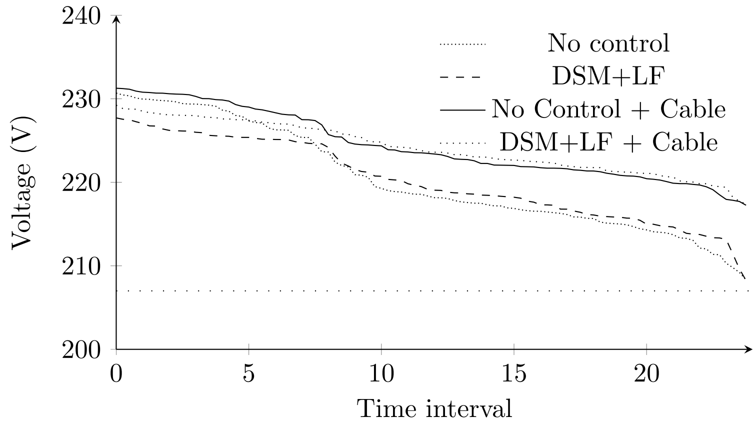

Figure 6: Voltage level duration curve of the worst-case voltage levels in the simulated network with improved heat pump specifications. The dotted line at 207V shows the minimum level allowed by the EN 50160. The "+ Cable" denotes the results with an additional feeder.

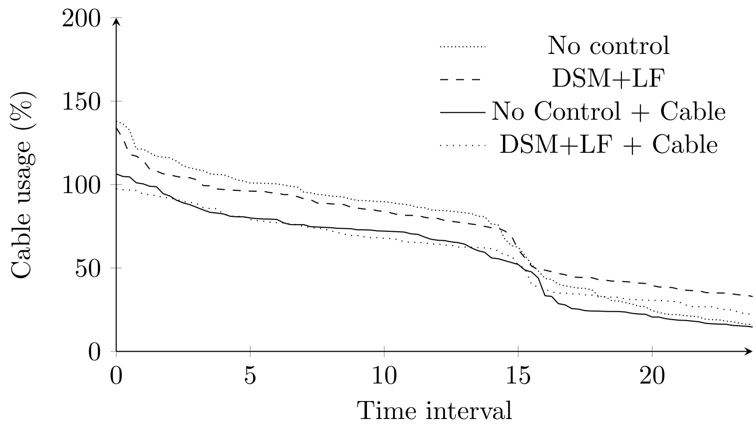

Figure 7: Worst-case calbe usage duration curve with improved heat pump specifications. The "+ Cable" denotes the results with an additional feeder.

From the results in TRIANA it is observed that the heat pumps need to be turned on less often and consume less energy. That also influences the voltage levels (figure 6) and cable usage (figure 7) figures. All the figures improve slightly over the worst-case situation. Notable is that the DSM+LF simulation is performing just within the cable boundaries. But not by so much that the combination of DSM+LF steering and an additional cable could be recommended.

5 Conclusions

Taking into account an error margin, all the simulations show that the network would not have been be sufficient in terms of cable loading. The voltage levels are also not compliant to the EN 50160 in all circumstances. The fact that some heat pumps had to be active whole day, whilst others were active a lot as well means that they can barely supply the heat demanded. This leaves very little planning freedom. Too little for TRIANA using DSM+LF to fix power quality issues. With the low source temperature, given heat demand and capacity of heat pumps, the only solution is to add additional feeders to cope with the high electricity demand in the winter, as is done.

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IEEE PES ISGT Europe 2013 paper submission

Integrating LV Network Models and Load-Flow Calculations into Smart Grid Planning

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***Abstract*—Increasing energy prices and the greenhouse effect demand a more efficient supply of energy. More residents start to install their own energy generation sources such as photovoltaic cells. The introduction of distributed generation in the low-voltage network can have effects that were unexpected when the network was designed and could lead to a bad power quality.**

These developments ask for better insight in the effects of a planning for a fleet of households in a network. This paper presents the results of adding network models to planning strategies. Forward-backward load-flow calculations for a three phase low-voltage network are implemented to simulate the network. The results from load-flow calculations are used as feedback for demand side management.

The results in this paper show that the implementation is both fast and accurate enough for integration purposes. Combining load-flow feedback and demand side management leads to improved worst-case voltage levels and cable usage whilst peak-shaving optimization performance does not degrade significantly. These results indicate that load-flow calculations should be integrated with demand side management methodologies to evaluate whether networks support the effects of steering production and consumption. More sophisticated integration of network models are left for future work.

I. Introduction

The adoption of alternative sources of electrical energy, such as photovoltaic cells and micro combined heat and power, changes the energy distribution landscape. Most low-voltage (LV) distribution networks were never designed for this ongoing move from centralized energy production to decentralized distributed generation (DG). With centralized generation of electrical energy, the voltage level would only drop in a LV feeder, with DG voltage rises are also possible. Without monitoring, it is also hard to tell in which direction current is flowing with DG. Measurements at the transformer might not be enough to guarantee a safe and stable supply of energy to households. Furthermore, introduction of large loads such as heat pumps and electrical vehicles (EV) might require additional investments in distribution networks. New networks are usually overdimensioned to cope with the uncertain future of networks. The higher initial costs mitigate future costs of strengthening the grid. However, a lot of capacity will never be used.

Demand side management (DSM) methodologies are developed to enable grid usage optimization by peak-shaving and matching consumption and production. This reduces the peak power consumption in a grid and enables the use of smaller transformers. Alternatively, the network capacity can be used more efficiently to allow the introduction of more load. However these techniques do not make use of the actual physical distribution grid and might lead to a worse power quality in certain cases. To get insight in voltage levels and cable usage, load-flow calculations can be executed. These are used to design networks and verify whether the grid can be operated safely.

Our approach is to integrate network models into DSM in combination with network constraints. The results of load-flow calculations can then be used as feedback by DSM to steer on power quality. This might involve multiple load-flow calculation iterations, so the computational time of the load-flow calculations has to be low. Thus a tradeoff between accuracy and complexity has to be made. These models and load-flow calculations are than integrated in the three-step DSM methodology TRIANA [1] [2]. In addition, more accurate load-flow calculations from an external software tool are integrated. This tool can be used when more accurate results are demanded.

The outline of the rest of this paper is as follows. First related work on relevant subjects is given. Then a brief overview of implementation of load-flow calculations is given. Performance evaluation results are given in the fifth section together with results of integrating load-flow feedback into DSM using a use-case. A discussion on possibilities and implications by integrating load-flow calculations is given in the sixth section. The paper ends with conclusions and future work.

II. Related work

The European norm EN 50160 [3] sets limits to the permitted voltage levels for public supply of electrical energy. Voltage levels at households in the LV networks must be within 10% of the nominal voltage level. For European networks that are operated at a nominal voltage level of $230V$ this results in a minimum of 207V and maximum of 253V. These power quality regulations are required to prevent damage on equipment.

In [4], [5] research is done on simulating the impact of DG in LV networks. These models are verified using real logged data from a residential area. Results show that voltage rises due to introduction of DG are worst in the end of the network. The simulations show overvoltages, but also voltages as low as 207V at other connections. Nykamp et al. [6] show that introduction of large penetration of heat pumps and electrical vehicles require huge investments when no control is applied. Using DSM, the required network investments can be reduced to support the integration of these loads.

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These developments also lead to different LV network design practices to cope with uncertain future developments. Generally thicker cables are used to minimize chances that these need to be replaced in the future. This may lead to unnecessary investments in thicker cables and larger transformers of which the capacity will never be utilized. In [7] the usage of shorter cables is advised as well to support more DG and larger loads. However, it is not only the network infrastructure that matters. Advanced monitoring of the network is suggested in [8]. Metering enables network operators to detect faults easier, adjust transformer turn ratios and gain insight in currents flowing due to injection by DG.

A typical residential LV network is the target for the DSM approach with load-flow feedback. Existing Dutch networks are operated radially and often include normally open points (NOP). Transformers between the medium voltage network and the LV network are not equipped with automatic tap changers. In past design practices the cross section of the used cables is usually smaller at the end of the network when compared to the cable sections close to the transformer. The networks consist of a three phase network with a neutral line. The connection of households to phases is usually distributed normally. Furthermore, households can be connected to all three phases as well. Allowed currents by the fuses installed might be as high as 40A. An example of a typical LV network layout is given in Fig. 1

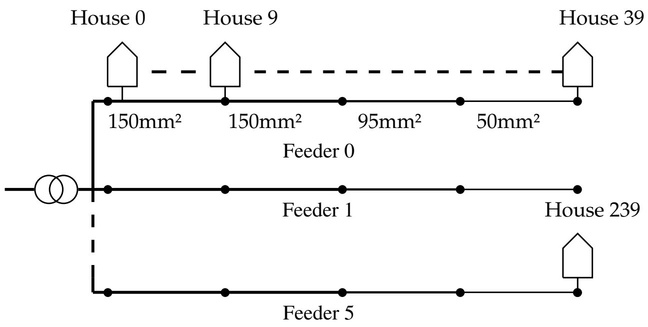

Fig. 1. Typical layout of a Dutch LV network with 6 feeders, usually up to 500m, and 40 connections per feeder. Feeder thickness decreases over the feeder length.

For existing networks it is unknown how much capacity is left for integration of more DG or large loads. In [9] rather conservative estimates for determining the capacity are given based on the consumption levels that are known, rather than actual network capacity. These measures are all required to ensure safety and stability in networks that lack monitoring and steering measures. This also means that a lot of network capacity is left unused. Better control, simulations and models of future and existing networks can help to decrease required investments or utilize existing infrastructure more efficiently.

In [1] research is done on a three-step planning methodology for smart grids, for which a simulator is implemented [2]. No knowledge of the network is available in this simulator however. Therefore, the first step is to integrate a model of the LV network. In [10] models for network components that are often used with load-flow calculations are given. The structure of the network are modeled using a tree model with nodes and branches. These branches represent the cables and are modeled using a pi-model. Loads and generators are connected to the nodes using PV and PQ-buses. The active power and voltage values are known for the former type of bus, whereas for the latter the active and reactive power values are known.

Several load-flow calculation algorithms are suitable for LV networks. Results in [11] and [12] show that the forward-backward sweep algorithms are simple in terms of complexity and require the least amount of floating point operations. The variant where voltage levels are updated in the forward sweep and currents are updated in the backward sweep performs best. Other variants of the forward-backward sweep, such as updating voltage levels in the backward-sweep as well, require more computational time despite the fact that they might converge faster. The same is true for other algorithms such as Newton-Raphson and Gauss-Seidel which converge faster in certain scenarios, but require significantly more computational time.

III. IMPLEMENTATION

The properties of typical LV networks are exploited for both modeling and load-flow algorithms. As radial operated networks are commonly used, the implementation is optimized for these networks. This allows the use of the forward-backward sweep algorithms that do not require a lot computational time. The simplest form of the algorithm using voltage level updates in the forward sweep and current updates in the backward sweep is implemented. As literature [11] has shown, this is fastest algorithm with the least amount of complexity. These values are calculated using Kirchhoff's voltage and current laws. Scenarios where other algorithms perform better, such as low power factor ratios, are not expected in the typical LV networks. The implication is that meshed networks or networks that contain a loop are not suitable for the method presented in this paper.

The network is modeled using a tree structure with branches to represent cables and nodes. Houses are connected to the nodes using a PQ-bus where a negative value represents injection of power by the household due to DG. The PQ-value for each phase for each house is the sum of all power consumed and produced by devices connected to that phase. Individual PV-buses for generators are not used since generators in LV networks are required to synchronize their voltage level to the level provided by the grid. However, PV-buses can also be converted in PQ buses by determining the required reactive power to achieve the voltage level the generator is set to provide.

Before the forward-backward sweep calculations are executed, the voltage levels at the nodes are initialized to the nominal voltage level U_{nom}. For the three phases L1, L2 and L3, these are 230V with a phase angle of -150°, 90° and -30° respectively. Voltage levels are updated during the forward-sweep starting at the node connected to a slack-bus, which represents the connection to the secondary side of the MV/LV transformer in the network model.

The forward-sweep walks over all branches in the tree using a recursive depth-first search algorithm. Consider a network with a node n_1 that is connected to a node n_2 via branch b_1, where n_1 is one branch closer to the slack bus (see Fig. 2). When node n_1 is the current position of the search algorithm, the next step will be to walk branch b_1 to visit node n_2. The rest of the order will force node n_3 to be visited first and then node n_4.

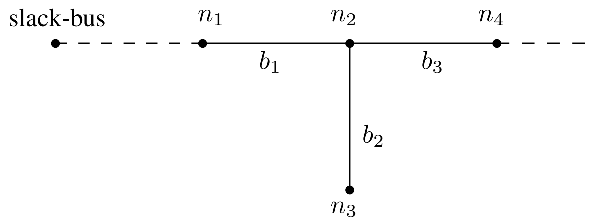

Fig. 2. Part of an example network.

For each visited node n, the voltage level U_n is calculated using the voltage drop U_{drop} over branch b that connects node n and m, with node m being closer to the slack-bus:

$$U_n = U_m - U_{\text{drop}} \tag{1}$$

where U_{drop} is calculated using the current I flowing through branch b obtained in the backward-sweep and the cable impedance Z (determined by the resistance R and reactance X) which is represented by the branch:

$$U_{\text{drop}} = I \cdot Z \tag{2}$$

The backward sweep uses the same depth-first search recursive algorithm in reverse order, hence the name. Currents are updated when walking a branch backwards towards the slack bus. The sum of all currents running to or from a node must equal zero. Suppose a branch b being walked from node n towards node m, with m being closer to the slack bus. The current I_b running over branch b towards node n must equal the sum of all currents flowing out $I_{n,\text{out}}$ of node n and the currents flowing to the PQ buses $I_{n,\text{bus}}$ connected to node n. These currents can be obtained by dividing the power consumption (S) through the voltage level obtained in the forward sweep ($I = \frac{S}{U}$). The current I running through branch b is then given by:

$$I_b = \sum I_{n,\text{out}} + \sum I_{n,\text{bus}} \tag{3}$$

The load-flow calculation sweeps are executed until convergence criteria is met. This is tested with the voltage levels at all nodes for all three phases. The difference in node voltage levels U_n between the current iteration (k) and the previous $(k-1)$ must be smaller than a predefined error ϵ. For all phases for all nodes in a network the following must hold:

$$\left| U_n^{(k)} - U_n^{(k-1)} \right| < \epsilon \tag{4}$$

This is the basis for implementing forward-backward sweep load-flow calculations. Note that all calculations are done in the complex plane. More details on the models and load-flow calculations can be found in literature ([11], [13] [14] and [7]).

The load-flow calculation is implemented in the TRIANA smart grid simulator [2] using the C++ language. The Qt-library is used to provide useful classes such as lists and maps. This combination of C++ with the Qt-library makes development easier while remaining portability between different target platforms. Instead of using sparse matrices, the network structure is implemented using objects for nodes and branches in a linked list structure. This results in less memory usage and complexity.

The already existing grid-exchangers for each household are connected to the corresponding PQ bus of the network model. These grid-exchangers pass the total power consumption of all devices connected to it to the load-flow algorithm and are treated as constant power. For each simulation interval the power consumption or production values are obtained. A load-flow calculation is executed to obtain voltage levels and cable usage. These results are fed back to improve the voltage level by altering the planning.

IV. Simulations

This section presents the performance of the load-flow implementation. The used network and house models are discussed in the first section. The second subsection presents simulation and performance evaluation of the load-flow calculation implementation itself. The last subsection consists of a use-case where load-flow results are used as feedback to improve power quality with DSM.

A. Use-case model

The network used for the simulations is a part of an existing Dutch LV network in the town of Lochem. The network files were provided by Dutch distribution system operator Alliander. The network consists of three feeders with a total of 121 households. The length of the feeders is approximately 400m and the feeder thickness decreases over the feeder length. Aluminum cables with cross sections (A) of 150mm^2 (Al 150), 95mm^2 (Al 95) and 50mm^2 (Al 50) are used for the feeder. Each feeder contains about 40 households connected using thinner aluminum cables with a cross section of 16mm^2 (Al 16). The properties of these cables are given in Table I.

TABLE I
Cable properties

Cable type	A (mm²)	R (Ω/km)	X (Ω/km)	I_{nom} (A)
Al 150	150	0.206	0.079	230
Al 95	95	0.320	0.082	175
Al 50	50	0.641	0.085	115
Al 16	16	1.91	0.096	60

These 121 households are modeled after futuristic scenarios by [15]. This model contains households with both controllable and uncontrollable loads and generation. Energy consumption patterns of devices and production patterns for photovoltaic cells for uncontrollable devices are generated. The controllable devices are dish washers, dryers, washing machines, hot plug electrical vehicles, heat pump and batteries in various penetrations. This results in a different configuration for each house for each day for a complete year. One day during the winter is being simulated.

B. Load-flow implementation performance

To evaluate the accuracy of the load-flow implementation, a comparison with load-flow results between the implementation presented and LV network simulator Gaia by PhaseToPhase is conducted. Gaia is the network simulater used by Alliander for designing LV networks. The model of the residential area was made available for this simulator and was converted to a configuration file for the implemented load-flow algorithm. A whole day was simulated with 15 minute intervals, resulting in 96 simulation intervals.

The error ϵ is set to 0.00001. The voltage levels converge within ten iterations for all 96 intervals and take 1.3ms on an Intel Core i5 430M processor running at 2.26GHz. The same simulations take approximately one second with Gaia. The calculated values by the implementation show a standard deviation of 0.50V and a mean deviation of 0.12V compared to the values obtained from Gaia. The maximum voltage deviation compared to Gaia was 1.31V for one single point in the network. The mean deviation of the current is 0.00A with a standard deviation of 0.10A. These results show that the implemented load-flow calculations are accurate enough for integration into DSM. Other parameters not taken into account in both load-flow algorithms, such as the ground temperature, can also lead to errors of this magnitude.

C. Performance of DSM with load-flow

One day during the winter is simulated using three settings: no control, DSM and DSM with load-flow feedback (DSM+LF). This DSM+LF is an initial implementation where energy prices at individual households are adjusted using the voltage level feedback from the load-flow calculations after the planning stage. The price is increased with a low voltage level U to encourage production and discourage consumption to increase the voltage level. The price is lowered when the voltage level is high for the opposite effect. Price based steering is only done when the voltage level is not within 5V of the nominal voltage level of 230V. A random number between zero and one (p) is generated to decide whether the price has to be changed or not. This prevents that prices for all houses are increased which can cause overshoots in the steering. The chance that prices change and the amount with which the price changes depends on the deviation from the nominal voltage level and increases with a larger deviation. The following formula is used to calculate with which amount the price will be changed c_{change}:

$$c_{\text{change}} = k * \left(\frac{230 - U}{20}\right) * \left\lceil \left|\frac{230 - U}{20}\right| - p \right\rceil \tag{5}$$

with k being a constant multiplier which is set to 75 units in the simulations. The initial price level is 1000 units. The DSM optimization goal is to flatten the overall consumption profile.

Simulation results show that the mean voltage level (U_{mean}) are comparable with all three settings (see Table II), but that the worst-case voltage levels U_{wc} become worse with DSM compared to simulations without control as shown in Fig. 3. Eight voltage level violations were reported with DSM, where no control resulted in zero violations. DSM+LF improves the voltage levels and resolves the violations introduced with DSM. When looking at the mean network voltage level during the worst case simulation interval, the simulation without control shows the worst results with an average of 223.9V. Using DSM results in an average of 226.0V whereas DSM+LF achieves an average of 226.3V.

TABLE II
SIMULATED VOLTAGE LEVELS (IN V) AND CONSUMPTION FLATTENING RESULTS

	U_{mean} (V)	U_{wc} (V)	η_{wc} (%)	3σ (W)
No control	227.3	210	93.3	203640
DSM	227.2	204	88.5	66111
DSM+LF	227.2	212	66.3	68179

Also the worst-case cable usage (η_{wc}) shows large improvements as shown in Fig. 4. Without planning, the currents in one cable reached 93.3% of the capacity, whilst DSM reduces the worst-case usage to 88.5% due to peak-shaving. Adding load-flow information reduces the worst-case cable usage to 66.3%. In the mean time, the addition of load-flow calculation feedback does not significantly affect peak shaving performance. This performance is measured in 3σ load deviation from the average energy consumption over all simulation intervals (see Table II).

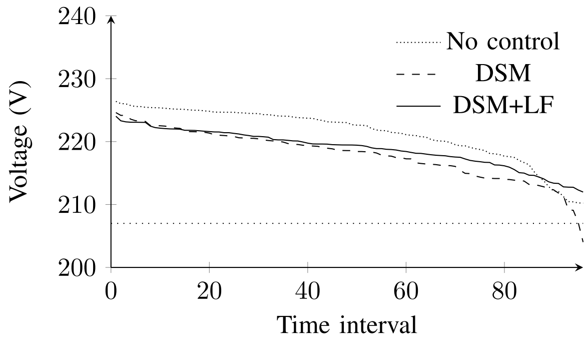

Fig. 3. Voltage level duration curve of the worst-case voltage levels in the simulated network. The dotted line at $207V$ shows the minimum level allowed by the EN 50160.

These results show that DSM decreases the worst-case voltage level and introduces voltage violations due to the lack of network information. The DSM+LF implementation shows a significant improvement in both voltage levels and cable usage compared to DSM and no control, without significantly reducing the peak-shaving performance. Enough flexibility is found in the network to achieve this result.

V. DISCUSSION

The simulation results show that DSM can introduce voltage problems when network layout and properties are not taken

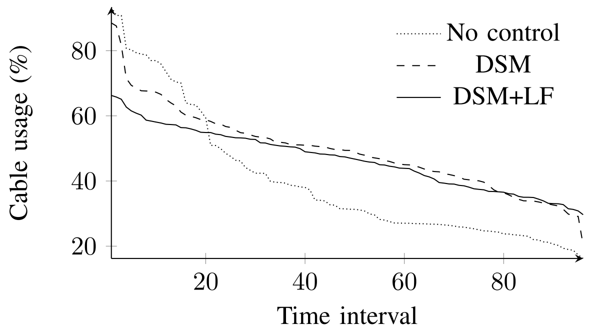

Fig. 4. Cable usage duration curve of the worst-case cable usage.

into account. The addition of network models and load-flow calculations is therefore advised to verify whether the results of certain DSM methodologies are feasible in realistic scenarios or not. The integration of these models and calculations is not limited to TRIANA.

The current implementation only uses voltage levels from load-flow calculation as feedback. As the voltage level is related to the currents and the cable properties, improving voltage levels also improves cable usage. This is an improvement after the initial planning, however. The network structure yields more options to incorporate network constraints in an earlier stage of planning by adding new planning partitions. These partitions could include balancing production and consumption of a fleet of households that are connected to the same phase or perhaps even the same feeder. From a network structure point-of-view these households are connected closest to each other.

The current approach with changing the prices based on local voltage levels is not a fair method. As voltage issues are more likely to happen at the end of the feeder, the chance of changing prices is higher for households connected at the end. These households have to offer more flexibility to prevent investments in the network that have to be paid by all users. Possible options could be to raise or lower the price for all houses connected to a certain phase on a certain feeder depending on the mean voltage level. Another option could be to set a fixed price for the amount of consumption or production that will not cause problems, while the rest is priced differently based on the situation of the network.

Note that changing prices does not give guaranteed grid stability as devices can be active regardless of high prices. To give these kind of guarantees, limits to consumption or production must be enforced. These limits can be lower than the installed fuses in households during certain intervals and depend on local grid constraints. These dynamic limits are possible with smart meters.

VI. Conclusions

Network models and a load-flow calculation algorithm with low complexity are integrated into TRIANA. The results show that the implemented load-flow calculations are accurate. The performance in terms of required computational time is also very good. The results of an initial implementation which combines DSM with load-flow feedback show a significant improvement in voltage levels and cable usage without a significant reduction of peak-shaving performance. Further improvement is required to guarantee compliance with EN 50160 regulations. This may also require hard consumption or production limits to ensure grid stability.

Integration of network models and load-flow calculations enable new optimization goals for planning, such as reducing transport losses and grid investments by utilizing the network more efficient. The information might also be useful to determine the locations and required capacity for energy storage . These goals and implementation improvements are left for future work.

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