

THE EFFECT OF RESIDENTIAL STORAGE AND CONTROL ON THE DISTRIBUTION NET COMPARED TO CENTRAL STORAGE AND CONTROL

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*“Each of you should use
whatever gift you have received
to serve others, as faithful
stewards of God’s grace in its
various forms”*

1 Peter 4:10 (NIV)

Abstract

Due to the emission of CO₂ and the depletion of fossil fuels, an increasing amount of research is done in the area of sustainability. One of the topics in the area is smart grids. A smart grid is an intelligent electricity network that connects all generators and consumers with each other. In such a network various technologies are used in order to make the network more stable and improve the quality of the power supply. Storage is one of the promising technologies for this.

Storage devices such as batteries or flywheels are used for various goals. Depending on the technology and application requirements, storage devices are used for, inter alia, power quality improvement or load levelling. However, it is not yet clear how these storage devices should be placed in the electricity network and how they should be controlled. This research compares various battery configurations, a central battery, residential batteries with central control and residential batteries without control (plug and play batteries).

A simulator is used to conduct simulations. The simulator that is used for the simulations, called Triana, is developed at the University of Twente and makes use of a real existing network with a scenario that consists of measured data. A new simulation step is introduced into the simulator in order to be able to use the batteries in the simulations. Moreover, analysis tools have been developed in Matlab for controlling the simulations and for analysing the data. A Multi-criteria analysis together with a sensitivity analysis is derived for rating the battery configurations on their performance on various network parameters.

A central battery (100kWh) next to the transformer feeding the low voltage network has been simulated first. It turned out that no effects in the low voltage network were observed as the situation on the secondary side of the transformer was unaltered and local problems were not resolved. Only the design load of the transformer was lowered. However, when the battery is shifted through the network, a positive effect on mainly the losses and the minimum voltage levels is observed. The multi-criteria analysis showed that the battery should be placed somewhere in the middle of the feeder with the severest PQ problems.

Second, the large battery is divided into 10 small batteries of 10kWh. An algorithm is developed that can place a battery in a house where the voltage levels deviate the most from an ideal voltage level. This procedure repeats until there is no storage budget left. It turned out that the improvement in the voltage levels, asymmetry and the reduction of losses is higher than the configuration with a central battery. Since the batteries are located at the most problematic areas, these areas are really improved. When there is a lot of generation in the network the improvement is even higher. Both the production and consumption peaks can be reduced in this case. Moreover, the minimum voltage level is already improved significantly with only three batteries in the network. The reduction in losses is proportional to the number of batteries.

Finally, the central Triana control is removed. The batteries are only steered on the local voltage levels. This improves the reliability and privacy since no communication system is necessary any longer. Moreover, a grid operator can easily deploy such a system since no demand-side management system is necessary. A Matlab tool that makes use of a droop controller is developed in order to determine the best possible (dis)charging thresholds for the batteries. This means that the behaviour of the plug and play batteries is shown assuming that a controller for the batteries can be developed in a smart way. The results show again an improvement of the voltage levels and the asymmetry. Furthermore, the losses are comparable to the residential batteries.

From the results described above, it can be concluded that batteries in smart grids can give a significant improvement in the stability and power quality in distribution networks. When it comes to voltage levels and asymmetry, the plug and play batteries outperform the other configurations due to the direct steering on the voltage levels, while it is technically the most simple approach as no communication infrastructure is necessary. When the plug and play batteries are compared with the Triana demand-side management approach, an improvement in voltage levels is obtained. The electricity durations curve is comparable and Triana obtained a higher reduction in losses. It is clear that the plug and play batteries are a very promising technology and that more research should be done on the development of a plug and play control system. In addition to this, more use-cases should be tested to see if the results still hold. Furthermore, it is interesting to look at the storage effects with the mid voltage network also taken into account, a steering system for the P&P batteries, an improvement of the battery models and to check if the results still hold for other use-cases.

Samenvatting

Door de emissie van CO₂ en het opraken van fossiele brandstoffen, wordt er steeds meer onderzoek gedaan naar duurzaamheid. Een van de onderwerpen op dit gebied zijn slimme energienetten. Een slim energienet of 'smart grid' is een intelligent netwerk dat generatoren en consumenten van energie met elkaar verbindt. In dit soort netwerken worden verschillende technieken gebruikt om de stabiliteit en de kwaliteit van het geleverde vermogen te verbeteren. Opslag van energie is hier een goed voorbeeld van.

Opslagmedia zoals bijvoorbeeld batterijen of vliegwielen worden gebruikt voor verschillende doelen. Afhankelijk van de specificaties van het doel worden opslagmedia gebruikt voor onder andere het verbeteren van de kwaliteit van het vermogen of het balanceren van lasten. Het is echter niet duidelijk hoe opslagmedia in het netwerk geplaatst moeten worden en hoe ze vervolgens bestuurd moeten worden. Dit onderzoek beschrijft een vergelijking tussen een centrale accu, accu's in huizen met centrale besturing en accu's in huizen zonder centrale besturing. Dit laatste type wordt ook wel 'plug and play' accu's genoemd.

De simulaties in dit onderzoek worden gedaan met een simulator genaamd Triana. Triana is ontwikkeld op de Universiteit Twente en maakt gebruik van een bestaand elektriciteitsnetwerk met een scenario dat bestaat uit gemeten waarden. Er is een nieuwe simulatiestap geïntroduceerd om in staat te zijn om de accu's te besturen. Bovendien is er een analyseprogramma geschreven in Matlab om de simulaties te besturen en de gegevens te verwerken. Een 'multi-criteria' analyse samen met een gevoeligheidsanalyse is toegevoegd om een score te bepalen van de effecten van de verschillende accu configuraties op verschillende netwerk criteria.

Als eerste is er een simulatie gemaakt van een centrale accu (100kWh) die naast de transformator die het laagspanningsnet voedt staat. Het bleek dat er geen meetbare effecten waren in het laagspanningsnetwerk omdat de situatie achter de transformator/accu onveranderd was. Alleen een aftopping van de piekbelasting op de transformator was zichtbaar. Echter, als de accu door het netwerk geschoven wordt, is er wel een zichtbare verbetering op met name de minimale spanning en de verliezen. De multi-criteria analyse liet vervolgens zien dat de accu het beste ergens in het midden van de tweede streng geplaatst kan worden. Hier zijn de problemen met de kwaliteit van de spanning ook het hoogst.

Hierna is de grote accu verdeeld in 10 kleinere accu's van elk 10kWh. Er is een algoritme ontwikkeld dat de accu kan plaatsen op de plek waar de afwijking van de spanningen het grootste zijn. Deze procedure wordt dan herhaald totdat alle accu's geplaatst zijn. Het is gebleken dat de verbetering in de spanningen, asymmetrie en verliezen groter is dan de simulatie met een grote accu. Dit komt doordat er op de slechtste plekken nu echt een accu staat die de problemen lokaal oplost. Wanneer er ook nog eens veel opwek is, is de verbetering nog groter doordat zowel de productie- als consumptiepiek kleiner wordt. Bovendien blijkt dat het al genoeg kan zijn om drie accu's te plaatsen omdat de minimale spanning dan al significant hoger is. De vermindering van de verliezen is proportioneel met het aantal accu's.

Tot slot is de centrale controle van Triana weggehaald. De accu's worden nu alleen gestuurd op de lokale spanning. Dit verhoogt de betrouwbaarheid en privacy doordat er niet langer een communicatienetwerk nodig is. Bovendien kunnen de plug and play accu's gemakkelijk geplaatst worden door de netbeheerder doordat er niet een heel 'demand-side management' systeem nodig is. Een Matlab programma dat gebruik maakt van een 'droop controller' is ontwikkeld om de

best mogelijke drempelwaarden te bepalen voor het op- en ontladen van de accu. Als gevolg hiervan is het resultaat de maximaal mogelijke verbetering laat zien voor het geval er een slimme aansturing voor de accu's gemaakt kan worden. De resultaten laten zien dat er wederom een verbetering is in de spanningen en asymmetrie. De reductie van de verliezen zijn vergelijkbaar met de vorige configuratie.

De resultaten zoals hierboven beschreven laten zien dat accu's in slimme energienetten daadwerkelijk een significante verbetering kunnen opleveren voor de stabiliteit van het netwerk en de kwaliteit van het geleverde vermogen. In het geval van spanningen en asymmetrie waren de plug and play accu's het beste doordat deze ook echt op de spanning werden aangestuurd. Als deze accu's vervolgens vergeleken worden met de aanpak van Triana dan presteren de accu's beter als er gekeken wordt naar spanningen. De 'electricity duration curve' is ongeveer vergelijkbaar en Triana wint het wat betreft de verliezen. Hieruit is het duidelijk dat plug en play batterijen een veelbelovende technologie is en dat er meer onderzoek naar gedaan moet worden. Met name een slim besturingssysteem is belangrijk. Ook moeten er nog meer netwerken en scenario's getest worden om te kijken of de resultaten dan nog steeds hetzelfde zijn. Daarnaast is het interessant om te kijken naar de effecten van accu's als ook het middelspanningsnet meegenomen wordt, naar een besturingssysteem voor de plug en play accu's, een verbetering van de accu modellen en een uitbreiding van de use-cases.

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1

Introduction

1.1 Motivation

Due to the emission of CO₂ and the depletion of fossil fuels, there is a growing awareness that energy must be generated in a sustainable way. Much research is going on to develop techniques for sustainable generation and reduction of the emission of carbon dioxide. As a result of this, a lot of wind turbines, photovoltaic cells, electric cars and other sustainable technologies are or will be deployed.

A number of trends can be observed in the energy field nowadays [1]. Besides the fact that the overall energy consumption is growing, it is also mentioned that an increasing percentage of the total consumed energy is electrically generated, consumed and transported. Next to this trend, more loads and generators are dynamic. This means that electrical loads and generators can sometimes be controlled. Finally, the different loads and generators are placed more decentralized.

The international community made agreements on the percentage of renewable electricity that is used. From the European Climate Forum [2]:

”To reach the EU target on emissions reduction of 80% by 2050, the European electricity system and its infrastructure need to be reinvented with the aim of reaching 100% renewable electricity by 2050.”

It is clear that a lot of work has to be done and all different types of new technologies need to be deployed.

One of these technologies is the so called smart grid. Smart grids are energy networks with smart (communication) technologies to make distributed generation possible. In [3] a definition is given for smart grids.

Definition 1. *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.*

An example of a smart grid is shown in figure 1.1. Besides the traditional central generation, a high penetration of electric vehicles, photovoltaic cells and other energy sources are shown. Communication devices and controllers are placed to make the network really smart. The controller in the middle of the image is the central place for all this communication.

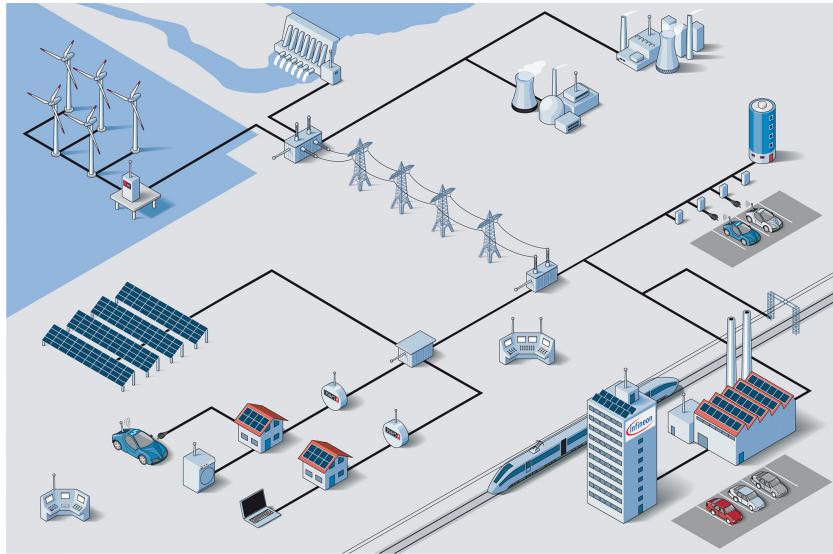


Figure 1.1: An example of the future smart grid (source: presseagentur ¹)

The high penetration of demanding loads and renewables comes with a challenge. The electricity network is developed decades ago. The design was rather simple since the electricity was produced only in a central place. With the introduction of new distributed generation and an increasing amount of loads, the grid is challenged and more flexibility is required [4]. One of the biggest challenges is to guarantee that the quality of the voltage and current in the network is within the norm set by the Autoriteit Consument en Markt in [5]. The quality of the voltage and current can be combined in the term power quality (PQ). Bollen introduced in his paper [6] a widely used definition of power quality.

Definition 2. *Power quality (PQ) is the combination of voltage quality and current quality. Voltage quality is concerned with deviations of the voltage from the ideal. And Current quality concerned with the deviation of the current from the ideal.*

In this definition the ideal voltage is a single-frequency sine wave of constant amplitude and frequency (in the Netherlands 50Hz) and the ideal current is a single-frequency sine wave of constant amplitude and frequency, with the additional requirement that the current sine wave is in phase with the voltage sine wave.

A lot of research is going on at the University of Twente and many other research institutes to improve the smart grid technologies. The university of Twente has developed Triana [7, 8]. Triana is a control strategy for matching generation and consumption patterns to improve the grid. Moreover, Triana can simulate this strategy even as the effects of various loads, renewable generators or batteries. Triana uses a three-step approach. The first step is the prediction of the demand, production and scheduling freedom. In the second step a planning of production and more important the consumption is made for the coming period. The last step covers real-time control of appliances. Controlling the grid assets is not yet implemented.

¹<http://www.presseagentur.com/>

1.2 Problem statement

The trends described in the previous section have a large influence on the electricity network. When more electricity will be used in the future, the infrastructure needs to be upgraded in order to be able to facilitate the electricity that has to be transported. Moreover, it becomes harder to guarantee a good power quality since the voltage levels become harder to control, harmonics are increasing due to power electronics in the network and so on. Since the amount of renewables is also expected to grow, generation in the lower parts of the network will grow. As a result of this the electricity network will become a 'two-way traffic' network.

Moreover, it can be observed that the generation curve of renewables and the demand curve are usually not equal. In most days, a peak in generation in the noon can be observed. However, the peaks in consumption generally occur during the morning and evening hours. This unbalance of energy demand and production should be balanced in order to facilitate the increasing amount of renewables and thus the reduction of CO₂. In figure 1.2 an example of a residential load profile and an example of a PV generation profile is depicted. It is clear that these curves do not match in time.

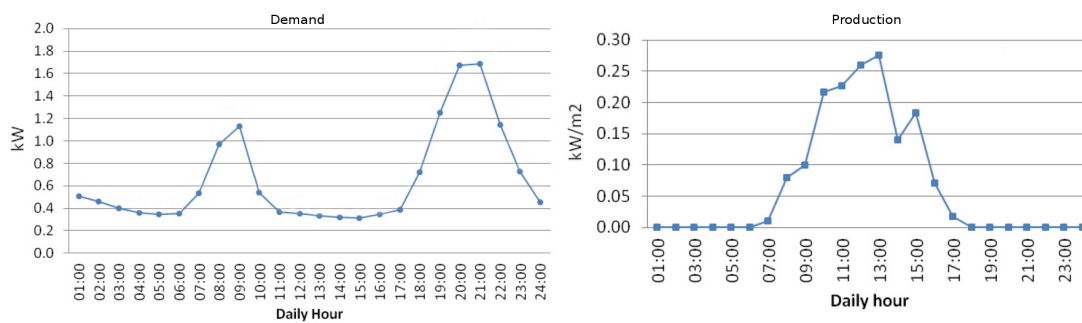


Figure 1.2: An example of a demand profile and a generation profile (source: [9])

One of the proposed solutions is energy storage. Energy storage can reduce the difference between the generation curve and the demand curve [10] by shifting the production or consumption in time. During peak periods of renewable generation which do not correspond with peak periods of demand, electricity can be stored and during peak periods of demand, the stored electricity can be injected into the network. From a transformer point of view the demand curve can be flattened with storage assets and a replacement of network components can be postponed. Furthermore, energy storage can be used for improving the different aspects of power quality.

Storage assets in electricity networks can be applied in two ways. First, the devices can be placed in a central place in the network and are controlled from a central network operator. Second, storage devices can be placed on household level. In both cases a positive effect on the network and power quality is expected. However, no real comparison between both techniques is available. This comparison will be the main purpose of this thesis.

1.3 Research questions

As mentioned before, the goal of this research is to make a comparison between central storage and residential storage. Both the effects on the network components and power quality will be taken into account. Furthermore, the placement and the sizing of storage devices will also be part of the research. The following research question and sub questions are formulated:

What is the effect of residential storage and control on the distribution network compared to central storage and control?

To answer this question some subquestions are defined:

1. What is the effect of central storage on power quality and network components?
2. Where should small storage devices be placed and what should be their characteristics?
3. What is the effect of residential storage and control on power quality and network components?

The answer to these three questions should give the answer to the main question.

1.4 Approach

This research consists of two phases. The first part of the research concerns a literature study and the second phase will consist of simulations in Triana and analysis of the results. In the literature study, general background is introduced even as recent studies on similar topics. The results of this literature research are described in the second chapter.

Next, the performed simulations will be described. When all simulation necessities are described in chapter 3, chapter 4 will address central storage. A central battery is placed in the network in order to simulate the effects on power quality and network components. The results of this chapter will give an answer to the first subquestion. Consequently, chapter 5 and 6 will describe the effects of respectively residential storage with and without central control. These chapter should provide answers to the second and third subquestions.

Chapter 7 addresses a comparison between all results obtained in previous chapters. The conclusion derived from this chapter and the previous chapters even as an overview of the answers to the research questions and future work are shown in chapter 8.

2

Related work

This chapter contains a study on the current state of literature related to the research questions. The structure of the chapter is as follows: The first section is an introduction. The structure of the Dutch electricity network is described, followed by the current trends in demand and supply. Since these trends have a large impact on the quality of the supplied power, power quality and solutions for improving power quality are addressed next. One of the solutions for power quality issues is electrical energy storage (EES). This is addressed in the second section in general and the next section addresses the applications for storage assets in the network.

Section 2.4 zooms in into the research question. Triana, a demand-side management methodology, developed at the University of Twente, is introduced since it will be used in the implementation phase of this research for simulation the effects of storage on the electricity network. Storage can be applied in two ways that are described in the remainder sections. Section 2.5 describes central storage in the distribution network and the last section describes local storage. In both sections the sizing and placement of the storage devices are mentioned even as the contribution to the quality of the electricity network.

2.1 Introduction

2.1.1 Electricity distribution networks

The function of the electricity network is described as the transportation of electrical power from the location where it is generated to the location where it is consumed [11]. This functionality is described in more detail in the book of Kundur [12]. It summarizes the main goal of the network with the following three items:

- The system must be able to meet the continually changing load demand for active and reactive power, without equipment and connections getting broken.
- The system should supply energy at minimum cost and with minimum ecological impact.
- The quality of power supply, mostly called Power Quality (PQ), must meet certain minimum standards.

Before zooming in into these goals, the Dutch network structure is described in more detail.

The Dutch electricity network can be divided in three main parts. The first part is the High Voltage (HV). This part of the network deals with transport of large amounts of power. To be

Part of the network	Function	Voltage levels
HV	High power transport	$50kV \leq U_{\text{nom}} \leq 380kV$
MV	Regional distribution	$3kV \leq U_{\text{nom}} \leq 25kV$
LV	Distribution to end-user	$U_n = 0,4kV$

Table 2.1: A short overview of the different parts of the Dutch electricity networks

able to achieve this, a high voltage is required. With a high voltage, the current can be lower. Hence the losses will be reduced significantly since this is determined by I^2R . Besides the transport of electrical energy, also bulk generation is connected to this part of the network. The HV network exists of several parts, but this is beyond the scope of this thesis.

The second part, the Medium Voltage (MV) network is via transformers connected to the HV network and is a lot bigger (in cable length) than the HV network. It transports the energy in smaller amounts to the substations where it is again converted to a lower voltage. Some large industrial users are connected to this part of the network just as some large scale renewable generation (e.g. wind turbine parks).

The last step in the network is the low voltage (LV) network. The LV network is responsible for delivering the energy from the substation to the end-user. Since more and more end-users are also producers, the LV network is also responsible for distributing the local generated energy through the network. Table 2.1 shows a short overview of the different parts of the Dutch electricity nets and their voltage levels.

Figure 2.1 shows a graphic overview of the structure of the network. The red and orange areas on the image are part of the High Voltage network. The green part is the MV network and the blue areas are the low voltage network.

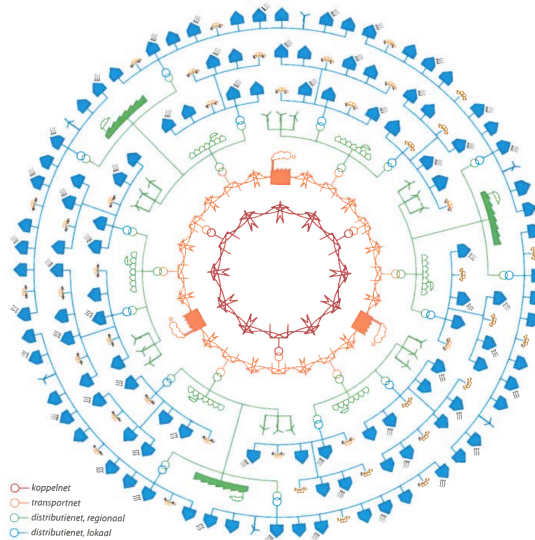


Figure 2.1: The structure of the Dutch energy network (source: [11])

Since the major part of the Dutch electricity network is in the MV and LV parts and most power quality problems occur in this areas [11], the HV part is not further considered in this thesis. There are still PQ problems in the HV [13], which is operated by the transmission system operator (TSO), but the focus of this thesis will be on solving PQ problems in lower parts of the network. Furthermore, when PQ problems in the LV and MV networks are reduced, less problems will be propagated to the HV network. The MV and LV parts together are called the distribution network (DN) and are operated by the distribution system operator (DSO).

Definition 3. *The distribution network is the aggregation of the MV and LV network.*

The various network levels are connected via transformers that are placed in substations. In a high power substation, the voltage from the HV network is transformed to the voltage suitable for the MV network and vice versa. In a distribution transformer, the MV and LV networks are connected. Households are usually connected to one of the three phases of the LV network, although new costumers are nowadays connected to all three phases. Figure 2.2 shows a typical layout of the connection structure. Six feeders, with a decreasing thickness, provide the connections to the households. The transformer on the left side of the figure is connected to the MV network.

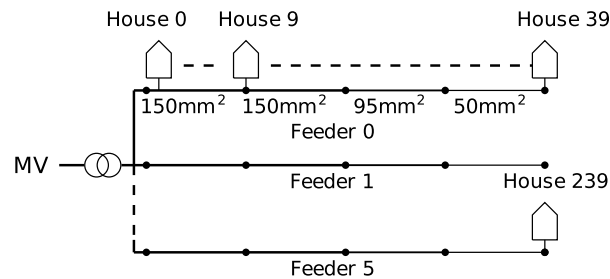


Figure 2.2: *Typical layout of a Dutch LV network with 6 feeders, usually up to 500m, and 40 connections per feeder (source: [14])*

The electricity network consists of more components (such as switches), but cables and transformers are the most important for this research since these network components are the most vulnerable to power quality problems [15].

2.1.2 Trends in demand and supply

As stated before, more and more small scale renewable and demanding loads (for example electrical vehicles) are deployed in the low voltage network. Since this trend has a large impact on the power quality they are mentioned in this subsection. This subsection describes the main techniques currently available. There is a separation between generators and loads.

Generators

In figure 2.3 a bar diagram is depicted with the percentage of penetration of the four most used renewable energy sources since the year 2000 in The Netherlands. It is clear that there is indeed a growing amount of renewables in the Dutch network. Furthermore one can see that the major part of the energy is generated using biomass, followed by wind energy. However, biomass is not very suitable for small scale generation [16] and for that reason not further considered in this thesis. This also applies to large scale hydro power.

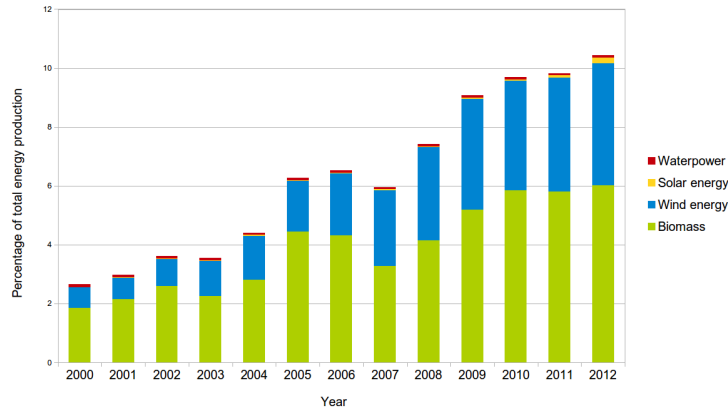


Figure 2.3: (source: CBS ¹)

Photovoltaic (PV) cells and Wind Energy Conversion Systems (WECS) convert respectively solar radiation and wind to electrical energy [17]. The wind turbine of WECS capture the kinetic energy via the rotors that drive a generator inside the turbine. Commercial turbines have typically a size between 300kW and 5MW [17].

Photovoltaic cells need an inverter to integrate to the grid [17] since they produce DC where AC is required. The produced energy can be fed into the grid via a DC-AC converter. In 2010 PV cells had a typical generation of 100 – 120Wp per m² [17] and a typical production of a house was about 0.5 – 2 kW. The efficiency of PV technology is getting better and better over time, but more efficient PV cells are still expensive.

The concept of micro combined heat and power (μ CHP) supplies both electricity and heat. With for example natural gas as input for the system. Since the wasted heat is captured, the efficiency of such a system can reach up to 90% [18]. μ CHP systems can generate up to 50kW of electrical energy [19].

Loads

Since electricity can be generated in a sustainable way, more and more loads such as heat pumps and electric vehicles are deployed. Both technologies are briefly introduced here.

A growing amount of heat pumps is deployed [11]. Heat pumps can warm houses in a more sustainable and efficient way than traditional techniques. Since the heat pumps use electricity (typically 2 to 5 kW), the total consumption of electricity will grow with the deployment of heat pumps.

Besides the introduction of heat pumps, the penetration of electrical vehicles (EVs) is also getting higher. It is not difficult to imagine that it has a high impact on the network when a large amount of EVs are charging at the same time. In [11] it is stated that the energy demand of households can even double with the introduction of new demanding loads with more PQ problems as a

¹<http://www.cbs.nl/>

result.

2.1.3 Power quality

As stated before, the quality of the supplied power is an important research topic nowadays. With an increasing amount of renewables and electric loads deployed in the distribution network, this research will become even more important since these trends have a large impact on the power quality. The power quality is determined by the deviations of the supplied power compared to an ideal supply. These deviations can occur due to changes in the loads, disturbances in appliances and the occurrence of short circuits. This is a co-operation between the customer and the network operator.

The extent to which these disturbances may happen are described in an European norm [20]. This norm is introduced for obtaining a consistency between all participants in the distribution network. In the Netherlands, a stricter version of the EN-50160 norm is implemented in the netcode [5]. Since this research is considering Dutch networks the netcode is used as norm in this thesis. Table 2.2 shows the most important restrictions stated in the Dutch netcode.

Quality aspect	Requirement
Frequency $\hat{A}\hat{U}$	- 50 Hz +/- 1% during 99.9% in a year - 50 Hz + 2% /- 4% during 100% of the time
Slow voltage fluctuations $\hat{A}\hat{U}$	- 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 fluctuations $\hat{A}\hat{U}$	- $\leq 10\%U_{nom}$ - $\leq 3\%U_{nom}$ in situations without interruption of production, large consumers or connections
Asymmetry $\hat{A}\hat{U}$	- 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 $\hat{A}\hat{U}$ $\hat{A}\hat{U}$ $\hat{A}\hat{U}$	- 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 - The total harmonic distortion (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 [5, 11]

In this table the asymmetry is defined as the deviation of the voltage of the three phases compared to the symmetry in the phases. Harmonics however refer to the decomposition of a non-sinusoidal but periodical into a sum of sinusoidal components [6]:

$$f(t) = \sum_{h=1}^{\infty} A_h \cos(2\pi h f_0 t + \varphi_h) \quad (2.1)$$

With A_h and φ_h amplitude and phase for harmonic order h , $f_0 = 1/T$ and T the period.

Depending on the various appliances and installations, the possible occurrence of disturbances may differ. Table 2.3 shows an overview of the expected disturbances of various appliances and installations.

Equipment	Voltage variations	Over-voltage	Harm- onics	Flicker	Asym- metry
Households, small business	x		x	x	x
μ CHP	x	x			x
PV		x	x		x
Heat pumps	x		x	x	x
Wind turbines	x		x	x	

Table 2.3: The expected disturbances of various appliances and installations [11].

Bhattacharyya et al. have written a paper about the consequences of poor power quality [21]. They state that complaints due to PQ disturbances are increasing every year among different types of consumers. Moreover it was found that about 70% of this disturbances are caused by the customers themselves. Besides this conclusions they also give an overview of the different reasons of the complaints. They state that the main PQ complaints in a distribution network are due to voltage dips and voltage transients. Since this paper is already written in 2007 and the penetration of renewables and demanding loads is increasing, it is likely that voltage problems are increasing. Röhrig simulated this in [22] with a 25% penetration of renewables and concluded that no limits were violated, although the obtained values were close in some cases.

In [23] a study is presented for calculating the costs of PQ violations. Since poor PQ can break equipment, it takes time and money to repair this. Figure 2.4 depicts the total costs of bad PQ in the European Union in 2007 in billion euros. Keeping in mind that the costs of over-voltage and other PQ problems will increase, it is clear that new solutions to improve PQ are very important.

2.1.4 Solutions for improving power quality

Since the growing importance of improving the power quality, all kinds of techniques are developed to reach this goal. This subsection describes the most important techniques. First the installation of new cables is discussed followed by a description of smart transformers (ST). After this net-based solutions demand-side management (DSM) is described. This subsection concludes with the introduction of electrical energy storage (EES). EES will be the main focus

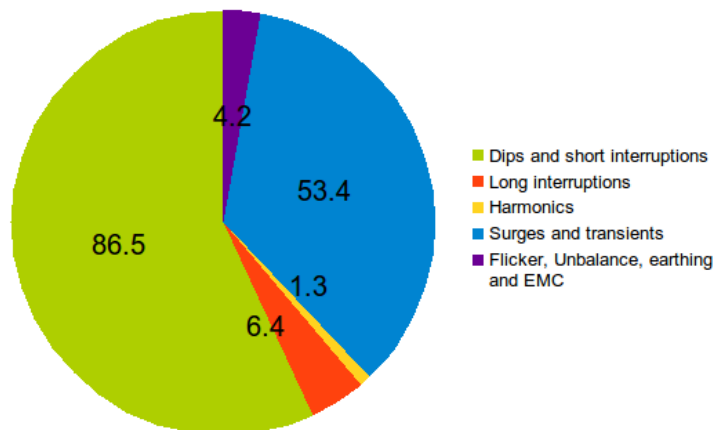


Figure 2.4: Costs of PQ wastage in the EU in 2007 in billion euros. (source:[23])

of the further parts of this thesis.

Power quality in the distribution network can be improved by simply adding more or thicker cables. As a result of this, the total resistance of the cable will decrease. Hence the total transport capacity will increase. However, adding more or thicker cables is expensive. Therefore this solution is not very feasible [24, 25].

Another solution to improve power quality is the introduction of smart transformers. Smart transformers are able to adjust the number of windings during operation, in order to be able to vary the transformation ratio. A more detailed description of smart transformers can be found in [26]. The impact on the future smart grid is discussed in [27] with a case-study in [28]. It is stated that the introduction of smart transformers between the MV en LV network will significantly improve the power quality. However, it is mentioned that it is very expensive to place and maintain a ST. Maintenance is expensive due to wearing on mechanical parts.

In addition to these net-based approaches, there is also a lot of research going on in the topic of demand side management (DSM). The goal of DSM is to match the demand and production of electricity. As a result of this less peaks will occur in the DN and thus the PQ will increase. In [29] an overview is given of the main benefits and challenges of DSM. In order to achieve a better match between consumption and production, the customer becomes an active participant in the energy market. When there is too much production, a central controller can send low prices to the customers. This will give an incentive to switch on some appliances since energy is now cheap. In the case that there is a low production, prices become high and as a result of this the consumption will also decrease.

However, most DSM approaches do not include the actual physical distribution grid characteristics. It is assumed that there are no limits on the network and its components, which is of course not true. This can be improved by adding load-flow feedback to the DSM system. This is described by Hoogsteen et al. in [14]. Load flow feedback is added to Triana. Triana is a DSM planner and simulator and is developed by the University of Twente. In section 2.4 more details about Triana are given.

Another way of reducing peaks is to add storage in the network. The principle is simple: The storage device is charged when the voltage level is too high and it is discharged when the voltage level is too low. As a result of this the peaks in the distribution network will be flattened with a better power quality as a result. A literature example of peak-shaving with storage can be found in [30]. A practical example is shown in figure 2.5. The most obvious form of EES is the use of batteries, but also other technologies are available such as flywheels. An overview is given in section 2.2.



Figure 2.5: A large battery is installed in The Netherlands. (source:Alliander²)

2.1.5 Conclusions

This section introduced background information for the further parts of this thesis. Since the aim of this research is to investigate the effects of storage devices for improving power quality in the distribution network, the introduction of new loads and renewables and known solutions for improving PQ are described. It became clear that the increasing amount of sustainable technologies have an enormous impact on the grid. A lot of work has to be done on all kind of solutions for keeping the PQ within limits. It is evident that a solution has to be found that is a combination of all available technologies.

2.2 Electrical energy storage

This section describes the most important types of electrical energy storage (EES). First pumped hydro storage and compressed air storage are described. After these technologies flywheel systems and super capacitor storage systems are addressed. Since there are a lot of battery types,

²<http://www.alliander.nl/>

subsection 2.2.2 contains a description of the most used battery types. In the section that follows, the applications of the different storage types are described. Subsection 2.2.5 summarizes the section and shows the conclusions.

2.2.1 Energy storage technologies

Pumped hydro storage (PHS) is a large scale storage system. When the system is storing, water is pumped into a lake. This is mostly done when there is a low electricity demand in the network. If the demand is high again, water flows from the upper reservoir to the lower reservoir due to gravity. This will activate the turbines and electricity will be generated. An example of a PHS system is shown in figure 2.6. The capacity of the stored energy is proportional to the amount of water in the upper reservoir and the height of the waterfall [31].

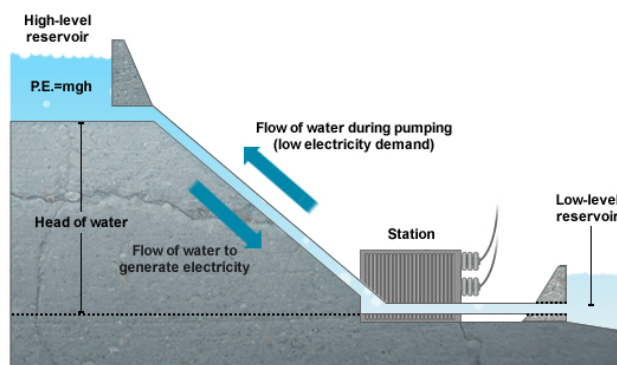


Figure 2.6: A pumped hydro storage installation (source: BBC³)

An other technology for large scale energy storage is compressed air energy storage (CAES). A CAES system can store air in an underground reservoir by means of powering an motor connected to a compressor [32]. When the electricity is needed again, the compressed air is drawn from the storage cavern, and drives a generator together with natural gas. Only two plants have been constructed at this time. One in Germany (290 MW) and one in the USA (110 MW) [31].

Both PHS and CAES systems deal with high powers and are quite slow. Therefore PHS and CAES are used for centralized storage and as a back-up when large amounts of energy are necessary in the network. A major drawback is that both systems have special demands on the landscape and are therefore not widely deployed.

Flywheels can store energy in form of kinetic energy. An internal mass is spinning at a very high speed and drives a generator when it needs to generate energy, or is driven by a motor when it is storing energy. The energy storage limits for flywheels are dependent on the mechanical strength and density of the materials which make up the rotor, typically high strength carbon composites [34]. Figure 2.7 shows an example of the internals of a flywheel. The rotor is placed in a vacuum for minimizing the air resistance. It is due to this resistance and the resistance from the bearings, that flywheels are not very efficient over time. In [35] it is stated that for a flywheel with an initial efficiency of 85 % the efficiency will drop to 78% after 5 hours and 45% after one day. However, storing energy in a flywheel is considered as an optimal storage technology for power smoothing and frequency regulation, where high power-to-energy ratios (short high power bursts) and high charge-discharge frequencies are required [36].

³<http://www.bbc.co.uk/>

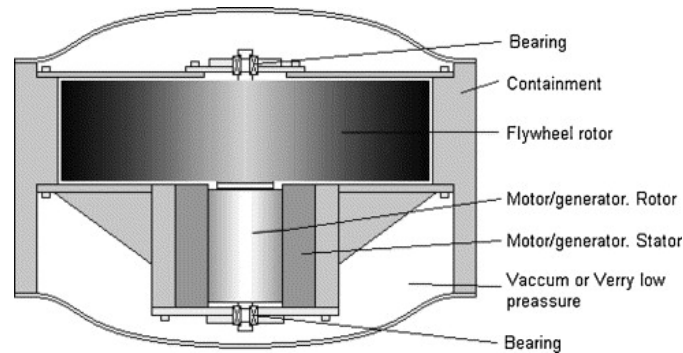


Figure 2.7: A flywheel system (source [33])

Super capacitors are based on electrochemical processes just as batteries, except that there is no chemical reaction [35]. This gives a large increase of the number of the cycling capacity. Due to their low-cell voltage (about 2.5-4 V), the voltage needed for connecting to the network is obtained by the series and parallel connecting of the cells [31]. A high power density combined with a high self-discharge, make super capacitors useful for systems where a short time response is required. An example can be found in [37] where super capacitors are successfully used in a laboratory experiment for increasing power quality.

Batteries are the most used form of electrical energy storage. Energy is stored in the form of electrochemical energy and the desired voltage and capacity are, as with the super capacitors, determined by series and parallel connections. The next subsection introduces some battery technologies that are often used.

2.2.2 Types of batteries

The lead-acid battery is the most mature type of battery [31]. Lead-acid batteries are often used in the automobile industry or as uninterruptible power supply (UPS) systems. Moreover, they are used for utility level energy management [38]. The benefit of this type of batteries is their relative low cost. As disadvantages, the low number of life cycles and the low energy density are mentioned.

The energy density of sodium sulphur (NaS) batteries can be up to three times higher than lead-acid batteries. Together with a long cycle life and low material costs, NaS batteries are very suitable for peak-shaving and energy management in a central place. It is not suitable for small scale applications since an operation temperature of 300 °C is required [39].

Lithium-ion batteries have been developed for powering consumer electronics such as mobile phones. More recently Lithium-ion batteries are used in (hybrid) electric vehicles [38]. The main advantage of this technology is the very high energy density combined with a high efficiency. This makes Lithium-ion batteries a good candidate for PQ applications like voltage support and smoothing fluctuations from renewable sources [39]. As a drawback, the high costs are mentioned.

An other technology mentioned in [40] is the redox flow batteries (RFB). A RFB stores energy in two tanks, an anodic and cathodic reservoir [31]. Divya et al. in [40] mentioned some advantages

and disadvantages. As advantages are listed: a high power, long duration, fast response and no self-discharge. A drawback is the low efficiency due to the energy needed to circulate the electrolyte and losses due to chemical reactions.

2.2.3 Characteristics of energy storage techniques

In [35] the most important characteristics for storage devices are listed. Since one of the research questions is about the characteristics of storage devices, an overview of these characteristics is given in table 2.4.

Characteristic	Explanation
Storage capacity	The quantity of available energy in the storage system after charging (W_{st} in Wh)
Available power	The power that is available (P in W or Wp)
Depth of discharge	The amount of energy that is already used (DoD in %)
Discharge time	The maximum power duration ($\tau(s) = W_{st}/P_{max}$)
Efficiency	The ratio between released energy and stored energy ($\eta = W_{ut}/W_{st}$). Where W_{ut} is the used energy
Cycling capacity	The number of times the storage unit can release its energy (N)
Autonomy	The maximum amount of time the system can continuously release energy ($a = W_{ut}/P_d$). Where P_d is the maximum discharge power
Costs	Generally, the investment costs of storage is factored out ($C = C_1W_{ut} + C_2P_d$). Where C_1 is in €/kWh, C_2 in €/kW and P_d represent, respectively, the unit cost per total energy capacity, discharge power and nominal discharge power. The operational costs, spread over the lifespan of the system, are supposed to be proportional to the investment costs. For the total costs the following formula is used: $C_t = (aC_1 + C_2)P_d$
Feasibility	The storage type needs to be closely adapted to the type of application
Self-discharge	The portion of the energy that was initially stored and which has dissipated over a given amount of non-use time (SD in %)
Density of energy	The maximum amount of energy per unit of mass or volume of the storage unit (MJ/L)
Operational constraints	Especially related to safety (e.g. explosions) or other operational conditions (e.g. temperature)
Reliability	The guarantee of on-demand service
Environmental aspects	The effects on the environment (e.g. recyclable materials)

Table 2.4: Storage device characteristics (source: [35])

2.2.4 Fields of applications for storage technologies

According to [41], permanent energy storage applications can be classified into three main operational categories:

- Power quality required: Stored energy is used for a small amount of time to ensure the quality of the delivered power.

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- Buffer and emergency storage: Stored energy is used for seconds to an hour to ensure service continuity and support black-starts.
- Energy management: Stored energy is used to decouple synchronization between generation and consumption.

The first category requires a fast response from the storage device and the last requires a large amount of energy over a longer time. Roughly, power quality applications are in the range of seconds, buffer and emergency storage in the order of minutes and energy management in the order of hours. In figure 2.8 the storage techniques are rated for these three types of applications. In further sections a larger description can be found of this categories.

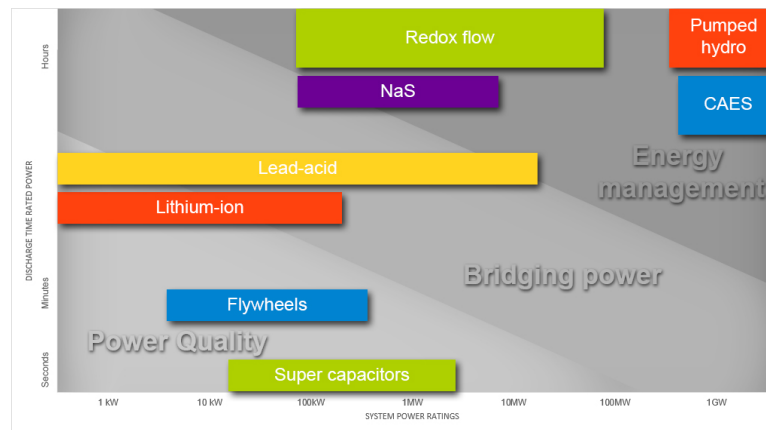


Figure 2.8: Distribution of storage techniques as a function of their field of application (based on [35, 41, 38])

2.2.5 Conclusions

This section introduced the most used storage technologies. It is clear that not all types of storage device useful for all types of applications. When a large amount of energy is needed and speed is not a crucial factor, hydro storage and compressed air storage seem to be good candidates. For peak shaving and load leveling applications, lead-acid, lithium-ion and sodium-sulfur batteries are favorites. When a high reaction speed and a high power density is needed for power quality applications, lithium-ion batteries, flywheels and super capacitors are a good choice. It is thus important to use the right type of storage for a certain application.

2.3 Applications of storage systems

As mentioned in subsection 2.2.4 energy storage applications can be divided in three types of applications, short-term, mid-term and long-term. This section gives an overview of these three categories and describes the contribution to the solutions for problems in the network. For each category some examples are mentioned and some recent research is described. A list of applications can be found in, inter alia, [31, 38, 39, 42]. First, power quality is addressed. In subsection 2.3.2 spinning reserve, black-start and renewable integration are addressed. Finally, in the long-term subsection, load following, load shifting and peak shaving are addressed.

2.3.1 Short-term applications

Power quality management

Power quality applications require a fast response and a high power density. For this flywheels, lithium-ion and super capacitors are most suitable for this type of application. Compared with other applications (e.g. load leveling), less literature is available about PQ applications of storage assets. Below some recent research is described.

In [43] an overview is given of some PQ aspects and the use of storage to gain PQ improvement. When it comes to compensating harmonics from nonlinear loads, Khadem et al. in [44] propose a system that includes a storage device and a static synchronous compensator (STATCOM) device for harmonic reduction. A STATCOM device can both source or sink reactive power to the grid. In combination with the storage device it becomes also possible to provide or consume active power. However, no test data are given.

Another example of a STATCOM for PQ improvement can be found in [45]. A STATCOM combined with a battery energy storage system (BESS) is used to mitigate flicker. A mitigation of 86.6% is obtained with the system.

An other aspect of PQ is described in [46]. Experiments are done to improve the power quality with a battery system. Significant improvements are gained in reducing harmonics and transient voltage variations. However, this improvement is not quantified.

More examples of PW improvement with storage devices can be found in [47]. An overview of literature addressing the topic of power quality improvement with the use of super capacitors is given. Besides the use of capacitors also flywheels are used. An example of this can be found in [48]. Zang et al. did research on improving PQ using flywheels. They found an improvement of mainly the voltage stability, although no exact numbers are given.

In traditional power systems, generators have been used to balance the frequency between power generation and load [49]. If the system detects instability in the frequency, the generation will vary its output to fulfill the requirement of demand. Since there is an increasing amount of decentralized generation, this will become harder to control. As a solution batteries are deployed for local frequency control to improve power quality.

Traditional frequency control mechanisms show a three step approach [50]. During the primary stage, the frequency deviation can be canceled very rapidly. A (de)central coordination is considered in the second step. In the final step, which is not always required, this coordination is done via the distribution system operator (DSO) in a central place. In [51] it is suggested that modern smart grid systems should follow a similar structure. Serban and Marinescu [50] implemented such a structure using batteries and they gained a significant improvement of the frequency stability.

In [52] a storage system is used for dynamic frequency regulation on a French island. Super capacitors were used because of their fast response. It is shown that the impact of PV and wind turbines on the frequency stability is reduced due to the capacitors. Therefore, more renewables can be deployed in the network without the need of grid reinforcements.

Finally in [53] network balancing is concerned. Once again a STATCOM/BESS combination is

used. When loads are unbalanced, the system is capable of providing or absorbing power to each of the phases in order to balance the loads among the phases.

In each of the above mentioned papers an improvement of the power quality is obtained. However, it must be said that this is not always the case with storage systems. An example can be found in [54] where the concept of vehicle to grid (V2G) is described and simulated. In a V2G system the energy stored in an electric vehicle can be used for improving the quality of the grid. Kim et al. connected a BESS to an EV charging system for voltage stability improvement. They concluded that the power electronics used for the BESS introduce harmonic distortion. Accordingly, when using storage for increasing power quality this effect has to be taken into account.

2.3.2 Mid-term applications

Spinning reserve

According to [31], spinning reserve is unused capacity that can be activated by the DSO when power problems occur on the grid. A large range of storage technologies is suitable for this purpose since power losses can occur for various time periods. When the time periods are small, flywheels can be used and with larger periods redox flow batteries are mentioned often in literature [31].

Black-start

According to [55] a black-start procedure is the procedure to recover from a total or partial shutdown of the transmission system which has caused an extensive loss of electricity supply. In general, all power stations need an electrical supply to start up. With a working grid connection available a plant can use the grid for that start procedure. In the case that the grid is down a battery can be used.

In [40] it is stated that the batteries will have a high economic value if they will be used for black start during grid outages. However, quantifying the exact economic gain provided by batteries when used for black start is still an open problem.

In [56] simulations are done for a black-start procedure in an islanded micro-grid. It turns out that storage devices play a key role in successfully recovering the system. Wang et al. in [57] describe a Chinese pumped hydro station in order to support the black-start procedure. An objective function is given for maximizing the black-start benefits and the peak shaving benefits. Field tests and simulations show the feasibility of the proposed method.

Renewable integration

With the intermittent nature of renewables, storage assets are needed to facilitate a higher penetration of renewables [58]. Barton and Infield investigated this in [58] and discovered that 10% more wind energy can be absorbed in the grid with storage (e.g. flywheel) available for covering 10 minutes of full generation power. Furthermore, when a 24 hour (e.g. redox flow) battery is available, 25% more wind turbines can be deployed in the network. However, in this situation it can not be guaranteed that curtailment is excluded. Besides this there is no real attempt to calculate the size of the battery and the system is far from economically feasible.

A more detailed use of batteries for integrating renewables is shown in [59]. Figure 2.9 shows a schematic overview of their system. A wind turbine is via an transformer and a converter connected to the storage system. This part of the system is connected to the grid and the loads via a STATCOM and inverter.

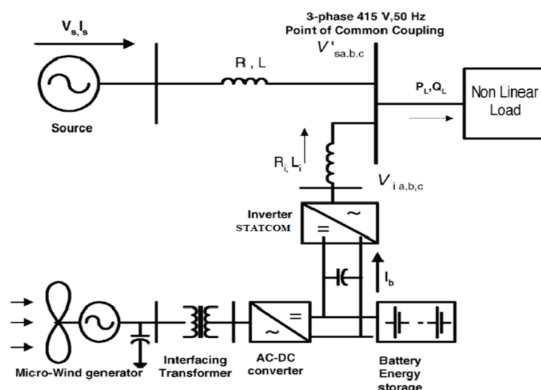


Figure 2.9: An example of a battery used for renewable integration (source: [59])

The battery together with a STATCOM system is placed between the generator and the network. It is shown that both grid side and generator side power quality is improved. As a result of this, more wind turbines can be installed in the system without power quality problems.

In [60] a network with a high penetration of PV is simulated for 60 minutes at a one minute resolution. It is shown that distributed energy storage has a large potential to mitigate the impacts on the energy network by acting as an energy buffer. Once again, a higher penetration can be reached without the need of grid reinforcements.

Finally, in [61] it is stated that energy storage of a single type cannot perform well when for example both peak shaving and power quality is the goal. With simulations it is shown that a combination of ultra capacitors and a large battery can perform very well for integrating renewables. This is result is as expected from the conclusions in the precious section. The capacitors are very suitable for power quality improvement and the large battery is suitable for peak shaving.

2.3.3 Long-term applications

Load following

According to [39], load following involves increasing or decreasing the output of some generation source to follow the load profile of the power system. With rapid fluctuations at the customer's side, the storage system can act as a buffer in order to follow the load and isolate the fluctuations from the grid [41].

In [62] a study is described where a large hydro installation is used for load-following to match the predicted load curve. They obtained that 83.9% of the prediction errors could be repaired with the storage system. Moreover a decrease of 46.4% in frequency deviation was obtained.

Load shifting or Arbitrage

In [39] it is stated that load-shifting is one of the main applications of storage assets in the network. The principle of load shifting is rather simple. When the amount of generated energy is high, a storage device will be charged. When there is a low energy production and a high demand, the battery will be discharged again. As a result of this, the demand and generation curves are matched better and the grid stability will increase.

This application is very close related to arbitrage. Economically, arbitrage is the process of the simultaneous purchase of a product at a low price in one market and selling that product for a higher price in another market. In power systems arbitrage is defined as the process of buying electricity when the price is low and selling it when the price is high. This has the same effect on the network as load shifting. In [63] it is stated that it is likely that the grid operator will not be allowed to exploit this benefit in a restructured energy sector since commercial optimization and technical optimizations overlap each other. Boa et al. [64] note that besides the advantages for the DSO, also the economical advantages for customers since they can buy energy cheap in valley periods. More about the different stakeholders can be found in [65].

In [66] arbitrage is described from a more economical point of view. Arbitrage is done with a PHS installation in the eastern states of the USA. It is mentioned that large-scale deployment of energy storage, which smoothes the load pattern by lowering on-peak and increasing off-peak loads, will result in a similar smoothening of the price pattern and reduce arbitrage opportunities.



Figure 2.10: A storage facility in China (source: [67])

An other example of load shifting can be found in [67] where a very large scale (14MW/63MWh) lithium-ion battery is used for energy management in the Chinese grid. The paper describes a system to control this large installation. A variety of applications has been integrated in this system including load shifting and load following. In figure 2.10 a picture is shown of this storage installation.

A load shifting example with the concept of a virtual power plant (VPP) is introduced in [68]. A VPP is an aggregation of renewable installations. In the described VPP, batteries are used for flattening the production of such a VPP.

Finally, in [69] a study with NaS batteries for arbitrage is investigated. It is stated that some major opportunities to make money are there, but due to rules (as noted in [63]) and initial costs it is not yet feasible.

Peak shaving

The concept of peak shaving is quite similar to load leveling. Electrical energy is stored when the generation peak is high and discharged when the generation peak is low. In case the load is higher than the local generation, the battery can be discharged in order to reduce the peak load on the transformer.

In [70] three methodologies are compared where the objective is to get the greatest possible peak demand reduction. The first one is set-point based. The battery is charging when a certain set-point in the consumption is reached. In figure 2.11 it is shown that the choice of the set-point is really important since it is possible that the highest peak is not reduced when the battery is already full.

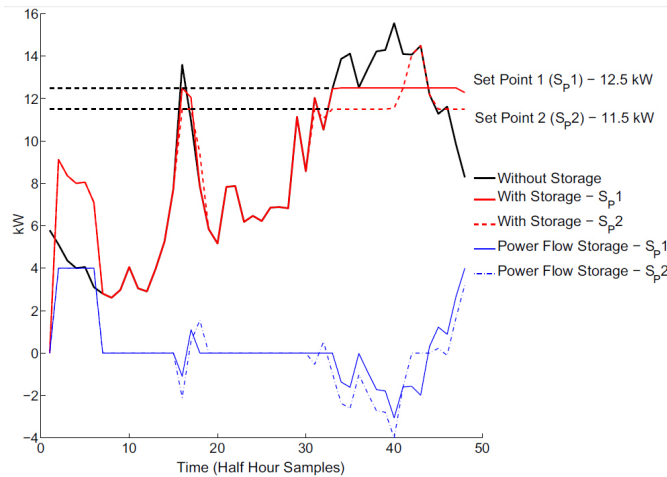


Figure 2.11: On time step 40 the battery is empty and the demand peak can no longer be reduced (source: [70])

Second, an off-line peak reduction algorithm is described where the energy is stored for the shortest possible time. Third, an algorithm where historical data is concerned is introduced. Data windows of various time spans are used. They conclude that the probability of a better result with the off-line algorithm is always higher than the set-point based approach. The probability for gaining a better result with the third approach depends on the window size. A smaller window gives less peak reduction, but a higher probability that the peak will be reduced.

In [71] the requirements on storage assets to reduce the feed-in peak of distributed PV and wind generation is derived. It turns out that storage assets used in combination with wind turbines are faced with an energy to power ratio that is twenty times higher compared to PV. For this, the peak can be reduced with storage technologies, but it is still very expensive.

In [72] the first findings of a peak shaving algorithm with a 580 kWh lithium-ion battery are described. It is shown that the algorithm can reduce the peaks significantly. The results are called promising and further research will involve voltage and frequency regulation.

Leadbetter and Swan [73] investigated the size and effectiveness of residential storage on peak shaving. They simulated a peak demand reduction between 42% and 49% in all Canadian regions except Quebec (28%). These reductions are achieved with a battery capacity between 5 and 8 kWh. The exception for Quebec was due to the high penetration of heat pumps.

An example of a storage system in the MV network can be found in [74]. Fleckenstein et al. described a sodium-sulfur system for peak shaving in Germany. Simulations are done with a 4, 8, 16 and 20 MWh battery. A peak reduction up to 42% is obtained with the 20 MWh battery.

An other strategy can be found in [75] where algorithms are proposed to minimize the maximum energy request. An efficient optimal algorithm for the off-line problem is derived and for the on-line problem heuristics are used. Furthermore an algorithm to determine the battery size is given.

2.3.4 Conclusions

This section describes three categories of storage applications in smart grids. It is clear that storage assets can be used for a lot of targets in the network. However, as stated before, the use of storage is both expensive and promising [25].

In figure 2.12 the applications that are mentioned are depicted in an organized way. From the previous section it is already clear that a high power density is necessary for PQ applications and a high energy density is necessary for high energy applications.

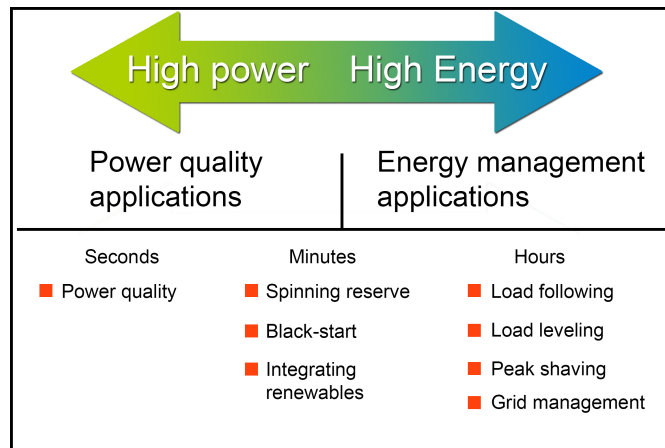


Figure 2.12: An overview of storage applications: (based on: [76])

2.4 Triana

The previous sections described some background related to storage in smart grids. The remaining sections of this chapter will zoom in into the topics related to the research questions. This section describes the basic concept of Triana. Triana can be used for demand side management (DSM) and load flow (LF) calculations. In the implementation phase Triana will be used for simulating the effects of storage on the networks. Other simulators are there, but Triana is most suitable for the simulations that shall be performed [24]. Besides this, Triana is developed at the University of Twente and the source code is available when changes have to be made to integrate new control strategies.

The first subsection introduces Triana for DSM. Triana for LF calculations is described in the second subsection. The third subsection addresses storage modeling in Triana and the section ends with some conclusions.

2.4.1 Triana for DSM

As mentioned before Triana is developed at the University of Twente and uses a three-step approach for controlling and simulating smart grids. Initially the tool was developed for DSM functionality. Other tools for DSM such as the PowerMatcher can be found in [24]. The three steps are forecasting, planning and a real-time control. The goal of Triana as described in [77] is to manage the energy profiles of individual devices in buildings to support the transition towards an energy supply chain which can provide all the required energy in a sustainable way. Figure 2.13 shows the three-step approach of Triana.

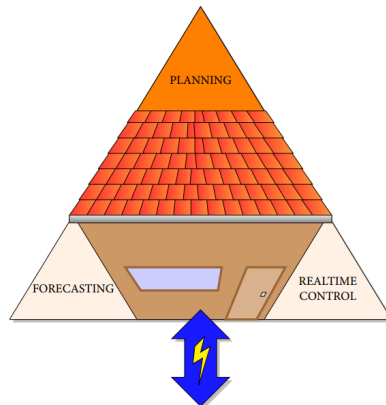


Figure 2.13: The three-step approach (source: [77])

The implementation of Triana is described in [78]. Triana is written in C++ and uses the Qt-libraries [78]. Furthermore, in [78] it is explained that four different types of devices are created for Triana. These devices are: buffering-, consuming-, producing- and converting devices. Energy between these devices are transferred via pools. The incoming energy of such a pool is equal to the outgoing energy. In figure 2.14 an example model of a house is shown using the devices and pools.

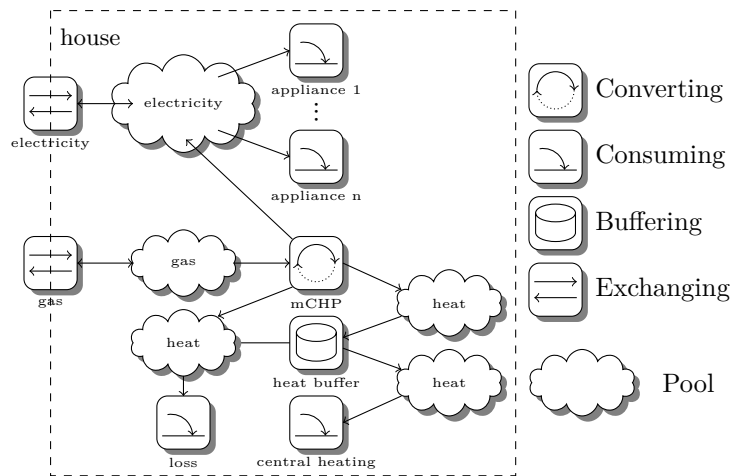


Figure 2.14: A house modeled in the TRIANA simulator using devices and pools (source: [78])

The networks that are simulated with Triana can be configured in many ways. Houses, PV installations, EVs etc. can be added to the network. The current version of Triana can perform simulations for different optimization goals. Since subquestions one and three from section 1.3 are about power quality and network components, it is important to see what Triana can simulate in these fields.

2.4.2 Triana for load flow simulations

According to [11] load flow (LF) calculations are focused on the design of the electricity network in both normal and failure situations. Hereby, voltages, currents, power distribution and losses can be calculated.

In [24] it is described how load flow calculations are added in Triana. Other simulators, such as Gaia, are available and are also described in [24]. When LF calculations are performed, the DSM output at the exchangers is used in the network. The results of the simulations can be plotted and exported to csv files. In figure 2.15 two screen shots of Triana are depicted. The left side shows the load on the three phases of a transformer in a network during one day. In this network a large amount of EVs is deployed and therefore a peak can be noticed during the evening hours when people start charging their cars. On the right the minimum voltage level of one of the phases is shown. It is clear that the Netcode is not violated, though the minimum voltage level is close to the lower bound.

However, it is not possible to model fast voltage fluctuations and harmonics with Triana. Models for this calculations are not yet implemented. It follows that when power quality is concerned only voltage levels (including asymmetry) can be measured. When network components are concerned both transformer- and cable load can be measured. Furthermore, the losses can be exported.

2.5. CENTRAL STORAGE AND CONTROL IN DISTRIBUTION NETWORKS

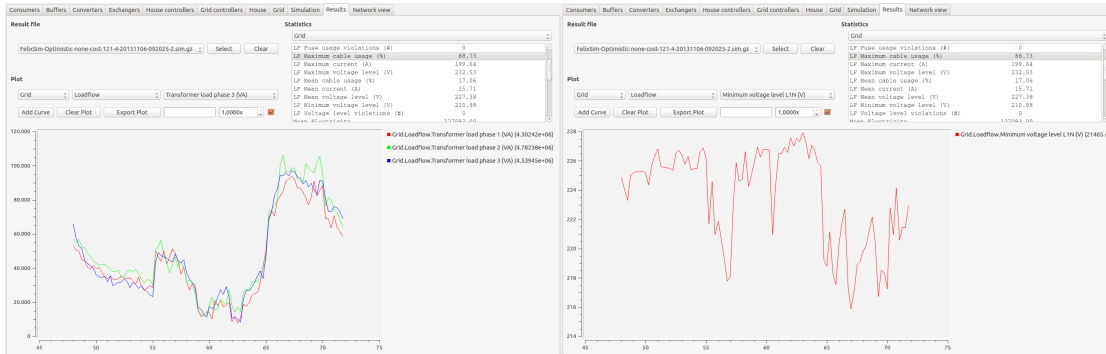


Figure 2.15: Two screen shots of Triana

2.4.3 Triana for storage modeling

Triana is capable of adding storage to a network. The storage device is modeled as a black box that is independent of the storage technology. When a simulation is configured the capacity, initial state of charge, efficiency and the maximum in- and output power can be set. As an output of the simulation, the state of charge, the energy in- and output and the losses can be shown.

2.4.4 Conclusions

This section introduced Triana for DSM simulations with LF feedback. It can be concluded that Triana is a suitable simulator for the simulations that shall be performed. Voltage levels, asymmetry, transformer- and cable loads and losses can be simulated. These aspects of PQ cause the most problems in distribution networks as stated before. Other aspects such as harmonic distortion can not be simulated with Triana and must be left for future research.

2.5 Central storage and control in distribution networks

In the previous section it is shown that Triana can simulate voltage levels, asymmetry, transformer load and cable usage. The first subsection of this section describes the effect of central storage on these network parameters. This is important since the research question is about measuring these effects and compare this with the effects of residential storage.

In figure 2.16 a system is depicted with such a central controlled storage asset. A central battery (in the green box) is placed in the LV network and the storage system is controlled by a central control station (in the red box). In subsection 2.5.2 the size and the placement of storage assets are considered. This section ends with the conclusions.

2.5.1 Impact on the distribution network

Since it is only possible to simulate the effects of storage on the voltage levels and network components, this subsection will describe some recent studies on the impact of storage on these

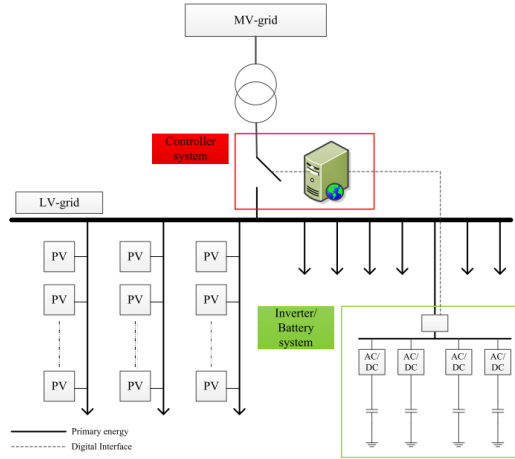


Figure 2.16: An example of central storage with central control (source: [79])

parameters. Only central storage is taken into account as section 2.6 addresses residential storage.

In [80] experiments are done with a storage device in a LV network in order to stabilize the voltage in a network with a high penetration of PV. First the storage device is placed in the MV part of the network. It was found that the effect on the voltage stability in the LV network was very small. In a simulation where the storage device is placed in the LV part of the network (somewhere in the middle of the feeder) the device has a positive effect on the voltage levels. The minimum voltage is increased from 170V to 214V. However, no details of the storage system are given, but it is clear that a storage device needs to be placed in the LV network itself when voltage stability in the LV network is the goal of the system.

An other example of storage assets used for voltage stability can be found in [81]. A network with large fluctuations in the voltage levels due to heat pumps and EVs. Especially at the end of the feeder under voltage is a problem. A 200kWh battery is used for injecting energy in the network when voltage levels are near the limits. As a result of this the stability of the voltage increases and the boundaries are less violated. Finally it is stated that a combination of demand side management and storage will gain more benefit than only storage.

A study on the effect of storage on network losses is presented in [82]. Since network losses are quadratically dependent on the current, it is important that the mean current is as low as possible. In [83] it is stated that load leveling with storage can significantly contribute to this. Next to this effect on network losses, also the effect on network capacity is concerned. The following formulas are given:

$$Loss = \sum_{t=1}^T R(t) \times I(t)^2 \quad (2.2)$$

$$Loss_{Leveled} = \sum_{t=1}^T R(t) \times (I(t) + I_{ESS}(t))^2 \quad (2.3)$$

where $Loss$ is the loss in the network, $Loss_{Leveled}$ is the loss in the network with leveled load

current, I_{ESS} is the storage current (which can be negative) and $R(t)$ and $I(t)$ are resistance and current at time t . In the network cables with a resistance of 0.78 Ohm per kilometer are used and the substation is rated at 1600 kVA nominal apparent power. The transformer is connected to a 20 kV MV network and a 0.4 kV LV network, has a resistance of 9.75 Ohm per phase and the yearly demand is equal to 8.6 GWh.

As a result of their simulations it is shown that the yearly losses in the cables and the transformer can be reduced with 3.06%. The released network capacity is between 12.2% and 24% daily. Finally the capacity of the storage device is calculated. It turns out that a capacity of 2.2MWh and an average power of 77.5kW is required. No explanation was given about the efficiency of this storage device and the method used to obtain this number.

Arif et al. in [84] simulated the role of energy storage on transformer load in an Australian distribution network with a large penetration of PV. They found that a storage device can reduce the load on the transformer from 87.22% of its maximum capacity to 66.76%. However, the capacity of the battery and the way it is controlled are not mentioned. Besides the reduction on the transformer load, an improvement of voltage stability is also mentioned.

2.5.2 Sizing and placement

This subsection addresses the topic of sizing (sizing in this chapter refers to capacity) placements of storage assets. The focus is on the methods that are used for calculating this. Since the placement (although this is about residential storage) and sizing is one of the problems mentioned in the research questions, it is of importance to know how these parameters are determined.

In [85] the size of a storage device is calculating for preventing overloading a transformer. Overloading the transformer is defined as an event where storage is depleted and the aggregated demand exceeds the maximum power the transformer can supply. The system is called reliable when the loss-of-load probability (LOLP) is less than 2.74×10^{-4} . This number is called the "one-day-in-ten-years" reliability criterion and it is claimed to be a widely used benchmark. A probabilistic sizing method developed for dimensioning buffers and links in the context of internet, to jointly size the transformer and the storage asset. As a result a trade-off curve is given where the minimal storage capacity and the transformer size are calculated for a certain residential area.

Etherden et al. [86] proposed a method for determining the size of a storage system for preventing overloading. A trade-off is made between the size of the storage system and the amount of overload prevention. The network in this paper is a Swedish distribution network with an annual transfer of 236 GWh.

The knee point at 4 MWh in figure 2.17 is considered as a good trade-off size as the contribution of the storage system to the overload prevention per MWh will decrease with larger storage systems.

In [34] a method is introduced for calculating the size of flywheels for peak shaving. A case study is presented for validating the results. The data for this case study is collected from a large smart grid in the USA. It is concluded that the capacity of a flywheel placed next to a transformer that supplies 741 houses requires to be 5.9 MWh for daily smoothening. Moreover, the power

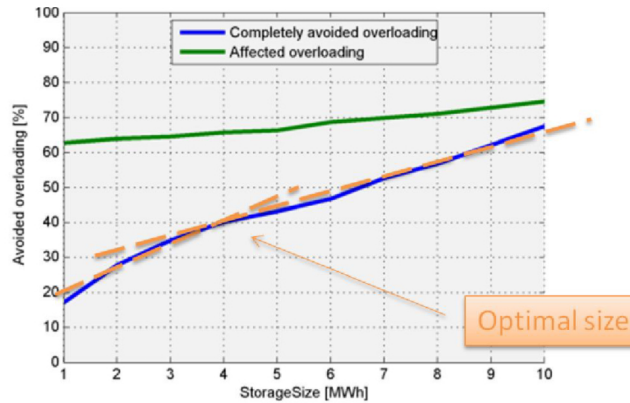


Figure 2.17: Overload preventing for various storage sizes [86]

capability is 1200 kW. When load following is the goal of the system, a capacity of 450 kWh at 200kW is required. In subsection 2.6.1 this results are compared with residential storage.

A more mathematical approach is given by Ru et al. [87]. They described a study on the problem of determining the size of a battery used in a grid with a high penetration of PV. The targets of the storage system are arbitrage and peak shaving. This results in a minimization function for minimizing the sum of the net power purchase cost and the cost associated with the battery capacity loss while guaranteeing that the demand from loads and the peak shaving requirement are satisfied.

For calculating the optimal placement and size, a mathematical framework is given in [88]. As a result of this framework the optimal size, placement and control is given for load shifting when a certain storage budget is available for a certain network. It is stated that it is always optimal to allocate zero storage capacity at generator buses that connect to the rest of the power grid via single links.

Atwa et al. [89] proposed a method for determining the storage capacity in a grid with a high penetration of wind turbines. First the total capacity that is required for preventing curtailment is calculated for the complete network. They continue with an objective function to calculate the optimal location for this capacity. It is allowed to spread the capacity over different storage systems.

A comparable approach can be found in [90]. An objective function is formulated to maximize the impact of storage in terms of voltage support. The system is tested with an IEEE test network and the total capacity of the storage systems is known a priori. In figure 2.18 the result is shown. The top graph shows the voltage occurrence in the network without storage involved. The second graph shows the voltage occurrence with storage with optimal placement.

Finally, in [91] a genetic algorithm is used for calculating the size and position of storage devices in a network. The tool that is developed, PLATOS, generates a lot of solutions and evaluates these. When a good solution is found new solutions will be generated close to that good solution. This will repeat until there is no longer improvement. The described method can not give guarantees about finding an optimal solution to the problem, but it is able to find a good solution.

2.6. RESIDENTIAL STORAGE AND CONTROL IN DISTRIBUTION NETWORKS

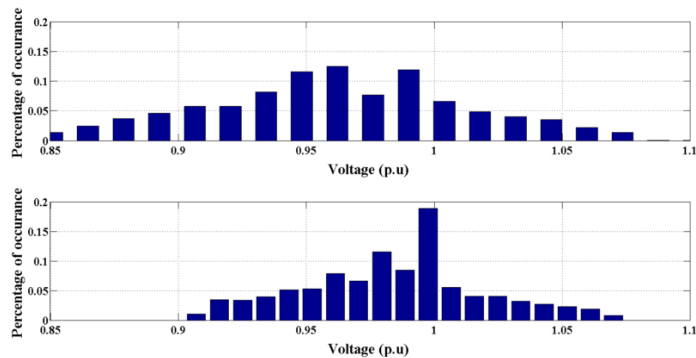


Figure 2.18: Voltage level occurrence with and without storage [90]

2.5.3 Conclusions

This section introduced the concept of central storage in distribution networks. The impact of central storage on the distribution network is shown. Different approaches to obtain voltage stability and preventing losses are introduced. It is clear that storage devices have a positive effect on these parameters. The size of this effects differs from paper to paper, since the network structures and the storage budgets differ. Besides this, methods for calculating the size and placement of storage devices in the network are introduced. Again the results differ for various networks.

2.6 Residential storage and control in distribution networks

This section describes the concept of residential storage. When this concept is applied, some small (compared to central storage) storage devices are placed in a residential area. Each of these devices can serve one or a few households. In literature it is stated that the amount of residential storage devices is expected to grow the coming years. Figure 2.19 is from [92] and shows the expected growth of residential storage devices.

Besides the expected growth, some advantages of residential storage compared to central storage are mentioned in literature. Veldman et al. [63] stated that storage closer to the customer will improve the reliability of the supply. This is due to the decreasing dependence on failure of network components. Moreover, in [93] simulations are done to determine the costs of residential and central storage. They concluded that for all types of simulations performed, residential storage (£250 per 1,5 kWh installation) is cheaper compared to central storage. This is due to the high installation costs of central storage (£10,000 per 12 kWh road side installation) and a better effect on balance between the phases. From this it is clear that the concept of residential storage and the effects on power quality is worth investigating and thus this is described in this section.

The remainder of this section is as follows: the effect of residential on the distribution network is described in the first subsection. Again, the focus is on voltage stability and network components

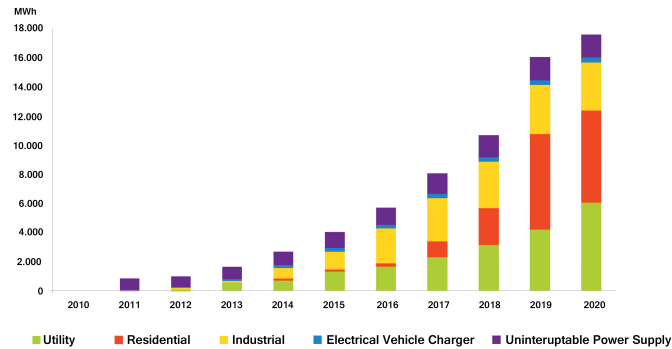


Figure 2.19: Expected grow of various types of storage (Based on: [92])

since these parameters can be simulated with Triana. The second subsection describes the way that the storage devices are controlled. Methods for calculating the size and location for residential storage are concerned in subsection 2.6.3. Finally the conclusions will be presented.

2.6.1 Impact on the distribution network

Zhu et al. [94] give a short overview of expected benefits of residential storage. A system is described where residential storage devices are used as a backup during power outages. Besides this function, they describe that residential storage devices can be used for power quality, peak shaving and power factor correction.

Residential storage combined with distributed generation and demand side management is described in [95]. The proposed system assumes that customers own some sort of renewable generator and/or a storage device. A game theoretical approach is used in order to minimize the monetary expense and calculate the optimal production and storage strategy. The algorithm can be run on the users' smart meter. It is shown that the demand curve from a transformer point of view is flattened.

In [96] a network is described with a high penetration of PV and customers who own a storage device. A method is proposed to optimize the peak shaving behavior of the storage devices. It is shown that the peaks in the network can be reduced significantly and the voltage is kept within the boundaries. Moreover, the reduction in network losses is described. A reduction is obtained between 6.6% and 7.3% when the storage devices are used in days where over voltage occurs. If the storage device will be used in days where no over voltage will occur the reduction of losses can be increased even more.

An other example of residential storage can be found in [97]. A Japanese distribution grid (voltage norms: 100V +/- 6V) is considered where the DSO is allowed to control the batteries owned by customers. The paper is mainly concerning the economical aspects of residential storage. It is shown that for different amounts of subsidy given to the customer by the DSO (and thus more capacity that can be used), a reduction of voltage regulation violations up to 84% can be reached.

As mentioned before Hearn et al. [34] performed analysis on peak shaving with flywheels. A

2.6. RESIDENTIAL STORAGE AND CONTROL IN DISTRIBUTION NETWORKS

flywheel with a capacity of 5.9 MWh is required for diurnal smoothening in a LV network supplying 741 households. In figure 2.20 flywheel sizes for individual homes are depicted. It is shown that flywheels with a capacity of 2.0 kWh can reduce the load peak between 30% and 60% for the majority of the households. However, it must be said that the aggregation of flywheels located in the homes would oversize the energy storage needs at the transformer by 71% and 150% for respectively diurnal- and power smoothening. However, this is not explained.

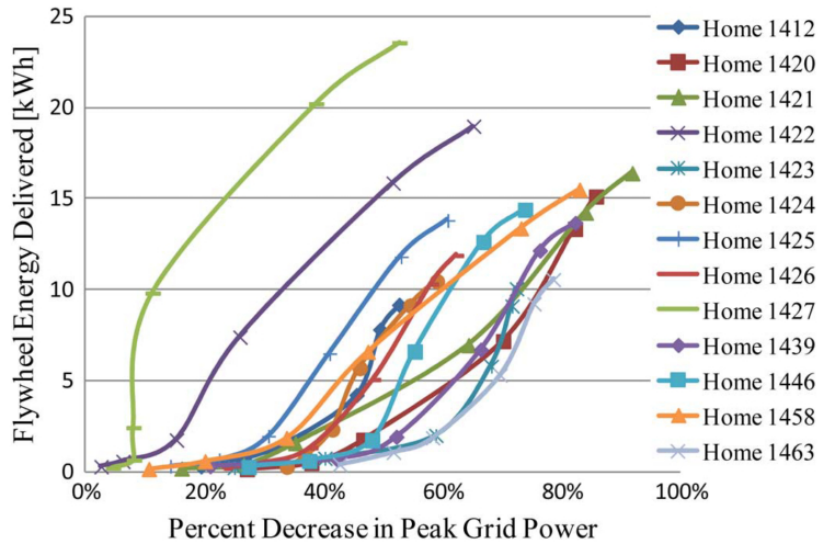


Figure 2.20: Flywheel energy storage for individual homes (source: [34])

2.6.2 Controlling residential storage

Two control approaches for controlling distributed energy resources (DER) are described in [98] by Tenti et al. These resources can be both storage devices and renewables. The goal is to optimize voltage stability and reduce distribution loss in a situation where the communication capability is limited to neighbor units or is not available at all. In the case that communication between neighbors is used, a token ring approach is adopted. When a DER device has received the token an action can be performed. As a result of this approach, one device at a time can respond. In this way, instability due to oscillation effects is prevented. In the case that there is no communication, (plug and play control) this potential problem cannot longer be solved this way. A random time slot (in the range of 40-60 ms) is selected in a time period of a few seconds. Only in this small time slot the DER is allowed to change state.

Simulations are done in order to simulate the effect on the line losses and voltage stability. When voltage stability is the goal of the system, it is shown that the voltage is indeed closer to the reference voltage in every case. Both controlling approaches do not differ a lot. In the case where distribution losses are calculated, a similar result can be shown. The token ring approach is capable of preventing a little bit more reduction loss, but this difference is small compared to plug and play control. More details about this study can be found in [99, 100, 101].

When a storage device is controlled via the plug and play strategy, the local measured voltage is used as a reference. In [102] the local voltage is used for controlling a DSM system. The goal of this system is to stabilize the voltage using the flexibility of smart devices within one household. Since there is no communication network necessary, the system is not influenced by communication failure or cyber security issues. Simulations showed that the amount of over- and under voltages (defined as voltages with a 10-minute mean RMS value beyond $\pm 10\%$ of U_{nom}) can be reduced by 20 to 30%. These results show that steering on only local voltage measurements is a promising technique.

2.6.3 Sizing and placement

In section 2.5.2 methods for determining the size and location for central storage are addressed. The major part of this approaches can be reused when residential storage is considered. This subsection describes some additional methods where residential storage is considered. Note that figure 2.20 in subsection 2.6.1 also addresses this topic.

In [103] some advantages of residential storage are listed. It is stated that the storage devices must be placed as close as possible to the source of the problems that occur. When, for example, a house is causing over voltage due to PV, a storage device should be placed as close as possible to that particular house. However, this statement is not supported by some simulations or field tests.

As mentioned before, in [96] research is done to obtain peak shaving behavior with the use of residential storage. The capacity of the storage devices is determined by increasing the capacity until violations of the EN-50160 norm no longer occur. In the case of 23% PV penetration the capacity is determined between 1.1 kWh and 3.8 kWh depending on the share of PV-output power used by the storage device for charging. With a penetration of 50%, the capacity of a single battery is 28 kWh which is considered uneconomical.

In [104] battery sizes are determined for a LV grid with various penetrations of PV and EVs. Simulations with data from a Danish island with 52 customers connected to a 100 kVA transformer are performed. In table 2.5 the minimum storage capacity is shown when preventing an over voltage is the purpose of the storage system. Various penetrations of PV and EVs and different positions of the storage device in the feeder are shown.

From this table it can be concluded that storage in the beginning of the feeder is not very useful as stated before. Moreover, over voltage is a smaller problem when the penetration of EVs increases. For this a smaller storage device is necessary when preventing over voltage is the goal of the storage device. However, it must be said that with a high penetration of EVs, under voltage can become a problem but this is not considered in the paper.

2.6.4 Conclusions

This section describes the concept of residential storage. The amount of papers on this topic is limited compared to the amount of papers on the topic of central storage, but some important conclusions can be drawn. First of all important advantages of residential storage compared to central storage are mentioned. It is clear that the concept is promising, but no real comparison

2.6. RESIDENTIAL STORAGE AND CONTROL IN DISTRIBUTION NETWORKS

	ESS capacity per customer (kWh)					
	EV pen	Begin feeder	1/4 feeder	Mid feeder	End feeder	Avg
100% PV penetration	0%	0	6.3	25.8	35.7	19
	50%	0	5.6	24.1	33.6	17.8
	100%	0	5.2	21.9	31.6	16.6
75% PV penetration	0%	0	2.7	14.1	23	11.2
	50%	0	2.5	11.9	21.1	10.2
	100%	0	2.4	10.2	19.1	9.2
50% PV penetration	0%	0	0	4.15	9.7	4.1
	50%	0	0	3.4	7.8	3.3
	100%	0	0	2.8	6	2.8

Table 2.5: *ESS capacity in various places in a LV feeder (source: [104])*

with central storage is made in literature.

Furthermore, it can be concluded that residential storage can be controlled using different approaches. Besides central control, also token ring and plug and play control is introduced. All three approaches have a significant effect on the power quality and extending the lifetime of network components.

The remaining parts of this thesis will describe a comparison between residential storage and central storage. For both ways of applying storage the effect on power quality, network components and losses will be simulated. Moreover the sizing and placement of the storage assets will be considered.

3

Simulation necessities

This chapter describes the simulation necessities for this study on storage in distribution networks and the tools used. The following chapters (chapter 4-6) describe the actual simulation approach and results of the effects of respectively central storage, residential storage with central control and residential storage without central control. Chapter 7 describes a comparison between the results from these chapters.

First of all, this chapter starts with a more detailed description of the criteria derived in the previous chapter. These criteria are used for rating the effects of the batteries. Since there are five criteria, a multi-criteria analysis is derived. This analysis together with a sensitivity analysis is written in Matlab and described in the second section.

Section 3.3 addresses a use-case for the simulations. The use-case consists of a network and an scenario. This use-case is already defined in earlier studies and will be introduced briefly. Consequently, the final section describes the reference simulations without storage. These simulation are necessary for measuring the effects of storage devices.

3.1 Criteria

In the previous chapter, some of the network statistics that can be exported from Triana are addressed. These data will be used to measure the performance of the various battery configurations. This section will describe these criteria more detailed. Subsequently, the sub-criteria and the reason why these parameters are important are described. The criteria of interest for measuring the effects of a storage device are listed below:

- Voltage
- Asymmetry
- Transformer load
- Cable load
- Losses

When the voltage levels and asymmetry are taken into account, all voltage levels at the point where houses are connected to the distribution network are considered. When the cable load is considered, all cables in the network are included in the calculations. Losses consist of one value, being the sum of all losses in cables for one time interval. Finally, the transformer load consists

of just a single value per time interval per phase.

It should be noted that the current is not added to this list, since it is only implicitly important. The current levels are not bounded by the Netcode and current reduction is not important in itself, only the result of the current reduction in terms of load or losses is important. When for instance the current through a certain cable at time t is lower then the current on time $t + \delta$, the losses in the cable at time t will also be lower then at time $t + \delta$.

In table 3.1 the criteria that are listed above are shown with all the sub-criteria that are involved. The third column of this table shows the goal of the parameters.

Criterion	Sub-criterion	Goal
Voltage	Max	As close as possible to 230V
	Min	As close as possible to 230V
	Std. dev	As close as possible to 0
Asymmetry	Max	As close as possible to 0%
Cable load	Max	As close as possible to 0%
	Mean	As close as possible to 0%
Transformer load	Max load	As close as possible to 0kVA
	Mean load	As close as possible to 0kVA
Losses	Sum	As close as possible to 0kWh

Table 3.1: The criteria that will be taken into account

When the voltage levels are considered, the minimum and maximum values are restricted by the Netcode [5] and are therefore important. The mean value is in an optimal situation 230V with a standard deviation of 0. The standard deviation is an indicator for the flatness of the voltage-duration curve and is therefore also considered.

Besides the maximum and minimum voltage levels, the asymmetry is also restricted by the Netcode and is therefore important. The reduction of the maximum cable- and transformer load (in Triana called design load) is important since the network components have been designed for the maximum load. When the load can be kept within the components' bounds with a growing penetration of demanding loads and renewables, it is not necessary to upgrade the components. Moreover, the goal of the cable and transformer load is defined as no load since this implies that every customer uses their own energy. Since this implies, inter alia, voltage stability and no losses, this is considered as an optimal situation from a network point of view. Finally, the sum of the losses is considered since a reduction of the losses will reduce the CO₂ emissions and saves money for the grid operator.

3.2 Matlab tools

During this research, Matlab is used as a central tool for calculations and comparisons. Matlab is often used for processing data and showing the results. Furthermore, Matlab can start Triana simulations and is capable of communicating with Triana.

Starting Triana from Matlab is explained in the first subsection. Next, a multi-criteria analysis (MCA) is addressed. Since there are five criteria that are taken into account for comparing battery configurations, a MCA is necessary in order to rate the configurations. This MCA results in a performance rating for all simulations, such that they can be compared. The weights used for the criteria, are also described. Finally in subsection 3.2.3 a sensitivity analysis is described for determining the sensitivity of the MCA to the weights of the criteria.

3.2.1 Starting Triana from Matlab

In order to automate the simulations, a Matlab function is written to start Triana. Since Triana can be started from a command line and Matlab can execute system commands, this function is very straight forward. The Matlab code for this function can be found in appendix C listing C.1.

3.2.2 Multi-criteria analysis

In later chapters, various configurations of storage devices will be compared. Since various network parameters are used, the effects of the storage devices on these parameters must be valued. This subsection describes the approach of this process.

In [105] various approaches are described. The two most used multi-criteria analysis (MCA) approaches are the weighted sum method and the analytical hierarchical process (AHP). The weighted sum method sums up the various parameters multiplied by a certain weight. The storage alternative with the highest score is considered as the best alternative. This method is very straight forward and easy to use. A drawback of this method is that every parameter must be expressed in the same range.

The AHP method gives the decision maker the opportunity to divide the problem into hierarchical sub-problems. Furthermore, it is no longer necessary that every parameter is expressed in the same unit since the parameter are normalized during the process. Besides these differences, the weights are no longer absolute, but relative to each other. The benefits will make the evaluation process more complex. This can be considered as a disadvantage.

For this study the AHP method will be used. A weighted sum method is possible since all parameters are expressed in percentages, but as the nature of the problem is hierarchical and more nuance can be introduced with relative weights, the AHP is in favorite. Moreover, when a future decision maker will use this process, there is still freedom to use the original units instead of percentages.

The structure of the problem is described below. In [105], a four step algorithm is explained. These four steps will be addressed in the further parts of this subsection.

1. Structuring the problem into a hierarchical model

The first step is structuring the problem into a hierarchical model. This structure is shown in fig 3.1 and follows directly from section 3.1. The top-level is called the goal. When for example the location for a central battery is considered (chapter 4), the goal is to find the best location for

the battery. Next, the criteria are shown, followed by the sub-criteria. The lowest level shows the alternatives for the problem. In case of the Lochem network, 128 different locations are possible.

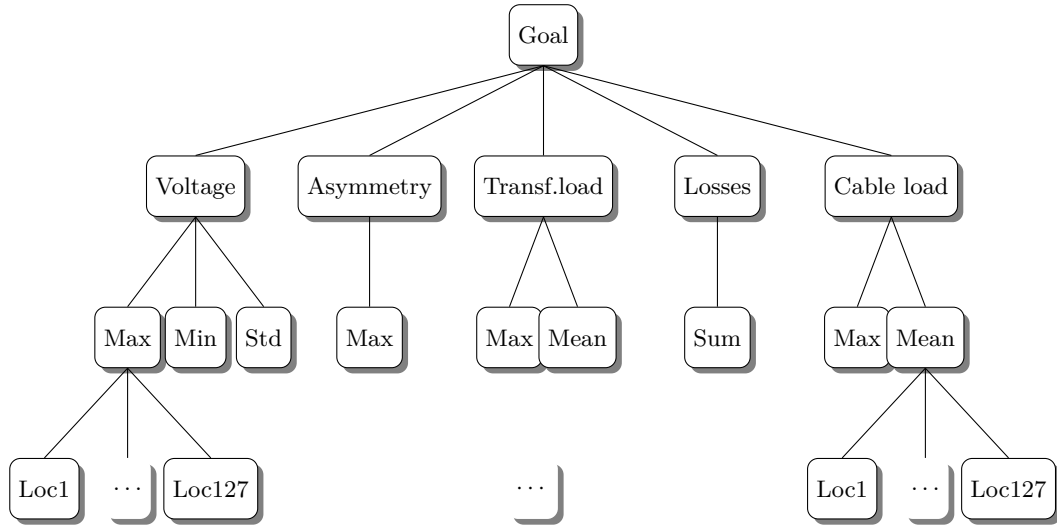


Figure 3.1: The hierarchical structure of the problem

2. Obtaining the weights for each criteria

The second step that is described concerns the weights for the criteria. These weights are obtained via the Dutch grid operator Alliander. However, it must be said that these weights are just an example. When a future decision maker will use this approach, the weights should be reconsidered.

The weights (for all sub-problems and the top-level problem) are depicted in a matrix. The elements in row i of this matrix A and column j of A (a_{ij}) indicates how much more important criterion i is than j with respect to the alternative. Furthermore, when $a_{ij} = \alpha$, then $a_{ji} = \frac{1}{\alpha}$.

In table 3.2 (from [105]) the meaning of the weights are shown. With this knowledge available, the weights can now be shown. The weights for the top-level problem are shown in table 3.3. The weights for the voltage levels, transformer load and cable load can be found in respectively table 3.4, 3.5 and 3.6.

For the top-level problem the voltage levels are considered as most important. Next, the load on cables and transformer are of importance. When these parameters are improved, this will result in a reduction of losses and the losses are therefore less important. When the asymmetry is within the bounds set by the Netcode, an improvement in the asymmetry is not that important.

When the voltage levels are considered, the standard deviation is very strongly more important than the minimum and maximum voltage. This assumes that the voltage levels are in the limits. Furthermore, the standard deviation is considered as a measure of the balance in the network and is therefore very important. Finally, when the transformer and cable loads are considered, the mean value is very strongly more important than the maximum load since a lower mean

Intensity of importance	Explanation
1	Objectives i and j are of equal importance
3	Objective i is weakly more important than objective j
5	Objective i is strongly more important than objective j
7	Objective i is very strongly or demonstrably more important than objective j
9	Objective i is absolutely more important than objective j

Table 3.2: Meaning of the weights

Total	Voltage	Transformer load	Asymmetry	Losses	Cable load
Voltage	1	3	7	7	3
Transformer load	1/3	1	5	5	1
Asymmetry	1/7	1/5	1	1	1/5
Losses	1/7	1/5	1	1	1/5
Cable load	1/3	1	5	5	1

Table 3.3: Weights for the top-level problem

Voltage	Max	Min	Std
Max	1	1	1/7
Min	1	1	1/7
Std	7	7	1

Table 3.4: Weights for the voltage levels

Transformer load	Max	Mean
Max	1	1/7
Mean	7	1

Table 3.5: Weights for the transformer load

Cable load	Max	Mean
Max	1	1/7
Mean	7	1

Table 3.6: Weights for the cable load

value leads to a reduction of losses.

A weight vector can now be obtained to indicate the weight of each criteria. To obtain the weight vector $W = [w_1, w_2, \dots, w_N]$ from A , A_{norm} (normalized) is calculated by dividing each entry in column i of by the sum of the entries in column i . The sum of the entries in each column i is now 1. w_i is the average of the entries in row i of A_{norm} .

The consistency of the weights can now be checked as explained in [105]. It is for example not consistent when criterion C_1 is very strongly more important than criterion C_2 and C_3 when C_2 is also very strongly more important than C_3 . This procedure will not be explained here since it is assumed that the experts gave consistent weights.

3. Finding the score of each alternative for each criteria

The score of each alternative for each criteria will be obtained from the simulations. Again the restriction for this matrix X are: if $x_{ij} = \alpha$, then $x_{ji} = \frac{1}{\alpha}$. Since X is constructed with simulated data, the matrix is consistent and the consistency check as mentioned before is not necessary. With the alternatives, criteria, weights and scores available, the situation is as follows:

Criteria	C_1, C_2, \dots, C_n
Weights	W_1, W_2, \dots, W_n
Alternatives	

$$\begin{bmatrix} Alt_1 \\ Alt_2 \\ \vdots \\ Alt_m \end{bmatrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

4. Obtaining the overall score for each alternative

The final step of the AHP process is to obtain the final score of each alternative. For calculating the final score for alternative 1 (P_1), the following equation should be used:

$$P_1 = \sum_{i=1}^N \text{Local priority Alt1 with respect to } C_1 \times \text{Local priority } C_i \text{ with respect to the goal} \quad (3.1)$$

A higher value in the vector P means a better score for the alternative. When for example P_{42} is de highest value in P , location 42 is the best location for the storage device according to this procedure.

3.2.3 Sensitivity analysis

The data from the multi-criteria analysis is useful, but since the weight factors are not very precise and there is a lack of insight in the criticality, a sensitivity analysis will be performed. This subsection will describe this procedure. The goal of the sensitivity analysis is to get insight in the sensitivity of the outcome to changes in the weight factors. Triantaphyllou and Sánchez [106] gave in their paper the approach for a sensitivity analysis for various multi-criteria decision making problems.

With the described method it can be calculated how much a weight factor should change to cause a displacement in the vector P . Since only a change of the highest value of P (denoted as Alt_1) is of interest, (only one storage device is placed) only this is considered. The following definitions are used:

Definition 4. Let $\delta_{k,i,j}$ ($1 \leq i < j \leq M$ and $1 \leq k \leq N$) denote the minimum change in the current weight W_k of criterion C_k such that the ranking of alternatives Alt_i and Alt_j will be reversed.

As mentioned before, only the reversion of alternative Alt_1 and Alt_j are of interest. Furthermore it is stated in [106] that the relative change is of a greater interest than the absolute change, since one would like to compare the change with the original value of W_k . Therefore the relative change is defined.

Definition 5. $\delta'_{k,i,j} = \delta_{k,i,j} \times \frac{100}{w_k}$, for any $1 \leq i < j \leq M$ and $1 \leq k \leq N$.

The most critical criterion for reversing Alt_1 and Alt_j can now be defined as follows:

Definition 6. The most critical criterion for reversing Alt_1 and Alt_j is the criterion that corresponds to the smallest $|\delta'_{k,1,j}|$ ($1 \leq j \leq M$ and $1 \leq k \leq N$) value.

Next, the equation for calculating $\delta'_{k,i,j}$ is given. The proof of this equation can be found in de appendix of [106].

$$\begin{aligned} \delta'_{k,i,j} &< \frac{P_j - P_i}{a_{jk} - a_{ik}} \times \frac{100}{W_k} && \text{if } (a_{jk} > a_{ik}) && \text{or:} \\ \delta'_{k,i,j} &> \frac{P_j - P_i}{a_{jk} - a_{ik}} \times \frac{100}{W_k} && \text{if } (a_{jk} < a_{ik}) \end{aligned} \quad (3.2)$$

Furthermore, $\frac{P_j - P_i}{a_{jk} - a_{ik}}$ should be smaller or equal than W_k , otherwise $\delta'_{k,i,j}$ is not feasible, which means that Alt_i and Alt_j can not be reversed by changing W_k .

Both analysis tools that are described (the MCA and sensitivity analysis) are implemented in Matlab and can be used in the larger Matlab frameworks that will be described in the following chapters.

3.3 Use-case

When the behaviour of the storage devices is tested in a simulation, there is a need of a use-case. A use-case defines the network structure and the production and consumption of all appliances in the houses connected to the network. First a scenario is introduced and second a network will be described.

3.3.1 Scenario

This subsection will briefly describe the used scenario for this study. A scenario simulates the demand of the appliances situated in the households and the production of the renewables. In [107] and [108] a description is given of the Flex-street scenario. This scenario is available at the University of Twente and the scenario, together with the network that will be described later, meets the requirement of causing PQ problems in the network.

In table 3.7 an overview is given of the four scenarios. A reference, a pessimistic, a moderate and an optimistic scenario are defined. Since the optimistic scenario causes the most power quality

Scenario	Penetration rates (%)					
	PV	Batteries	Heat Pumps	Washer/dryer	Dishwasher	PHEV
Reference	0	0	0	0	0	0
Pessimistic	5	0	0	20	20	10
Moderate	15	5	50	60	60	50
Optimistic	30	20	100	100	100	90

Table 3.7: The penetration of demanding loads and renewables in various future scenarios

problems in a network, this scenario is used in the simulations that will be performed.

The optimistic scenario contains models of smart appliances (PHEV, dishwasher etc.) which offer planning freedom. An overview of the appliances and their power ratings can be found in [109]. The planning freedom is used in the demand side management algorithm of Triana, but will be turned off during the simulations that will be performed such that only the effects of the batteries are shown. Furthermore, both a sunny and a cold winter day will be used for the simulations in order to test the battery effects in various weather conditions. The third of January will be used as reference day even as the third of May.

3.3.2 The Lochem network

Hoogsteen [24] modelled an existing network structure in Triana. This network is located in the Dutch town of Lochem and is a typical 90's residential area [24]. Simulations with a widely used benchmark network such as [110] is left for future work. The model consists of 121 houses distributed over three feeders, a transformer feeding the feeders and the cables between all the nodes.



Figure 3.2: The structure of the cables in Lochem projected on a satellite image from Google maps. (source: [24])

The annual demand of this network is 872MWh and the annual loss is 19.48MWh [109]. With

the Triana DSM approach, these losses can be reduced to 14.24MWh.

In appendix B, an image of the structure of the network in Lochem is shown. The transformer is located at the top of this image. Furthermore, the houses are marked with a blue color and the thickness of the cables is also marked. A red cable is a thick cable and green marks the thinnest cables. Orange and yellow mark intermediate thicknesses. When a network node (a node without a connection nor a house) is connected to the transformer via only thick cables, the node is considered as a suitable location for a large battery. If a battery would be connected to thin cables, an overload situation will take place. The 128 nodes that are suitable for a battery connection are marked with a pink color. In table 3.8 from [109], the specifications of the cables are shown. Furthermore, it should be mentioned that the power factor is fixed at 0.9 and that the transformer supplies a fixed 230V for simplicity.

Cable type	A (mm ²)	R (Ω/km)	X (Ω/km)	I_{nom} (A)	Color
Al 150	150	0.206	0.079	230	red
Al 95	95	0.320	0.082	175	orange
Al 50	50	0.641	0.085	115	yellow
Al 16	16	1.91	0.096	60	green

Table 3.8: Cable properties

3.4 Reference simulations

This final section describes reference simulations with the Lochem network combined with the Flex-street scenario. All batteries are removed from the scenario in order to compare this situations with later battery configurations. In the first subsection a simulation without the Triana demand-side management approach is shown for both a winter and a summer day. The second subsection shows a simulation with DSM. The DSM output will be used later to compare the battery effects with the DSM effects.

3.4.1 Reference simulation without DSM

The results of a simulation without DSM and batteries is shown in figure 3.3. This figure clearly shows the small morning peak due to the morning consumption of the residents. Moreover, a large evening peak can be observed due to the charging of the PHEV's. Since there is not much PV input, the main problem is under voltage. The minimum voltage in this network is 204.4V. This violates the Netcode. Besides this violation, the maximum cable usage is 106.9%. This is also a situation that is not allowed to occur and the use-case is therefore suitable for the simulations that will be performed. Note that the x-axis contains 96 time intervals of fifteen minutes each.

Figure 3.4 shows the minimum voltage across the network of Lochem with the Flex-street use-case. A low voltage level is marked with a blue color and higher voltages with green. A real dark blue color is below 207V and a green node in the network is 230V. It can be observed that the majority of the voltage problems is observed at the end of the second feeder. This feeder is the

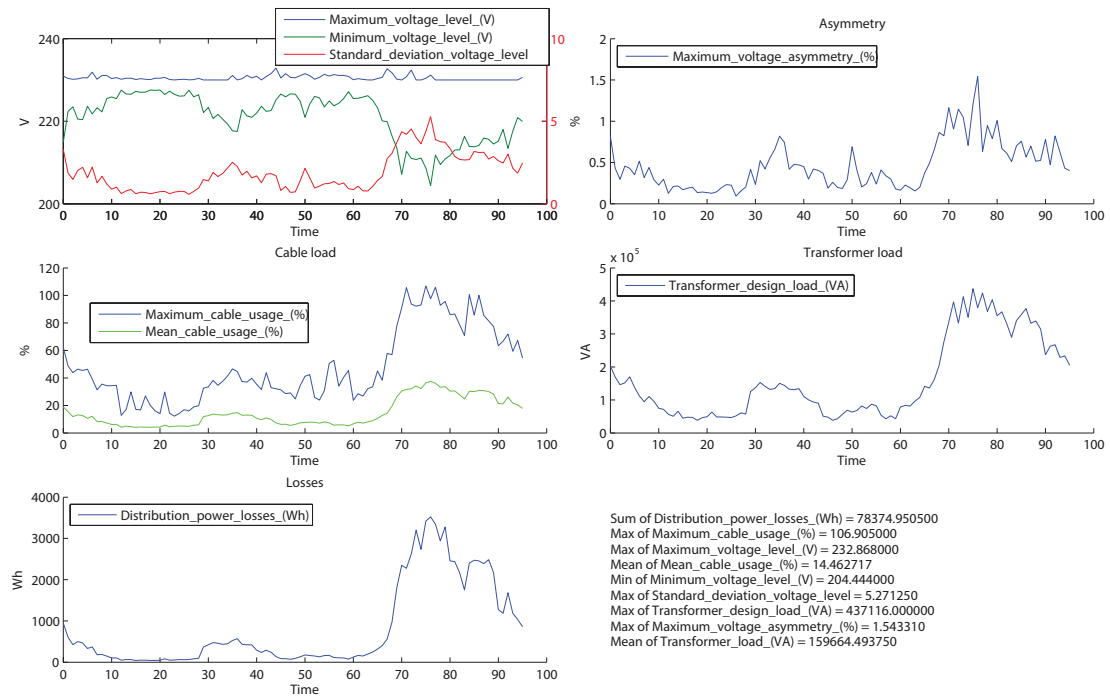


Figure 3.3: Results of simulations without storage nor demand side management

longest feeder with the most connections.

Below, in figure 3.5 a reference simulation is shown for a sunny day. However it is observed that no real over voltage problems were there. Since the behaviour of the batteries is of interest and not the scenario, all houses are equipped with PV in order to obtain a high voltage. This is not the case in the simulation of the third of January, but is done only for the sunny day simulations. It can be obtained from the figure that the voltage levels are significantly higher than the previous simulation due to the PV. Furthermore, two peaks in the losses and loads can now be observed. The first peak is due to the production of the PV and the second is a result of the electrical vehicles. The minimum voltage in the left upper sub-plot shows a flat line in the middle part of the day. This is due to the fact that the minimum voltage in these intervals is measured at the transformer since the transformer is fixed at 230V.

3.4.2 Reference simulation with DSM

A simulation with DSM enabled is done next. Figure 3.6 shows the results. It can be observed that the peak in consumption is shifted in time. As a result of this spreading, the losses are significantly lower and all other parameters are also improved. The Netcode is no longer violated.

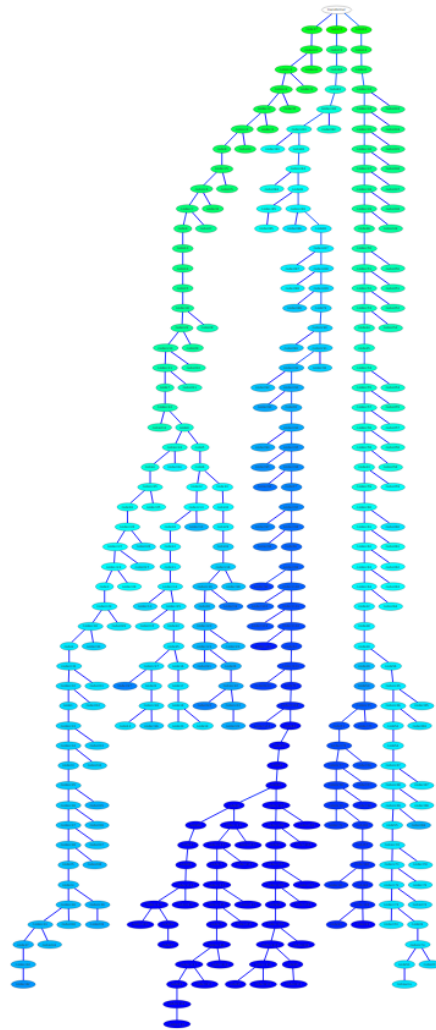


Figure 3.4: The minimum voltage across the Lochem network

3.5 Summary

This chapter described the simulation necessities for this study. Since various battery configurations will be compared in the following chapters, a network and a scenario are introduced. Triana can now perform network simulations and calculate the effects of storage devices.

The network parameters that were derived in the previous chapter are described in more detail. With this criteria, the battery configurations can now be rated using a Matlab script. This script contains a multi-criteria analysis and a sensitivity analysis. The MCA can determine the best configurations based on the weighted criteria and the sensitivity analysis can calculate the most sensitive criterion. Furthermore, some initial simulations are performed in order to see the effects of adding the storage devices in the network in the following chapters.

CHAPTER 3. SIMULATION NECESSITIES

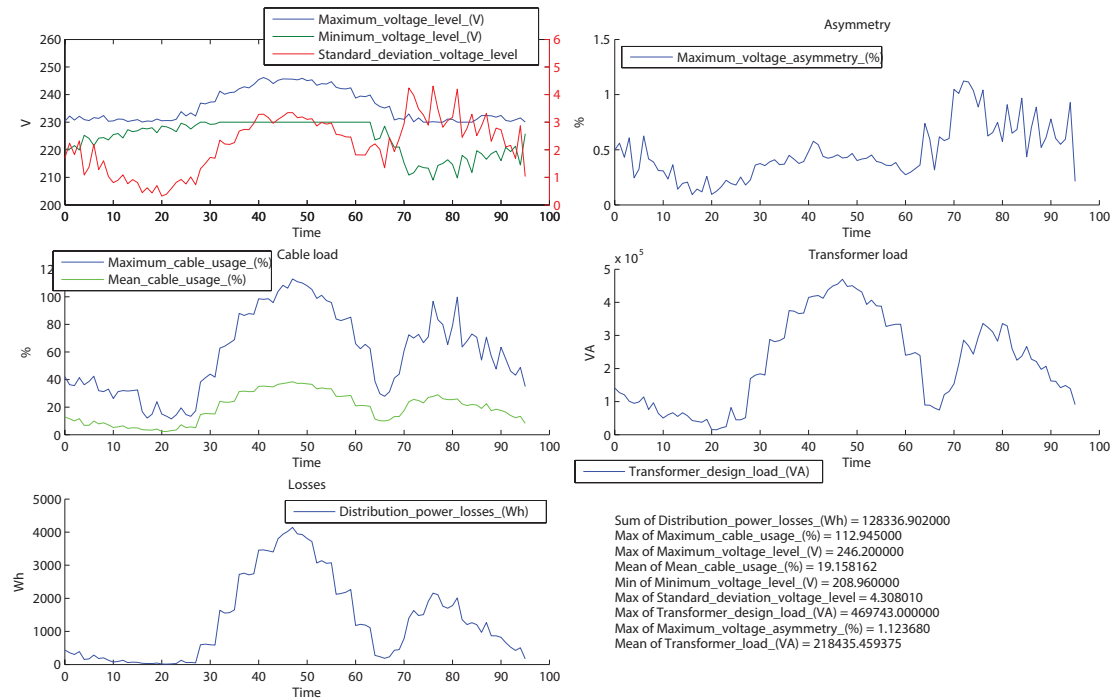


Figure 3.5: Result of a simulation of day 123 with all houses equipped with PV

The next chapter will describe a single central battery, chapter 5 addresses residential storage and chapter 6 describes the effects of plug and play storage. These chapters also include a more details approach for that specific configuration.

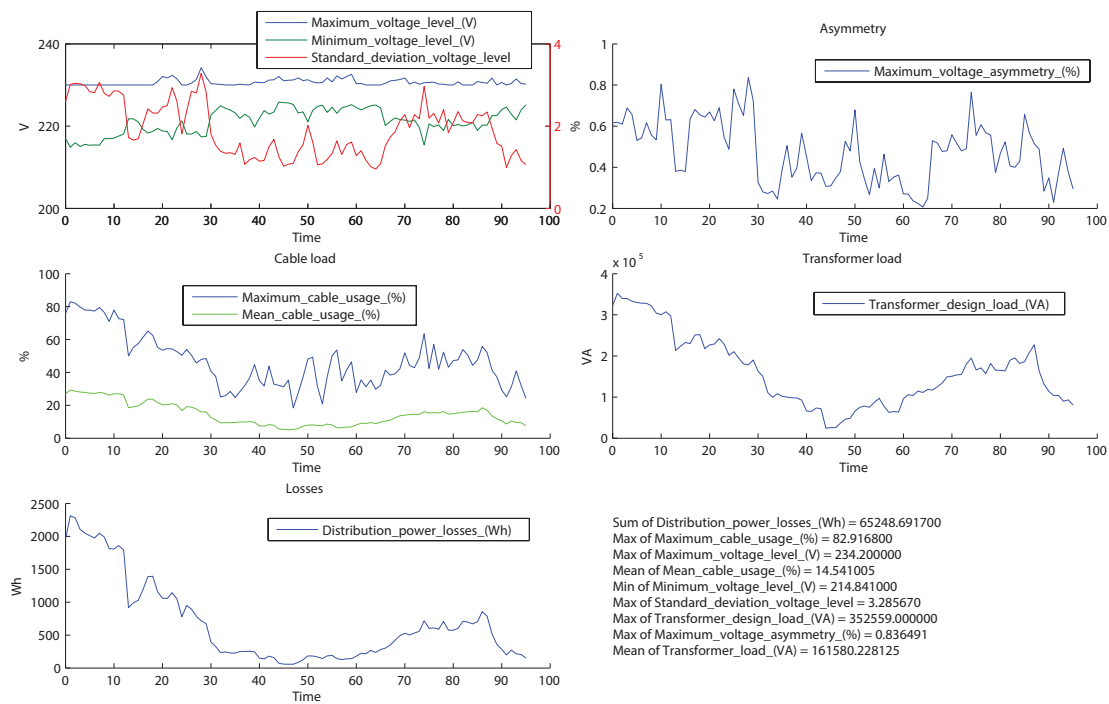


Figure 3.6: Results of simulations without storage but with demand side management

4

Central storage

This chapter describes the performed simulations with central storage in Triana. In the first section, control of such a battery is addressed. Since the Triana DSM approach uses (artificial) prices to steer controllable devices, it should be possible to integrate the battery in this system.

Section 4.2 describes a situation where the battery is placed besides to the transformer. Subsequently, the battery is shifted through the network and the results of the multi-criteria analysis are described. From this analysis, the best location for this battery is obtained. This chapter ends with a summary.

4.1 Battery control in Triana

This section describes the method that Triana uses for steering a battery. Triana uses a price vector with the length of the planning horizon as input for a dynamic programming algorithm. The implementation of this algorithm is described in more detail in [111]. A dynamic programming algorithm creates a state space with all possible transitions from the begin state s to another state in the next time interval s' . If we consider time intervals of one hour and the state of charge (SoC) at $t = 0$ is 10000 kWh and a (dis)charge of 0, 5000 or 10000 W is possible, then the possible states SoC' in $t = 1$ are 0, 5000, 10000, 15000 and 20000 kWh. This procedure can be repeated until the end of the planning horizon is reached.

Every transition in a dynamic program comes with a certain cost. The costs in Triana are the product of the price λ_t and the power P_t in that time interval. In the battery example, a high power output results in a cost that is twice as high as charging at half of the maximum power. Using a backtrace, a cost minimization is performed to find the cheapest path from the current state to the desired end state.

With this system, some initial tests are performed. However, it was observed that the behaviour of the batteries was not as expected. When a price is high it is in every case the best option to discharge at full power. It does not matter how much modulation steps there are, the battery always (dis)charges always at the maximum power. When a large battery is used, this will result of course in a worse power quality and grid stability.

To solve this problem a quadratic term is introduced in the cost function. The purpose of this approach is to punish the use of a high power output. The new cost function is as follows:

$$cost_t = \lambda_t P_t + \beta P_t^2 \quad (4.1)$$

Where, $cost_t$ is the cost for a certain transition at time t , λ_t is the price at time t , P is the power at time t and β is a small factor.

Again a simulation is performed with this improved cost function. It is observed that more intermediate modulation steps were preferred by Triana, but the results are still far from what can be expected from literature. It was already observed in the reference simulation that the load peak was shifted in time due to the high prices in the evening. This approach turned out to be already successful without batteries. When storage is added to the network, the batteries will try to discharge at the original price peak. However, this peak is already shifted and thus there is no improvement observed with the batteries.

Within Triana, this problem is not easy to fix. Therefore, a second planning step is introduced. First, all devices except the batteries can be planned. When these devices are planned, the batteries can be scheduled in the second planning iteration. Since the effects of all devices in the first planning iteration are already known in the second step, a smart algorithm can determine the behaviour of the batteries. The following subsection describes a Matlab algorithm that determines two thresholds for charging and discharging in the second planning iteration.

4.1.1 Determine the thresholds for charging and discharging

This subsection addresses the calculation of the battery profile in the second planning iteration that is introduced above. Since the behaviour of all devices is already known in this step, a perfect profile can be calculated. Besides this perfect knowledge about the network, the batteries are technology independent and ideal.

First, a straight forward method is implemented in Matlab. Matlab will start with the energy profile from the previous iteration and will search for two bounds, an upper bound and an under bound. The area above the upper bound and under the energy profile must be smaller or equal than four times (4 samples per hour) the capacity of the battery. The first line that will be found (started from the mean) where this is true, is considered as the upper bound for the battery. The same is done for the under bound. The most important lines of code can be found in appendix C listing C.2.

The loop that is listed will continue until both up and down are zero. The function can now return a battery profile. When the power consumption at time t is larger than the upper bound or smaller than the under bound, the battery will charge or discharge respectively with the difference between the bound and the sample. Note that the capacity under and above the lines are both the same and equal the capacity. It should be noted that it is possible that the maximum capacity will not be reached when discharging is necessary in an early stage. Since this is not the case in the Flex-street scenario, this limitation is not relevant. Moreover, it should be noted that a battery with this profile is technology independent and is considered as ideal. This is done for simplicity and can be refined later on.

The next section describes the results of a storage device next to the transformer. The process as described is not further optimised, since it only takes one minute to do the calculation.

4.2 Storage next to the transformer

This section describes a situation where a large battery is placed next to the transformer. The battery profile from the Matlab script is imported in Triana such that the energy can be injected into the network during the second planning iteration. Due to the nature of the models in Triana, it is not possible to connect the battery directly to the network. Only houses can be connected to the phases. Therefore a new house is added to the network with a connection to all three phases. The cables from the house to the network are very short to prevent network losses in this cable. This house contains only the battery and divides the power equally over the phases.

Since the results of this simulation will be compared with smaller distributed batteries later, a capacity of 100 kWh is used. Later on this will be divided in to 10 batteries of 10 kWh each. These numbers are a bit arbitrary, but the capacity for both central and residential storage turned out fit in the size of the network and the consumption of the households. Figure 4.1 depicts the results of the simulation as described above.

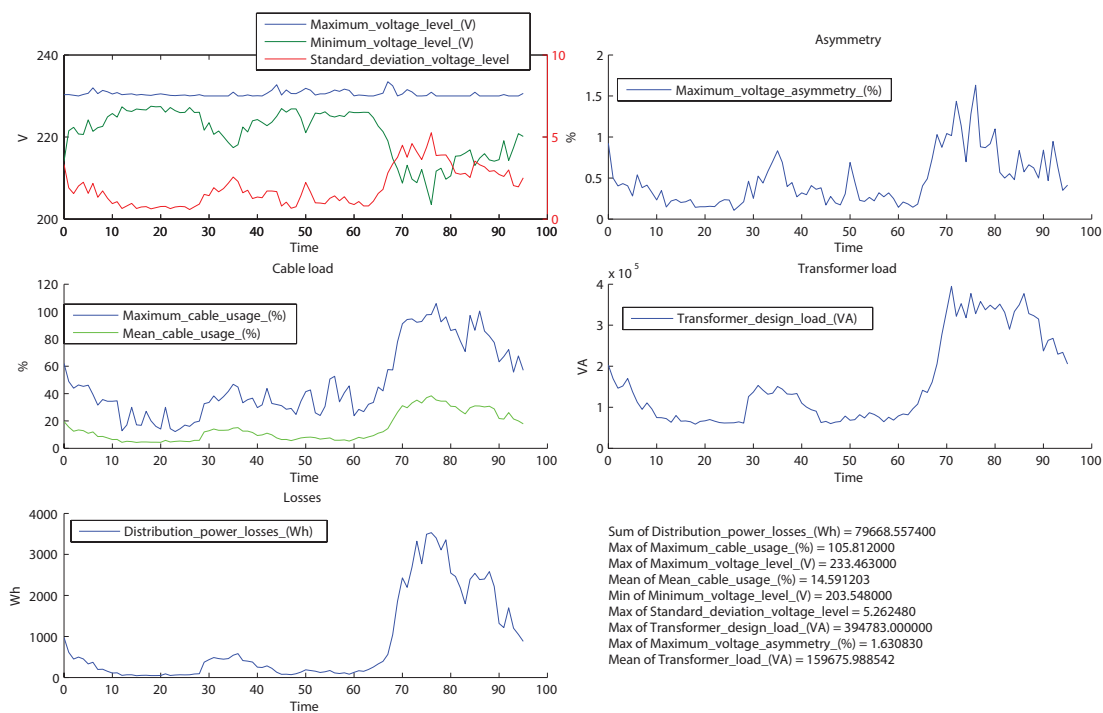


Figure 4.1: A single battery next to the transformer

It can be observed that there are no real significant improvements in the network. The voltage levels for example are almost equal and the asymmetry is even a bit higher. Only the transformer design value is reduced significantly, which is what one would expect as this battery offloads the transformer. The problems in the rest of the network remain unchanged as electricity flow from and to the transformer/battery is still the same. Figure 4.2 shows that this also holds for a summer day simulation.

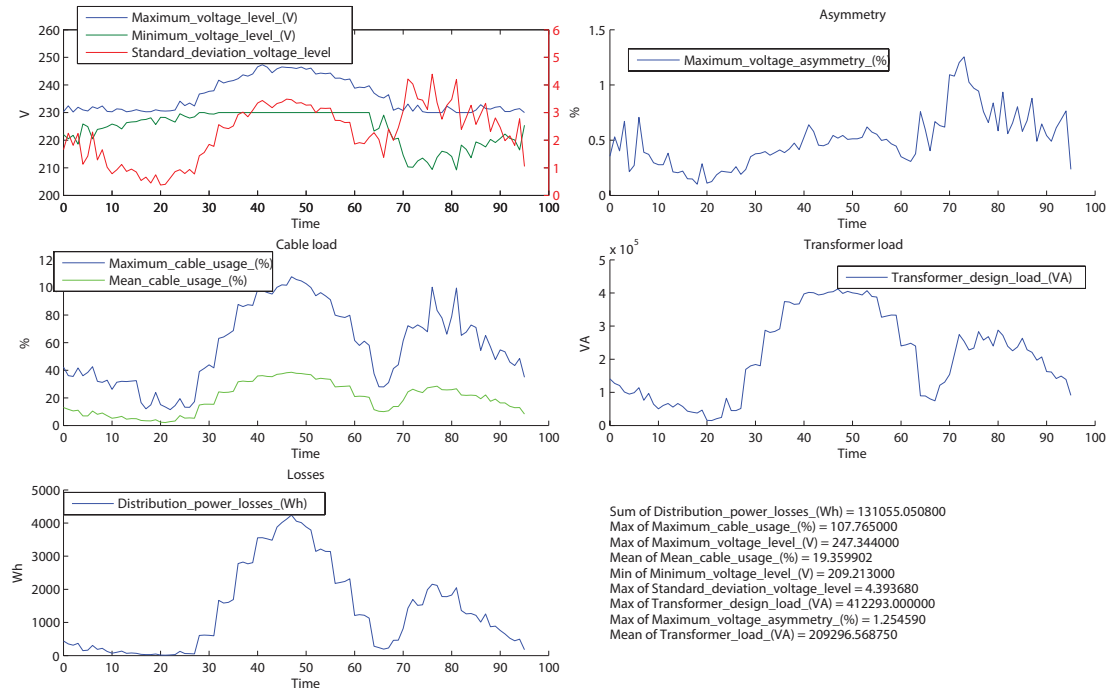


Figure 4.2: A single battery next to the transformer during a sunny day

However, it must be said that the reduction of the peak load in the LV network will result in a reduction of losses in the MV network. This and other possible effects in the MV network can not be simulated with Triana. However, the effects in the MV network are still interesting and could be simulated in later studies.

4.3 Shifting storage in the LV network

Since the effect of a battery next to the transformer on grid assets except the transformer is negligible, it is of interest how the same battery performs at other locations in the network. In section 3.3.2, 128 possible locations were marked in the Lochem network. These locations are network nodes that are connected via only thick cables with the transformer. This section will describe the procedure of iterating over these locations and shows the results of the simulations.

First, a small program is written to generate 128 network config files. Besides the normal network structure an empty house is added on the proposed 128 locations in the network. This program is written in the same language as Triana (C++ with Qt libraries). A Matlab program can copy these network files to the current network file of Triana and can start Triana for a new iteration. The Matlab code that performs the procedure of shifting the battery across the network is listed in listing C.3 in appendix C.

Figure 4.3 shows the result of this simulation for a winter day and figure 4.4 for a summer day. The criteria are expressed in percentages of the situation without storage. Furthermore, the plot

4.3. SHIFTING STORAGE IN THE LV NETWORK

at the right under corner shows the output of the MCA. A higher number in this plot means a better location according to the MCA.

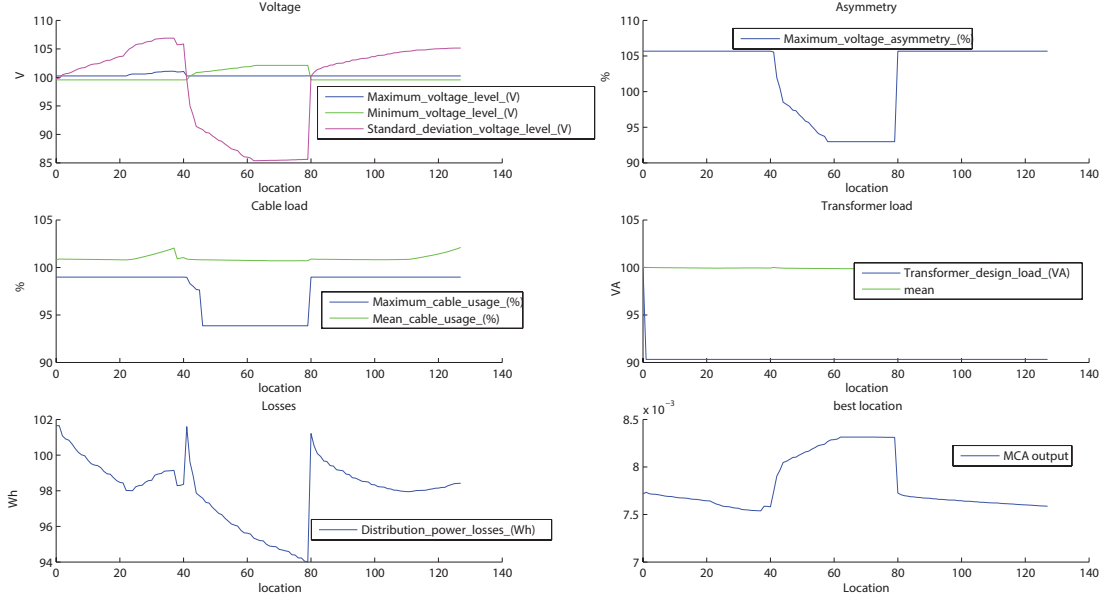


Figure 4.3: The results of a serie of simulations shifting the battery through the network

It can be observed that the locations are clearly divided into three sections. This corresponds with the three feeders in the network. Secondly, it is clear that the battery performs best in the second feeder. Since section 3.4 already showed the voltage problems in this part of the network, this behavior is easy to understand.

The sensitivity analysis for the winter day shows that the voltage is the most critical parameter. When the weight is changed by 3.17 percent, the best location will no longer be location 68. Furthermore, the sensitivity analysis shows that the weight of the transformer load should change with 73.2%, the losses with 3.81% and the cable load with 20.2%. It is not possible to change the best position of the battery by changing the weight of the asymmetry. Below in figure 4.5, the results of the best possible location, location 68, are shown.

Unlike the simulation with a battery next to the transformer, an improvement in PQ can be observed. The minimum voltage level no longer violates the Netcode and the asymmetry is also a bit lower. Moreover, the maximum cable load is reduced to 100.3% and the losses are reduced by 5.1% to 74357 Wh.

In chapter 2, three papers are mentioned with the same type of simulation. First, in [80] an improvement was observed in the minimum voltage levels. This is also observed in the Triana simulation, but a detailed comparison can not be made since the paper lacks a detailed description of their set-up. The same observations were done in [81]. Finally, in [82] a reduction of 3.06% in losses was observed. This is a bit lower than the Triana simulations, but the battery in [82] is not assumed to be ideal. From this it can be concluded that the Triana results as described

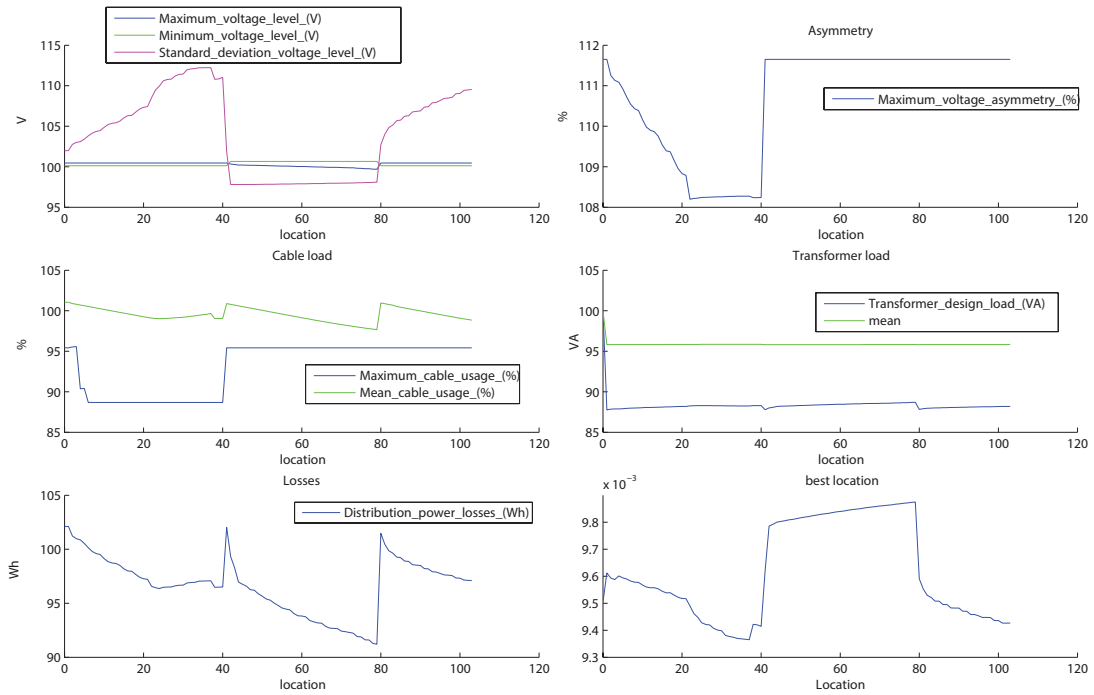


Figure 4.4: The results of a serie of simulations shifting the battery through the network on a sunny day

are roughly comparable with the results mentioned in literature under the assumption that the battery loss will be low.

To conclude this section, a heat map is made of the network. Figure 4.6 shows this heat map. A red color in this map corresponds with a high output of the multi-criteria analysis and a blue color with a low output. From this image it becomes clear that the best battery locations are somewhere in the middle of the second feeder. Moreover, figure 4.7 shows a heat map for a capacity of respectively 50kWh and 200kWh. It should be observed that the battery locations differ a bit, but the location is still clearly in the second feeder.

4.4 Summary

This chapter described the effects of a central battery on the network of Lochem with the Flexstreet scenario. First, a second planning step is introduced in Triana in order to control the battery. This planning step is used to see the effects of a central storage device next to the transformer. It turned out that there were no real effects in the network. Only a reduction in the design value of the transformer was observed.

Next, the battery is shifted through the network to see the effects of the battery at all possible locations. It turned out that the multi-criteria analysis determined an optimal location somewhere in the middle of second feeder independent of the battery size or the weather conditions. A reduction of losses and an improvement of the voltage levels comparable with other studies

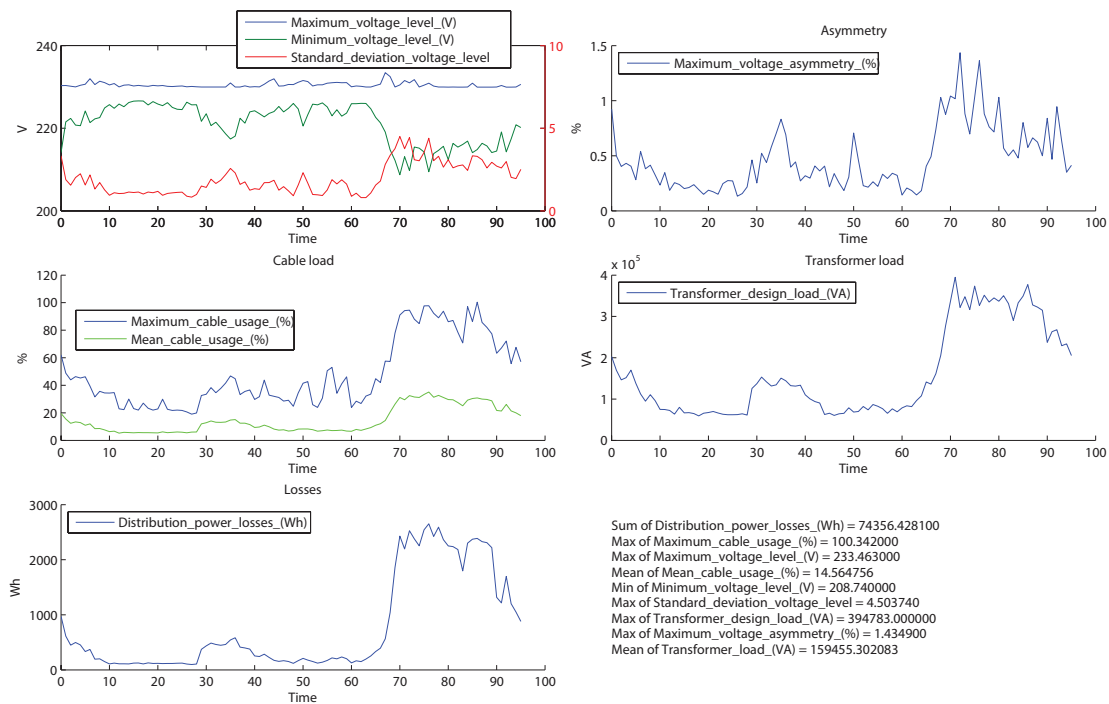


Figure 4.5: The simulation results with a 100 kWh battery on location 68

where observed. Moreover, the obtained results are comparable with the results derived from literature.

Consequently, it can be concluded that a central battery should be placed in the feeder with the most power quality problems. The battery can improve the network stability and power quality. However, as the transformer is fixed at 230V, the effects in other feeders and the MV network can not be shown. It is recommended to implement the MV side of the transformer to see these effects.

The next chapter will describe the effects of ten smaller batteries spread over the network. A comparison between the effects on the network will be made.

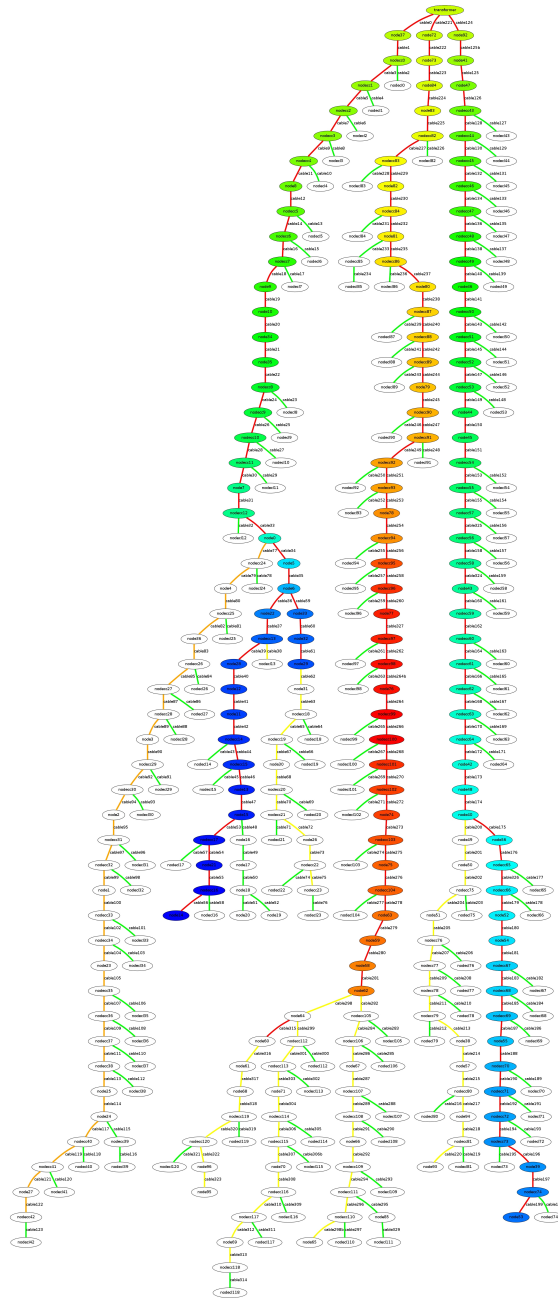


Figure 4.6: Heatmap for a battery of 100kWh

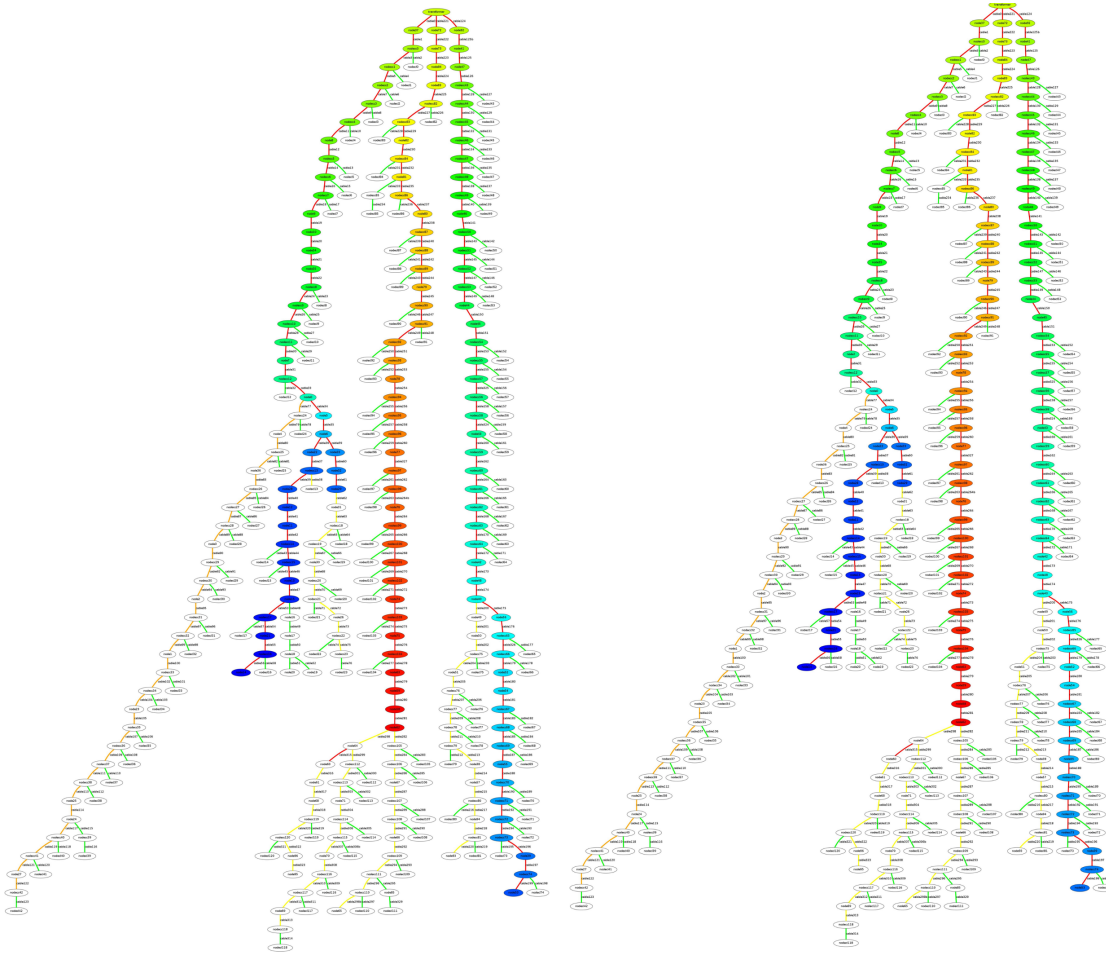


Figure 4.7: A heatmap for a 50kWh battery (left) and a 200kWh battery (right)

5

Residential storage

As mentioned before, this chapter describes the effects of residential storage with central Triana control on the distribution network. The 100 kWh battery from the previous chapter is divided into 10 smaller batteries of 10 kWh. The first section will address the simulation with these batteries steered on the same global energy profile as before. Section 5.2 describes a simulation where the batteries are controlled using the local profile. The last section summarizes the chapter.

In chapter 2 it was already stated that batteries should be placed as close as possible to the problematic areas in the network [103]. Furthermore it is stated in section 3.1 that only the voltage levels and asymmetry can be measured across the network. Due to this, a battery should be placed in the house (at the costumers' side) with the largest deviation in asymmetry and voltages from an ideal situation, measured at the point where the house is connected to the network.

However, it can not be stated that a battery will solve an asymmetry problem. Since the houses are only connected to one phase, it is also possible that the asymmetry becomes higher. For this, the asymmetry will not be taken into account for placing a battery.

5.1 Steering on global energy profile

This section describes the effect of residential batteries on the network. The batteries will be steered on the global energy profile in order to make a fair comparison with the central storage. A battery is added to the network at the location where the deviation in the voltage level is worst. When the battery is placed, a new simulation is done. This will generally result in another location with the largest voltage deviation and the next battery will be placed there. It is not possible that a house has two batteries. This process is implemented in Matlab again. Below, in figure 5.1, a flowchart of the process of placing batteries is shown.

When an initial simulation without storage is performed, the global energy profile, being the aggregation of all consumption over time, is imported into Matlab. The same function of calculating a battery profile as described before (subsection 4.1.1) is called next. When the new battery profile is available, the worst location is determined and the profile for that particular house is exported to Triana. A new simulation is started and if there is storage budget left, a new iteration is entered.

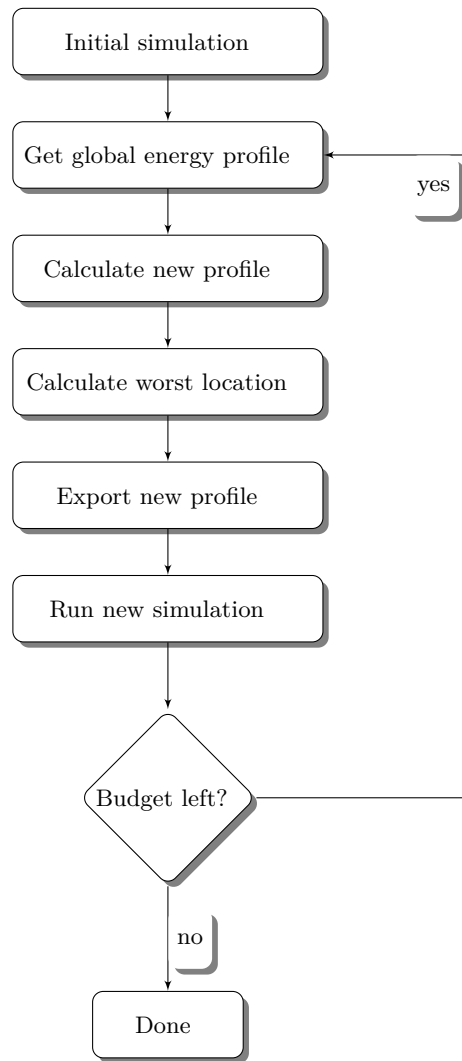


Figure 5.1: Flowchart for simulating residential storage steered on the global energy profile

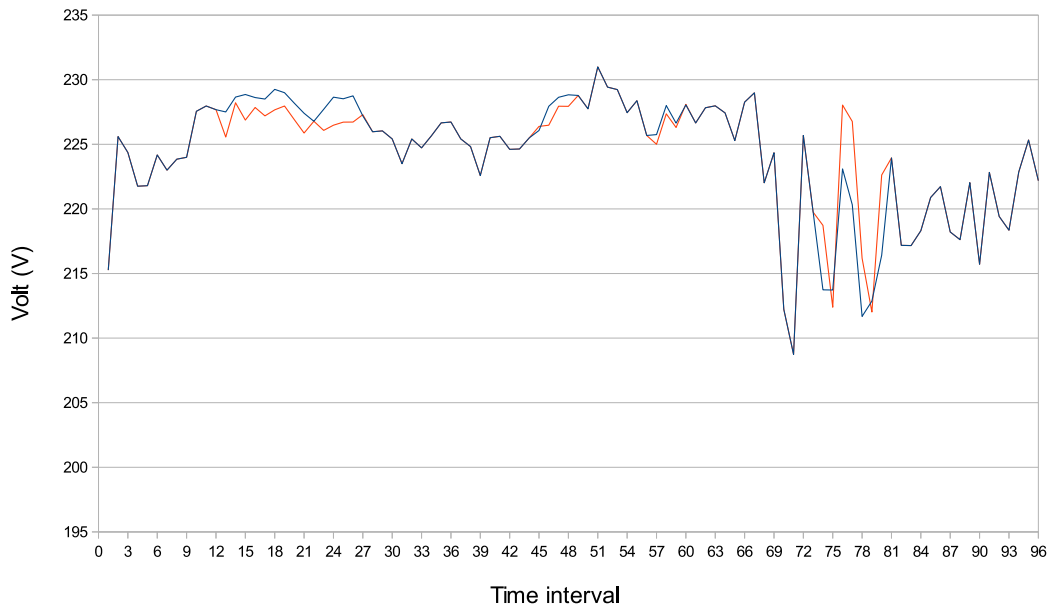


Figure 5.2: The voltage levels are not improved at the proper time intervals

However, from the results of the simulation as described above, only a small improvement in voltage levels is observed. Figure 5.2 shows the reason for this behaviour. A difference exists between the global problems and the local problems in terms of time. When a battery at the end of the feeder steers at time interval t where the global problem is most severe, it is not sure that there are also problems at that time interval in the end of the feeder. Therefore, it is not certain that these problems are solved with local storage. In the figure above, the worst voltage level is at $t = 71$ (blue line). However, the global peak in energy consumption is apparently not at that time interval as the red line (with the battery) shows. Therefore, the voltage level is not improved with the battery that is placed in this house. Moreover, the peaks in the voltage levels are also different. This problem can be solved by steering the batteries on the local energy profile. A description of this solution is in the next section.

5.2 Steering on local profile

Since it is clear that a residential battery used for PQ improvement should not be steered on a global profile, the batteries are steered on the local energy profile in this section. Local problems should now be reduced since the battery really steers on local problems.

The flowchart from the previous section is modified a bit. After the initial simulation, the worst location is calculated first as shown in the new flowchart depicted in figure 5.3 A new battery profile is now determined (see subsection 4.1.1) with the energy profile of that particular house in the previous simulation. Again, this procedure continues until there is no storage budget left.

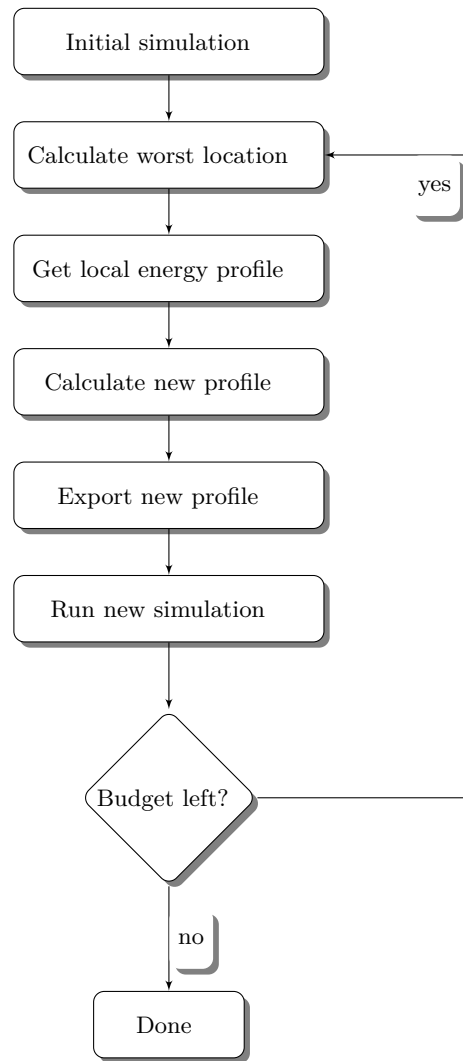


Figure 5.3: Flowchart for simulating residential storage steered on a local profile

The new results are depicted in figure 5.4 and the locations are shown in figure 5.5. The houses with a battery (mainly located at the end of the second feeder since problems are worst in that area) are marked with a red color.

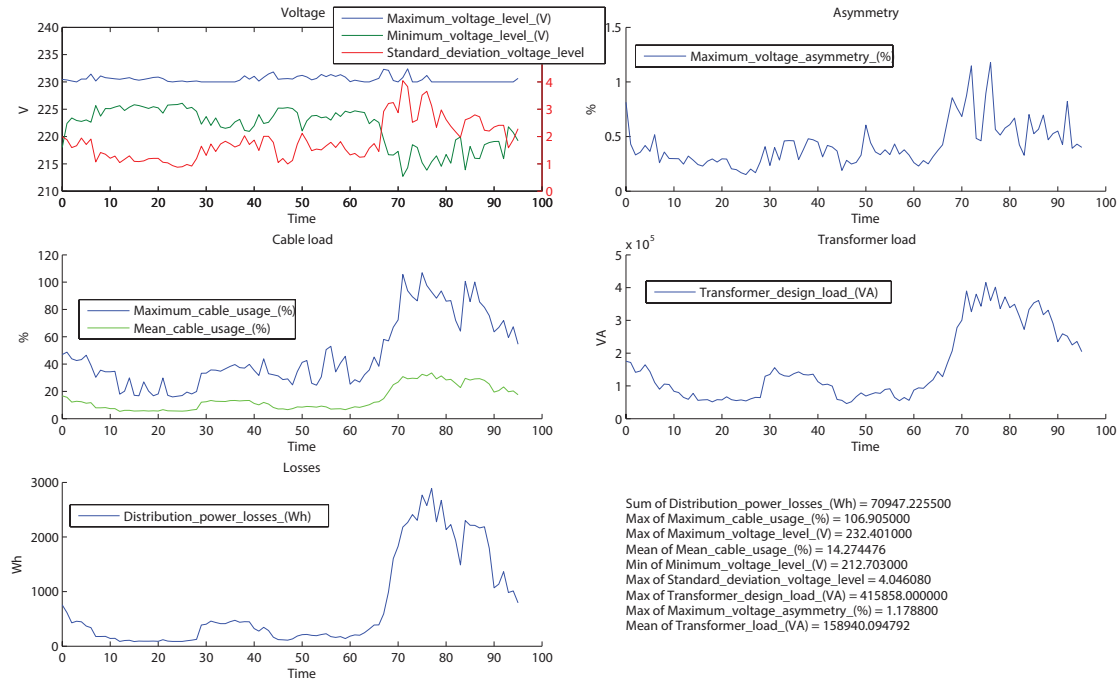


Figure 5.4: The results of a simulation with 10 residential batteries steered on a local profile

This image shows that there is a significant reduction in the distribution losses compared to a situation without storage (section 3.4). The sum of the losses is 70947 Wh, which is a reduction of 9.5%. Furthermore, the minimum voltage is now 212.7V, which is an improvement of 4%. Next to these improvements, an improvement of the asymmetry and the voltage standard deviation is observed. However, the maximum cable usage is not improved. This can happen if the batteries are in an other feeder than the location of the maximum loaded cable. Moreover, the batteries are placed based on the voltage levels and not on cable load.

Figure 5.6 depicts the results of a simulation with 10 residential batteries during a sunny day. It is observed that both the minimum and maximum voltage levels are improved with respectively 2.3% and 1.34%. Moreover, the losses are reduced with 13% and the the asymmetry is improved with 20.5%. These results are even better than a simulation during a day in the winter since now both the PV and PHEV peak can be reduced due to the increasing self consumption.

Figure 5.7 depicts the minimum voltage and the losses as a function of the number of batteries for a winter day simulation. It is observed that the reduction of losses is more or less linear with the number of batteries. Each of the batteries can reduce the peak usage of the cables around the battery and thus the losses in the cables. Furthermore, it is observed that the minimum voltage in the network is already improved a lot with only three batteries placed. This can happen if there are only a few locations in the network where low voltages are observed. When

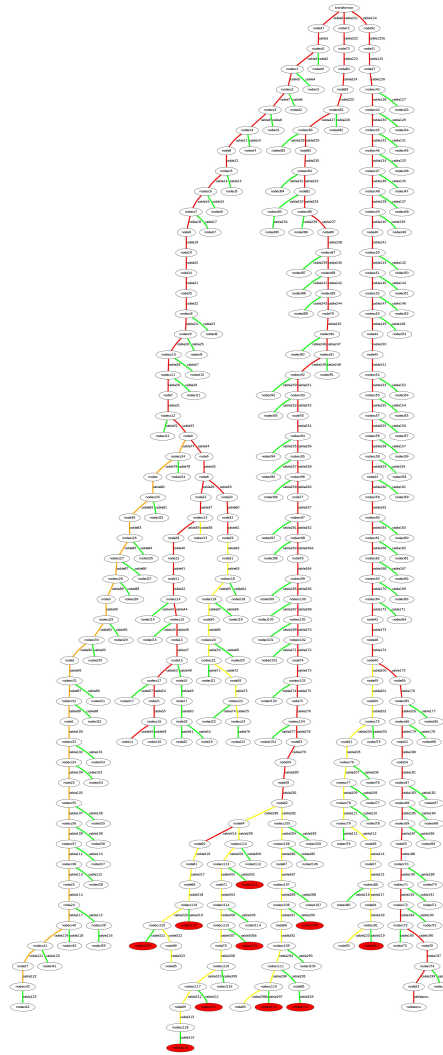


Figure 5.5: The houses that are equipped with a battery

more batteries are placed, it is not sure that the voltage levels will improve since it is possible that the minimum voltage is observed at a house that already contains a battery. Moreover, it is possible that the voltage drops due to an increase of the asymmetry and thus a shift in the neutral conductor. This effect is already known in literature (for example: [112]) and explained in figure 5.8 below.

In the example above, a battery or power source is placed in conductor A . As a result of this, the voltage in conductor A will increase and the neutral point N will shift to N' . The shift of the neutral point will then result in a decrease of voltage v_B and v_C .

Except for the maximum cable usage and the transformer design value, the residential batteries outperformed the central battery. The voltage levels are improved significantly and the losses are reduced with almost 10%. The problems occurring in the network are solved since the batteries

5.2. STEERING ON LOCAL PROFILE

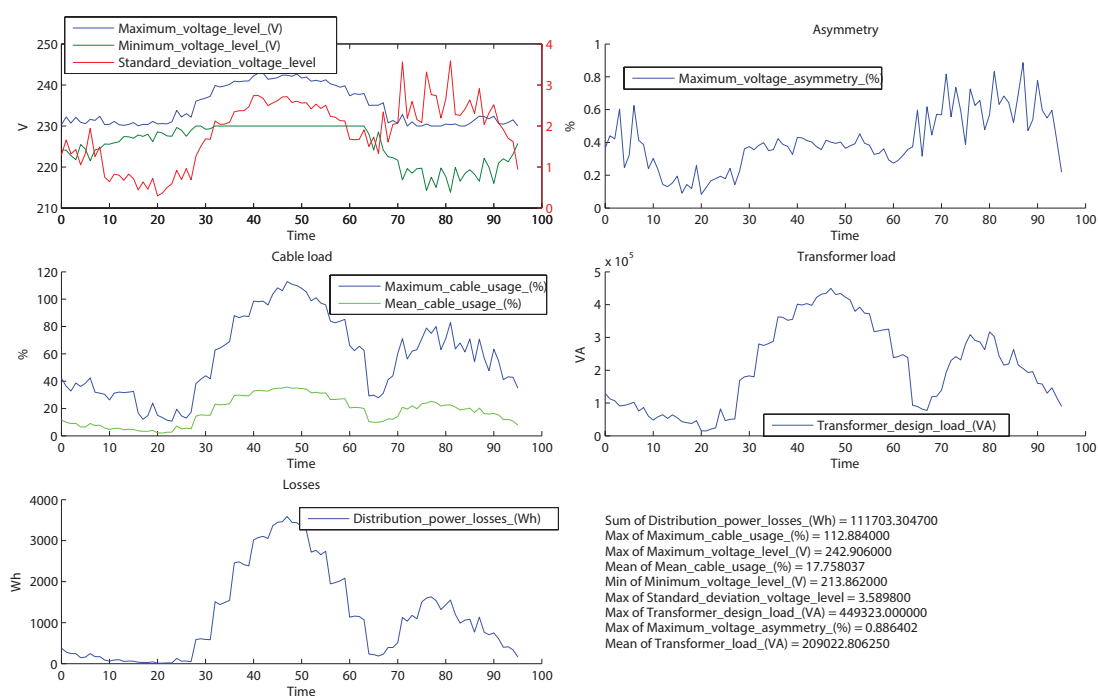


Figure 5.6: The results of a simulation with 10 residential batteries steered on a local profile during a sunny day

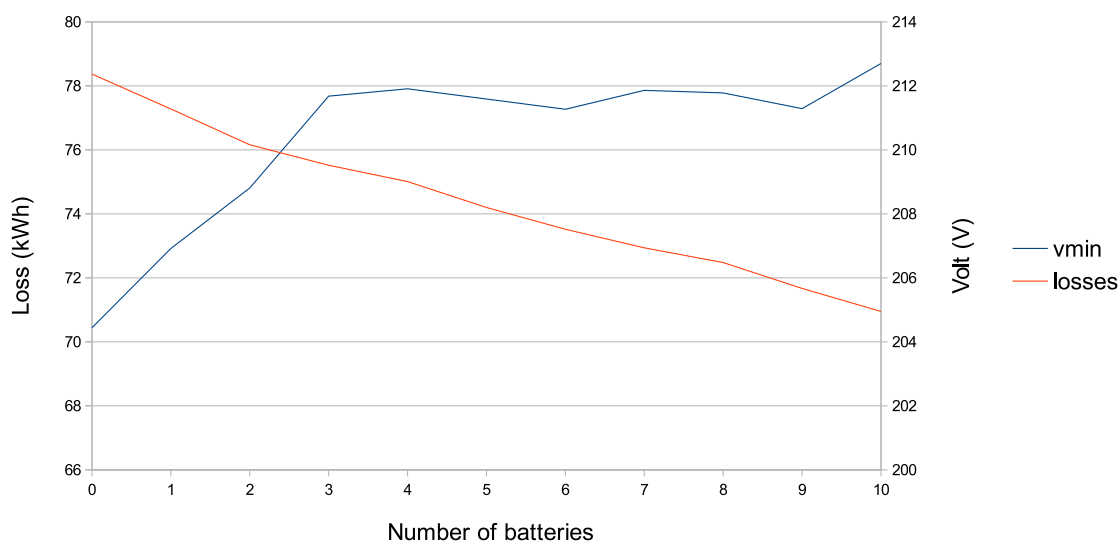


Figure 5.7: The minimum voltage and losses as function of the number of batteries

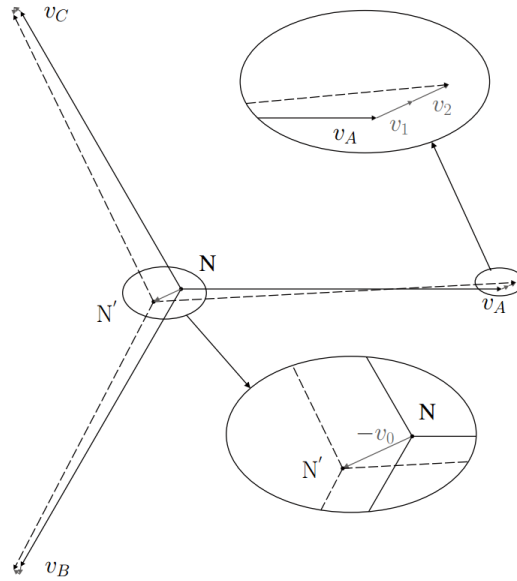


Figure 5.8: A drop in the voltage due to a shift in the neutral conductor (source: [112])

are located at the houses with the largest problems.

The results also outperformed the results derived from literature. Marra et al. [96] observed a reduction of 7.3% in losses in a network of 33 houses with a total storage of 48.6kWh divided into 9 small batteries. This is a lower reduction with a higher storage capacity per house. This is due to less knowledge about the future in the network compared to the Triana control. However, it must be noted that the used batteries are not ideal and therefore more realistic. Moreover, more simulation and use-case parameters are different compared to the situation in this study. But even with these differences, it supports the value of the results from the simulations, especially during a summer day.

5.3 Summary

This chapter described the effects of residential storage with central control on the distribution network. First, the batteries were steered on the global energy profile in order to make a fair comparison with a central battery. However, this approach was not successful as the local problems could appear at an other time interval than the global problem.

Next, the local energy profile was used for the steering of the batteries. This approach outperformed the central battery and the results from literature. With only three residential batteries the minimum voltage is already improved from 204.4V to 212.7V. Furthermore, it was observed that the reduction of losses is more or less linear with the number of batteries. Finally, the effects during a summer day are larger than a winter day as both the generation and consumption peaks are reduced.

6

Plug and play storage

This chapter addresses plug and play storage. The central Triana controller is removed and no knowledge of the energy profiles is kept. Since the voltage level is the only reference of such a battery, the battery is controlled with this voltage level. A high voltage implies a low demand and/or a high generation and a low voltage implies a high demand and/or a low generated power. The battery can be equipped with a smart controller for making decisions based on the voltage level. Again, two bounds are introduced. A lower threshold for discharging and an upper bound for charging.

Benefits of such a battery, as already mentioned in chapter 2, are an improvement in terms of reliability and privacy. Since there is no communication to a central controller any more, the system will not be influenced by communication failures or cybercrime issues. This improves both reliability and privacy. Moreover, a DSO can easily place a plug and play (P&P) battery in the network without installing a complete DSM system.

This chapter describes the effect of P&P storage on the distribution network. Matlab is used again for determining the thresholds for (dis)charging based on a previous simulation. This results in the best possible bounds and therefore, the results indicates the best possible improvements with a P&P battery. The Matlab approach for determining these bounds is described in the first section. A droop controller is used. Section 6.2 will address the results of the simulations with voltage steered P&P batteries. Finally, a summary of this chapter is given.

6.1 Droop control

As mentioned before, this section describes the approach of calculating the bounds for the P&P battery. Since only a voltage level is used as input and the output should be power, a mapping from voltage to power is necessary. For this type of control, a droop controller is introduced. Examples can be found in literature [113, 114, 115]. This section describes the implementation of the droop controller in Matlab.

Figure 6.1 is based on an image from [115] and shows the principle of a droop controller. The x-axis shows the voltage. If the voltage level is higher than the upper droop limit (UDL) or lower than the lower droop limit (LDL) the battery will charge or discharge respectively. The power that will be injected into the network is shown on the y-axis. If the voltage level is higher or lower than respectively the UDL or LDL, a power proportional to the distance to the limit should be injected. The Matlab function that implements this droop controller should return

the UDL and LDL given the angle α ($\alpha_{upper} = \alpha_{lower}$) (or the slope of the curve), the voltage profile from the previous simulation iteration and the capacity of the batteries.

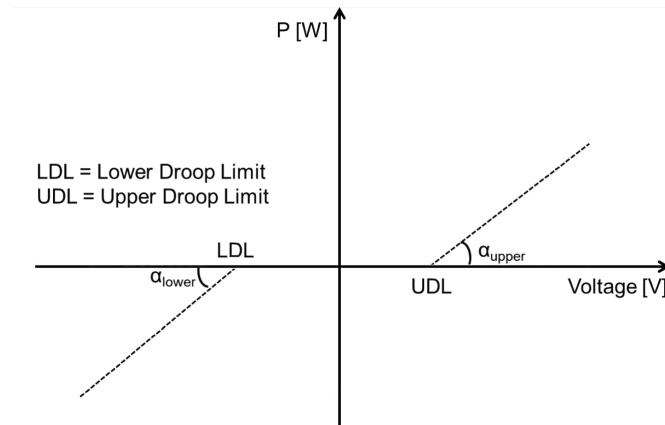


Figure 6.1: A droop controller (based on: [115])

When both bounds are determined, they are exported to Triana. If Triana also knows α , a new iteration can be performed in the same way as done in the previous chapter. The capacity will stay again within the 10 kWh with this implementation and still no losses are modelled. However, this implementation is not completely fair. The second battery that will be placed influences the behaviour of the first battery. This dependency between all batteries can not be solved easy in the simulation and is left for future work. Moreover, it should be noted that the use-case data is divided in 15 minute intervals. As a result of this, real-time fluctuations in the voltage profile can not be measured. In a real-life situation the voltage levels will fluctuate heavily since the voltage level is a result of all things happening in the network. Triana cannot deal with these quick fluctuations or with for example switching in the transformer. An implementation of P&P batteries that is capable of dealing with these difficulties, is also left for future work.

As mentioned above, the voltage profile is a result of all events in the network. When a house that is connected to the same phase switches on a washing machine, the voltage profile in the complete phase will change. This makes that a system of P&P batteries can potentially perform better than the energy steered residential batteries. The P&P battery is steered on the voltage profile measured at a house and that profile contains information about the entire feeder. This will potentially perform better from a network point of view than a battery that is steered on an energy profile of a single house. The next section describes the results of the simulations done with the P&P batteries.

6.2 Steering on the local voltage levels

As mentioned before, this section describes the results of plug and play batteries. These batteries are implemented as a function in Triana with the current voltage as input variable. With a given slope and the bounds imported from Matlab, the power is calculated. The slope of the droop controller curve is fixed at 500 W/V. This number is derived from several experiments. It turned

6.2. STEERING ON THE LOCAL VOLTAGE LEVELS

out that a larger slope resulted in overshoots since there were only a few time intervals where the battery reacted heavily. A lower slope resulted in a situation where the UDL was smaller than the LDL because there were too many time intervals where the battery should react. This may of course not happen.

In order to make a fair comparison between these results and the previous battery configurations, there is again 100kWh storage budget. The batteries will be placed at the location in the network where the deviation from an ideal 230V supply is largest and again every house can own only one battery. Figure 6.2 depicts the results of the simulation.

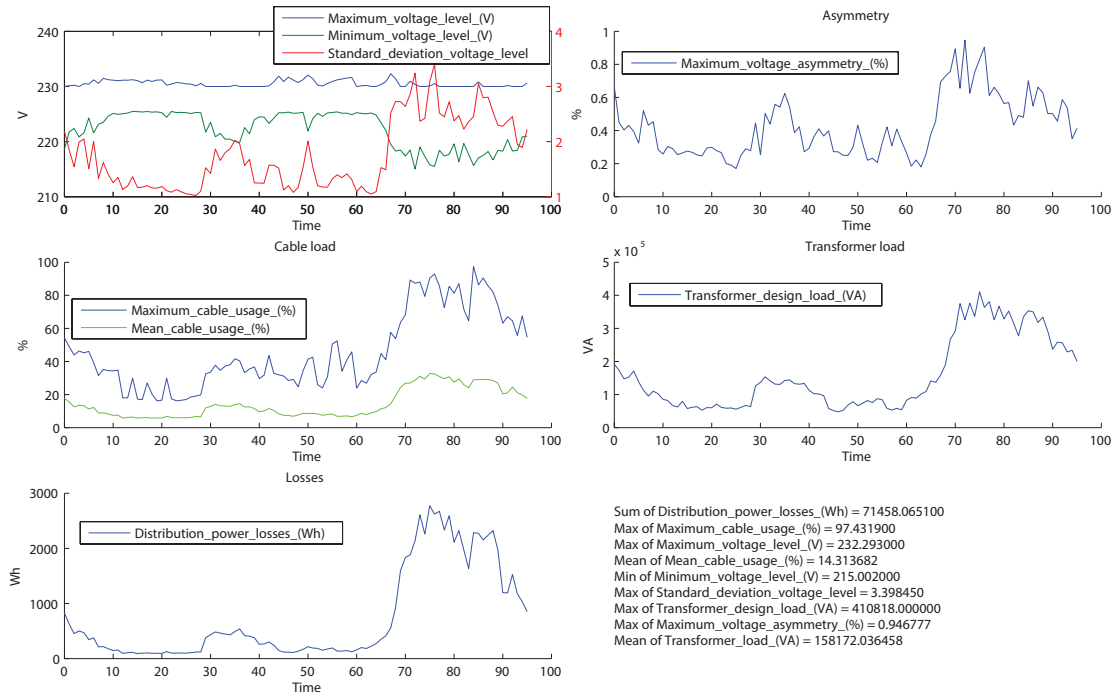


Figure 6.2: The results of a simulation with 10 P&P batteries of 10 kWh

From this figure it can be obtained that the minimum voltage is indeed higher compared to residential storage. Furthermore, the maximum cable load is reduced to 97%, the voltage standard deviation is reduced, the design load is slightly lower and the asymmetry is lower. The losses are a little higher than residential storage, but there is still a significant improvement compared to the situation with only one large battery. To summarize: except for the minimum voltage and the cable load, these results are almost the same as with residential storage.

When the same simulation is performed on a sunny day, the improvement is even larger. Figure 6.3 shows that the losses are reduced with 14.9%. Furthermore, the minimum voltage is improved with 4.1%, the standard deviation with 37% and the asymmetry is reduced with 34.8% compared with the reference simulation during the same sunny day. Again, it is observed that both the generation and consumption peak are reduced. When these results are compared with residential storage, an improvement in mainly the voltage related criteria is again observed.

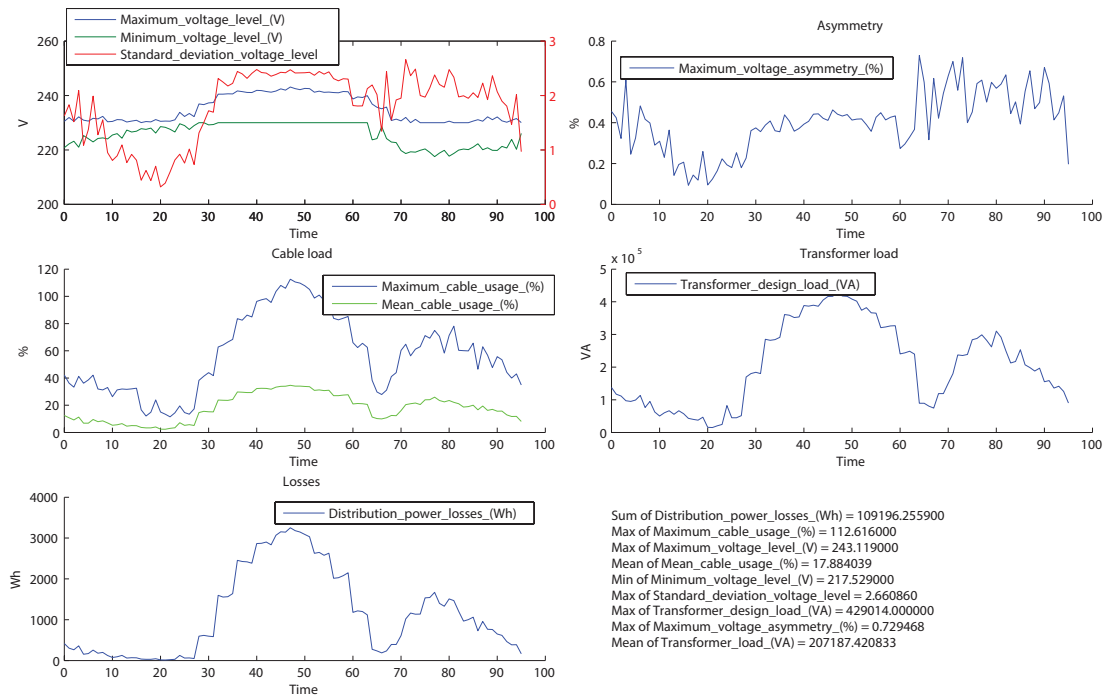


Figure 6.3: The results of a simulation with 10 P&P batteries of 10 kWh during a sunny day

Figure 6.4 shows again the reduction in losses and the improvement of the minimum voltage as a function of the number of batteries for the winter day. Again, it can be observed that placing three batteries already solves most voltage problems and that a decrease of the voltage is possible due to asymmetry. Furthermore, the reduction of losses is again more or less linear with the number of batteries. Finally, figure 6.5 shows the locations of the batteries. The majority of the batteries is again located at the end of the second feeder. However, some batteries are also placed in other feeders as most problems in the second feeder are already solved.

As mentioned before, no losses are taken into account. In literature various examples can be found of battery technologies and their characteristics. When for example Lithium-ion batteries are taken into account, a round-trip efficiency is often calculated around 95% [116, 117]. With these losses taken into account the losses will increase with 5% of the total stored energy. Since 100kWh is stored, this will be 5kWh. This will reduce the benefit from the batteries. However, these numbers are just an example of the current state of the technology. A lot of research is done on improving storage technology. For example, in [118] it is stated that projects teams are working on a battery with a round-trip efficiency of 99.99%.

6.3 Summary

This chapter introduced the effects of residential storage without central control (plug and play batteries) on the distribution network. A droop controller is introduced in order to make a map-

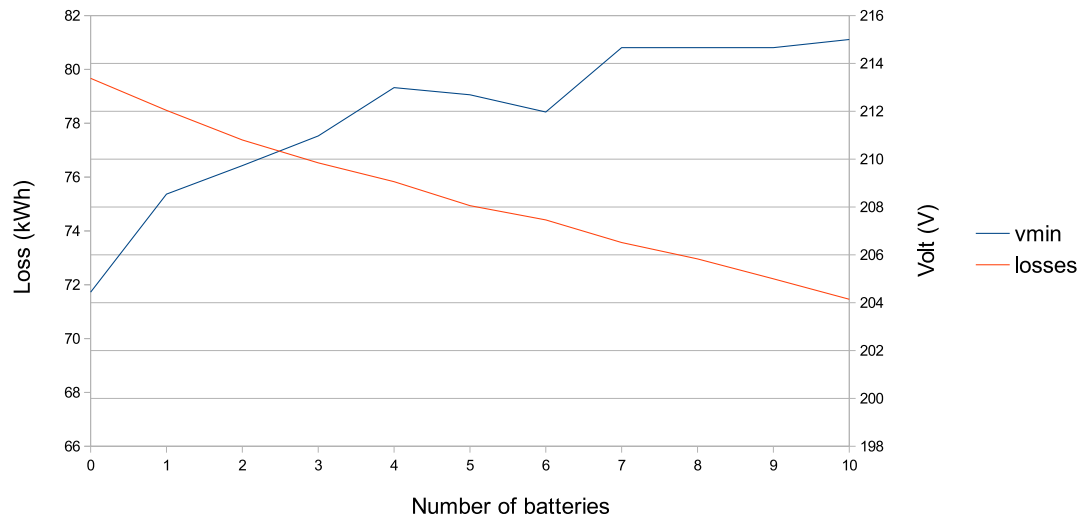


Figure 6.4: The minimum voltage and losses as function of the number of batteries

ping from the voltage measured in the network to the power injected from the battery. Matlab is used to implement this controller and a function that determines the upper and under droop limits. With these scripts available, a simulation is done with 10 P&P batteries of 10kWh.

The results turned out to be almost the same as the previous simulation with residential storage with central control. Only significant improvements in voltage related criteria are observed. These improvements are due to the direct steering on the voltage. Furthermore, the improvement is larger during a sunny day since both the production and consumption peaks can be reduced. Again, it is observed that most voltage problems were solved with only three batteries.

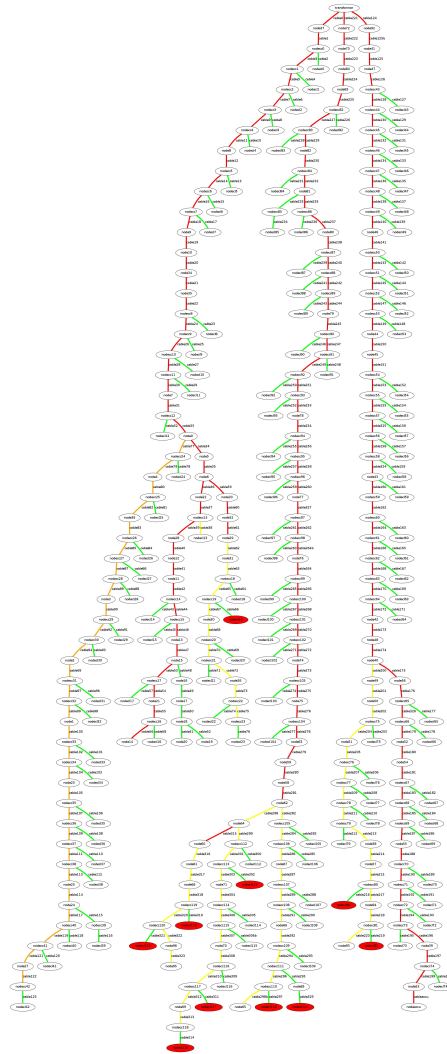


Figure 6.5: The location of the P&P batteries

7

Comparing the results

This chapter summarizes the results from the previous chapters and describes a comparison of the effects on the distribution network. All parameters as derived in section 3.1 are mentioned. Since it is observed in the previous chapters that the minimum voltage, the losses and the asymmetry gave the most interesting results, these criteria are described in more detail in the first section. The second section describes a comparison between the P&P batteries and the Triana DSM approach.

7.1 Comparing the battery configurations

This section describes a comparison of the results of the battery configurations from the previous chapters. First, table 7.1 shows an overview of all previous results.

Criteria	No storage	Central	Residential	P&P
Max Voltage (V)	232.9	233.5	232.4	232.3
Min Voltage (V)	204.4	208.7	212.7	215.0
Std dev. Voltage (V)	5.27	4.50	4.04	3.39
Max Asymmetry (%)	1.54	1.43	1.17	0.94
Max Cable load (%)	106.91	100.34	106.91	97.43
Mean Cable load (%)	14.46	14.56	14.27	14.31
Max Transf. load (VA)	437116	394783	415858	410818
Mean Transf. load (VA)	159664	159455	158940	158172
Sum Losses (Wh)	78374	74356	70947	71458

Table 7.1: The effects of 100kWh of storage in various configurations on various network parameters

It can be observed that for almost all parameters and for almost all battery configurations, an improvement is reached. Only for the central battery, the maximum voltage and the mean cable load are worse than a situation without storage. Below in figure 7.1 respectively 7.2, the minimum voltage and the asymmetry are shown for the four battery configurations and the Triana DSM approach. The values of the 96 time intervals are sorted from high to low to obtain a duration curve.

Figure 7.1 shows that the minimum voltage level is improved significantly when batteries are placed in the network. A central battery already gives an improvement, but decentralized stor-

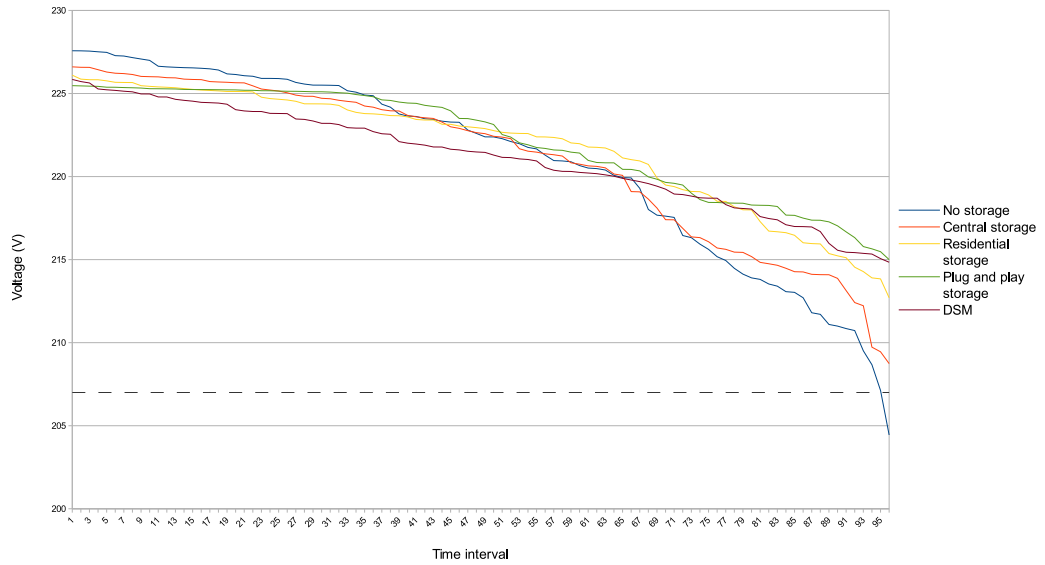


Figure 7.1: The minimum voltage appearing in the network

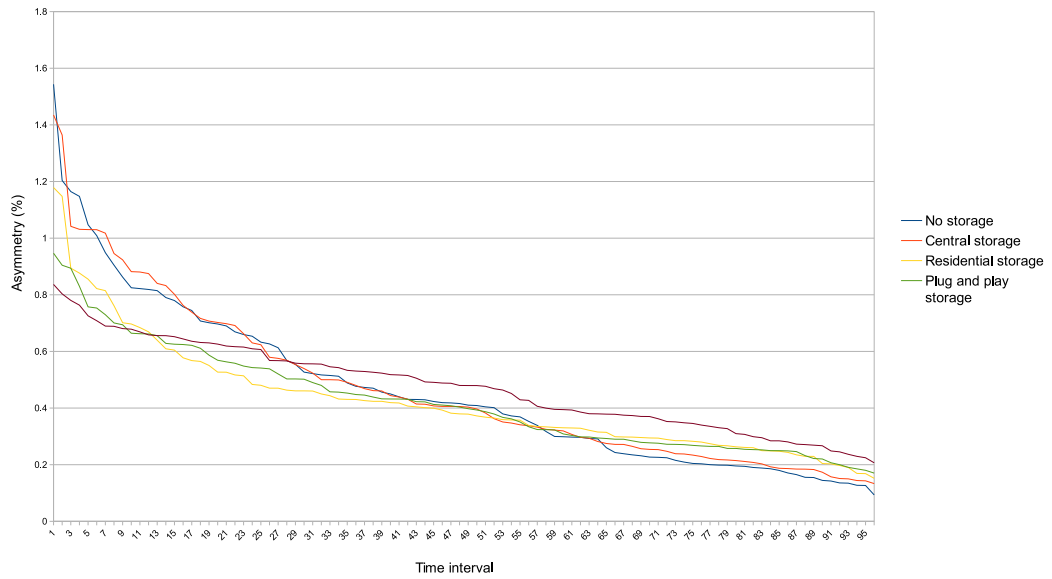


Figure 7.2: The maximum asymmetry appearing in the network

age gives a higher improvement. Moreover, the voltage steered P&P batteries give the largest improvements in the conducted experiments. Even the DSM approach is outperformed.

7.2. COMPARING PLUG AND PLAY BATTERIES WITH TRIANA

Although a direct relation between the asymmetry and the placement of a battery is not clear, an improvement in the asymmetry is observed as shown in figure 7.2. Again the voltage steered P&P storage performs the best of all battery configurations. The DSM approach results in this case in a flatter curve. Next, in figure 7.3 the losses in the network are shown for the four battery configurations and the DSM. It is observed that there is again a significant improvement when storage is placed. Moreover, decentralized storage outperforms the central battery again. A significant difference between residential and P&P storage is not observed. The DSM approach performs best in this situation. The complete peak is shifted and the sum of the losses is lower.

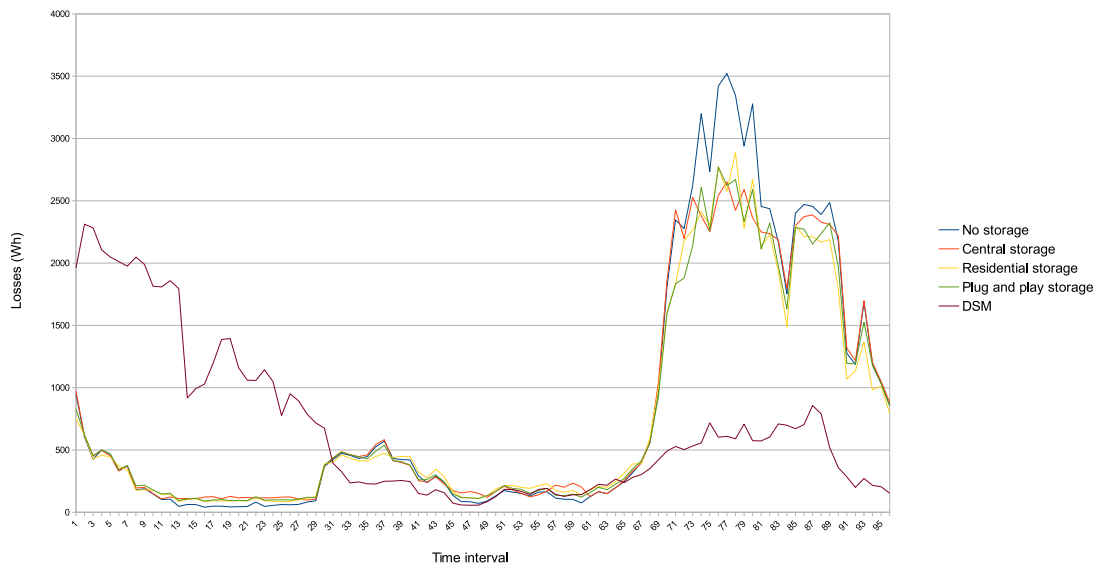


Figure 7.3: The losses in the network over time

7.2 Comparing plug and play batteries with Triana

Since P&P storage turned out to be the preferred storage configurations, a comparison is made between P&P storage and the Triana DSM algorithm. Triana is steered on electricity profiles and tries to flatten the electricity consumption. Plug and play storage is steered on voltage levels and tries to flatten the voltage profile. In figure 7.4 the power respectively minimum voltage duration curve are shown for both DSM and P&P. Since P&P storage steers on the voltage levels, it is expected that the batteries perform better than Triana. From the figure it can be observed that this is indeed the case as the minimum voltage for P&P storage is almost everywhere higher than for the DSM approach.

However, when it comes to the electricity duration curve, there is no longer a lot of difference. It can still be said that the Triana line is more flat, but the difference is small. Furthermore, as already shown in figure 7.3, Triana performs best when the reduction of losses is most important. From this it can be concluded that 10 P&P batteries can outperform the Triana DSM approach

CHAPTER 7. COMPARING THE RESULTS

in some cases assuming the existence of a perfect working operating system for P&P batteries and loss-free battery technology. Since a few of these battery systems can be more easily installed than a DSM system, it is clear that more research should be done on the topic of P&P batteries.

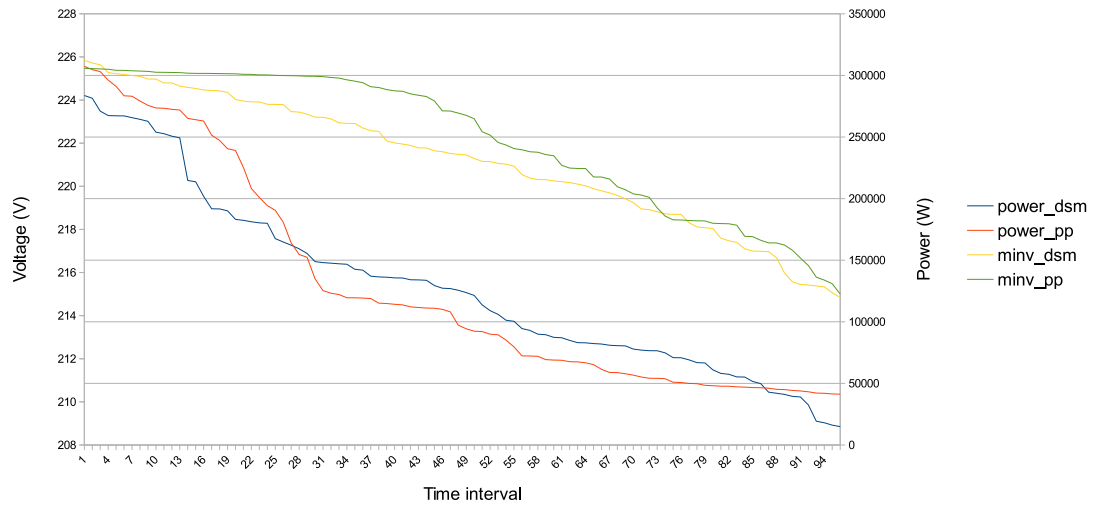


Figure 7.4: The performance of P&P storage and DSM on electricity flatness and minimum voltage levels

8

Conclusions and future work

This final chapter describes the conclusions that can be derived from the previous chapters and the future work that is recommended. In order to do so, the first section addresses the answers to the research questions. The second section summarizes the main conclusions derived in this study and the final section will describe the recommendations for future work.

8.1 Answers to the research questions

This section addresses the answers to the research question as derived in section 1.3. The answers follow from the simulations in the previous chapters and the comparison. First, answers to the sub-questions will be given. Consequently, the main research question will be answered.

What is the effect of central storage on power quality and network components?

Literature shows that a storage device can have a positive effect on mainly the voltage levels and the losses. Triana simulations show that a battery located next to the transformer, only has effect on the design load of the transformer. Since the situation behind the transformer/battery stays the same, no effects were observed in the network itself. However, with much local generation, the battery can reduce the load and thus the losses in the MV network, but Triana cannot simulate the MV network.

When the battery is shifted through the network, a multi-criteria analysis shows that the battery should be located somewhere in the middle of the feeder with the most PQ problems. An improvement in the minimum voltage, standard deviation of the voltage, asymmetry, maximum cable load, transformer load and losses is observed.

Where should small storage devices be placed and what should be their characteristics?

It is derived from literature that a small storage device should be placed as close as possible to the location of the PQ or network problem. If a house causes PQ problems due to local power generation, that particular house should get a battery in order to mitigate the problems. Simulation results with Triana show that this is indeed the case and that this approach is successful.

Furthermore, the preferred battery type and thus the characteristics, depends on the type of application. A PQ problem can be solved with for example a flywheel or a lithium-ion battery and large scale energy management should be done with for example a redox flow battery.

What is the effect of residential storage and control on power quality and network components?

The effects of residential storage and plug and play storage (which is residential storage without central control) are comparable. Since the batteries are located as close as possible to the problems in the network, all network parameters are improved compared to a situation without storage. The effect on the minimum voltage, asymmetry, the voltage standard deviation and the losses are significant. An effect on network components is also observed. Both the transformer and cable load are reduced. Furthermore, it can be observed from table 7.1 that plug and play storage slightly outperforms residential storage for most parameters. This is due to direct control using voltage levels as input.

The answer to the main question can now be given:

What is the effect of residential storage and control on the distribution network compared to central storage and control?

Both residential and central storage have a positive effect on the distribution network. A central storage device located next to the transformer only flattens the peak load on the transformer. When the battery is placed in the middle of a feeder, improvements in the other parameters are also observed. However, when network parameters as for example the minimum voltage and losses are of importance, it is more beneficial to place a few smaller batteries as close as possible to the problems. Even with only three batteries of 10kWh each, most voltage problems are solved in the used use-case. Using P&P storage shows significant improvements whilst it also improves reliability and privacy. Therefore, in most cases the batteries should be steered with the local voltage profile.

However, it must be said that not all PQ aspects are taken into account. Since 15 minute time intervals are used, fast voltage fluctuations and higher order distortion are not taken into account. Moreover, it is possible that the battery systems are introducing harmonic distortion due to the steering electronics. Furthermore, the batteries are modelled as ideal batteries without losses. This will reduce the benefit of battery systems.

8.2 Conclusion

This study showed that storage in a distribution network can have a significant impact on both network assets and power quality. When problems with for example overloading or power quality occur, batteries can be a good solution for the problem. Furthermore, this study shows an overview of various battery configurations and compared their effects on network components and power quality. A DSO can use these results when a decision has to be made for a solution for existing problems.

First, it can be concluded that a central battery next to a transformer has no effects on the low voltage network except for reducing the load on the transformer. However, when a battery is located centrally in a feeder with power quality problems, there is an improvement in mainly voltage levels and losses. When the same amount of capacity is divided over smaller batteries, the effect is even larger. Local problems can be solved as the batteries are placed as close as possible to the problems. Moreover, the improvements are highest during sunny days since both

the production and consumption peaks can be reduced.

When the communication to the central controller is removed in order to improve on privacy and reliability, the batteries can be locally steered on the local voltage level. Simulations showed that there is again an improvement in the voltage related criteria and that the losses are kept more or less the same. The effects during a sunny day were again higher than a winter day. However, this assumes an operating system for these batteries that can steer the batteries optimally, which is not yet available. When such a system can be developed only a few of these batteries can already improve the network parameters significantly, which makes these configuration the best solution in situations with power quality or overload problems.

These conclusions hold for the use-case that is used (a typical 90's residential network with real measurement data), but it can not be concluded that the results hold in every network. Moreover, the batteries are considered as ideal, which is also not true. Literature showed however that the efficiency of modern technology is high. Furthermore, the fixed 230V influences the location of the central battery, as there are only effects in the feeder where the battery is located. This is also not true. Nevertheless, this study yielded nice starting points for further research in the field of storage in smart grids.

8.3 Future work

During this study, various topics not directly related to the research questions are encountered. Moreover, some parts of this study could not be researched due to for example a lack of tools or time. These topics are listed below as a suggestion for future work.

First, as already mentioned the transformer is fixed at a voltage of 230V. As a result of this, the batteries do not have an effect near the transformer. The MV side of the transformer should be added to the Triana models in order to perform a more detailed simulation.

Furthermore, since the P&P batteries are a very interesting technology, a real steering system for such a battery can be developed. If the battery is equipped with a small intelligent system that can deal with all switches in the network and prediction of the voltage boundaries, the technology can be used in practice with little effort.

Next, it was already stated that the network used is a typical 90's network. However, the generality of the results can increase when the simulations are tested with a benchmark network. This makes it also possible to make a more fair comparison with other solutions. Furthermore, houses with a connection to all three phases should be added in this network since new houses are nowadays always connected to all three phases.

Finally, the results of this study are obtained under the assumption of perfect knowledge and ideal batteries. Since this is not the case in a real-life situation, the models can be improved in terms of reality. It would be very interesting to combine the improved models with real measurements. The results can be entirely validated if there are real batteries placed in the network.

A

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Optimize Power Quality with Only Local Storage and Measurements

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Jan Oene Krist



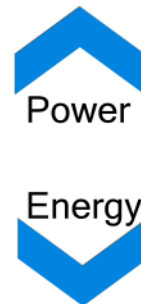
A possible solution is storage...

CHALLENGES IN SMART GRIDS

- Due to an increasing penetration of heat pumps, electrical vehicles, PV and wind turbines, the electricity network becomes less controllable and less stable
- Power quality problems are increasing
- Main problem is voltage (Unom +/- 10%)

STORAGE APPLICATIONS

1. Short term applications
 - Power quality improvement
2. Mid term applications
 - Black start support
 - Spinning reserve
3. Long term applications
 - Arbitrage
 - Peak shaving
 - Load shifting



Two ways of applying storage will be compared...

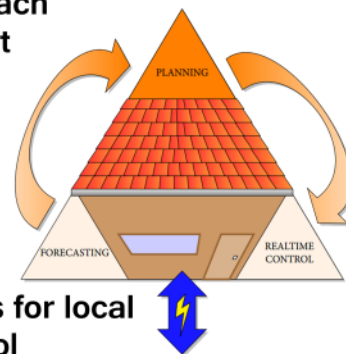
RESEARCH

- Load flow simulations using Triana
- Comparing central- and local storage
- What is the effect on voltage stability and network components
- What is the effect of removing central control?

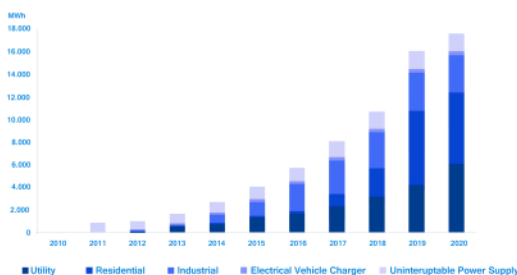
Triana is developed at the University of Twente

TRIANA

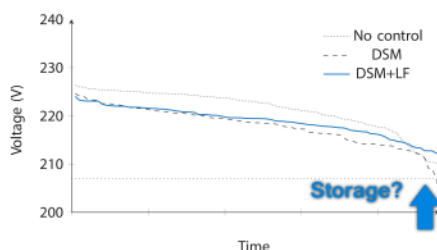
1. Three step approach for planning in smart grids
2. Load flow calculations for grid analysis
3. Control strategies for local and central control



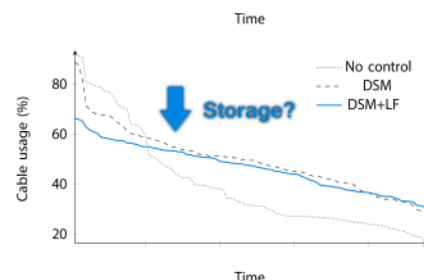
RESIDENTIAL STORAGE FOR NETWORK APPLICATIONS



▶ Residential storage is expected to grow (source: Leclanché)



▶ Flattening the voltage curve to be EN-50160 compliant

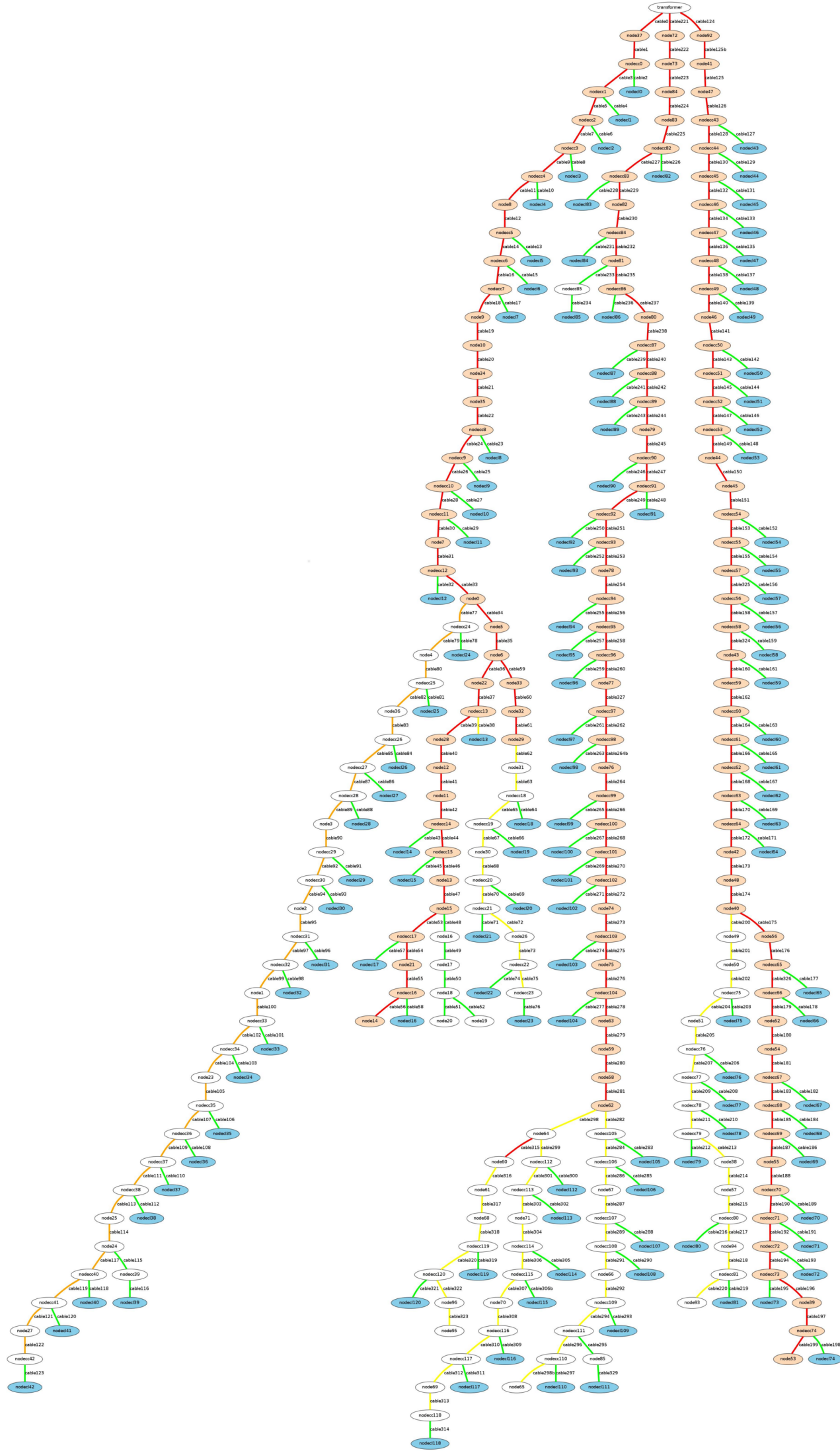


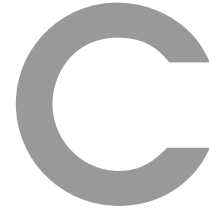
▶ Defer transformer / cable reinforcements

Storage will be the key to a stable and sustainable electricity network!

B

Lochem network





Code samples

Starting Triana from Matlab

```
1 function startTriana(path, nrSim)
2     %copy ini file
3     command = sprintf('cp %sbuild/configurations/networks/bat/one-
4         networknodes/lochem%u.ini %sbuild/configurations/networks/bat/
5         lochem_current.ini', path, nrSim-1, path);
6     system(command);
7     %Execute Triana
8     command = sprintf('bash/start_triana.sh matlab-single_%i %sbuild'
9         , nrSim, path);
10    system(command);
11 end
```

Listing C.1: Starting Triana from Matlab

In the first part (line 3 and 4) of this code, a file that contains the network information for a certain battery location is copied to Triana. The second part (line 7 and 8) of this code calls a bash script that calls Triana. A tag (in this case Matlab-single with the number of the iteration) can be passed to Triana. This flag is used in the name of the output files and makes it easy to find the corresponding output.

Find the bounds for (dis)charging

```
1 for line = mean(profile):1:max(profile)
2
3     a_above = zeros(1,96);
4     a_under = zeros(1,96);
5     for sample = 1:1:96
6         if (profile(sample) > line)
7             a_above(sample) = (profile(sample) - line);
8         end
9         if (profile(sample) < lineDown)
10            a_under(sample) = (lineDown - profile(sample));
11        end
```

```
12 end
13
14 if ((sum(a_above) < 4 * capacity) && up)
15     upperBound = line;
16     up = 0;
17 end
18 if ((sum(a_under) < 4 * capacity) && down)
19     lowerBound = lineDown;
20     down = 0;
21 end
22 end
```

Listing C.2: Most important lines for finding the bounds for (dis)charging

Shifting the battery through the network

```
1 fprintf('\nPerform a initial simulation without storage\n');
2 startTriana(pathTriana, 0);
3
4 fprintf('Start simulation with a large battery on %u locations\n',
5         nrLocations);
6 addBatToTriana(pathTriana, batterySize);
7
8 for loc=1:1:nrLocations
9     fprintf('Place a battery on location %u and perform a simulation\n
10            n' , loc-1);
11     startTriana(pathTriana, loc-1);
12 end
13 fprintf('Done\n');
```

Listing C.3: Shifting the battery through the network

On line two, an initial simulation is started without a battery. In the function *addBatToTriana*, the energy profile of this initial simulation is loaded and an upper and lower bounds are determined as before (subsection 4.1.1). These bounds are exported by Matlab to a CVS file that can be loaded by Triana. The for-loop on line 8 starts Triana *nrLocations* times.

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