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Battery Sizing and Placement in the Low Voltage Grid including Photovoltaics

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LINKÖPING UNIVERSITY

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Sammanfattning

Installationer av solceller för privatpersoner ökar varje år i Sverige. Detta kan ha negativa konsekvenser i lågspänningsnätet där detta leder till spänningsökningar. Eldistributionsbolagen i Sverige har en skyldighet att hålla nätets spänningar på en viss nivå i förhållande till den nominella spänningen, vilket innebär att de har en skyldighet att förstärka nätet när detta överskrids.

Den här uppsatsen undersöker skillnaden i att förstärka nätet med hjälp av kablar eller batterier och fokuserar framför allt på de ekonomiska skillnaderna mellan bägge samt när de olika lösningarna är möjliga, både i ett nutidsperspektiv och ett framtidsperspektiv. Ett riktigt case där solcellsproduktionen blev för hög i förhållande till den befintliga infrastrukturen ligger som grund för uppsatsen. I detta case kopplades problemzonen där det fanns för mycket produktion till ett närliggande nät, vilket minskade spännningstopparna signifikant. För att undersöka vilka lösningar som hade varit möjliga i detta case har ett tidigare utvecklat simuleringsverktyg byggts vidare på. Med verktyget är det är även möjligt att simulera byten eller kabelförstärkningar i nätet. Därefter byggdes ett optimeringsverktyg, som användes till att testa var någonstans batterier kan placeras och hur stora de behöver vara för att hålla spänningar inom tillåtna intervall.

Den mest signifikanta slutsatsen är att i nuläget är inte förstärkningar med hjälp av stationära batterier lika lönsamt som kabelförstärkningar. Detta beror framförallt på höga batteripriser och låga batterilivslängder i förhållande till kablar. I framtiden däremot, finns det situtationer där batterier skulle kunna vara ekonomiskt försvarbara. Det finns dessutom en portabilitetsaspekt hos batterier som gör att de fungerar väl som temporära lösningar där det kanske inte är möjligt att omgående förstärka nätet. Ett annat resultat är den optimala placeringen av ett batteri är så nära problemzonen som möjligt då detta leder till minsta möjliga batteristorlek. Det innebär att med växande intresse för hemmabatterier och elbilar finns det stor potential för sådana lösningar, både ur elnätsägarens samt kundens perspektiv.

Abstract

Installations of photovoltaic power production increases each year. This can have a negative consequence on the distribution grid where the voltage can increase. The electric distribution companies in Sweden have a responsibility in keeping the grid at certain voltages, and have to reinforce the grid if these voltages are outside these levels.

This Master's Thesis investigates the difference in strengthening the grid with help of cables or with help of batteries, especially the economic differences between the two and in which cases they might be viable, both today and in the future. A real case in a low distribution grid, where photovoltaic production was too large will be used as basis of the thesis. In this case, the problematic part of the grid with most production was moved to a network station close by which lead to a significant drop in voltages on the first grid. To evaluate the different solutions a simulation tool developed previously is further built upon, to be able to create simulations of the grid investigated. It is also possible to test replacing or strengthening cables with this tool. An optimisation tool is then created, that is used to test where batteries can be placed and how large they have to be to keep the voltages and currents within set ranges.

From the results, the most significant conclusion is that batteries are not yet viable as a replacement for grid reinforcements in the base case evaluated. Today this is mostly due to the steep prices of batteries, and long life-lengths of cables where they can be used for significantly longer than batteries as grid reinforcements. However, in the future, there are situations where batteries may be economically more viable. There is also a portability aspect in batteries, where batteries could be used as a temporary solution where it may not be possible to install cable reinforcements immediately. Lastly, the optimal placement of batteries was established to be as close to the problem zone, i.e. the photovoltaic power production as possible. This means that with growing popularity of stationary batteries at home and electric vehicles, these types of solutions could possibly be used in the future.

Acknowledgments

We would like to thank our examiner Christofer Sundström, Ph.D. at Linköping University for helping us throughout this Master's Thesis and especially in the field of power engineering, which before this we hade never truly done before.

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Notation

Electric Quantities

Notation	Description
I	Current [A]
P	Active power [W]
Q	Reactive power [VAr]
S	Power [VA]
Z	Impedance [Ω]
U	Voltage [V]
E	Energy or charge [kWh]
A	Area [mm^2]
R	Resistance [Ω/km]
X	Reactance [Ω/km]
L	Length [m]
SoC	State of charge [%]

Abbreviations

Abbreviations	Description
BSS	Battery Storage System
PV	Photovoltaic (solar power)
FBSM	Forward Backward Sweep Method
MPC	Model Predictive Controller
DST	Dynamic Stress Test

1 Introduction

In Sweden, the interest for renewable energy is growing every year. Tekniska verken, the electric distribution company in Östergötland, has seen an increase in installed solar panels (photovoltaics or PV) by consumers. These types of consumers are called prosumers, both consuming and producing electricity. With many prosumers starting to produce electricity, the voltage in the grid may become too high. This due to the grids originally being built for having a fixed set of producers.

When the production becomes larger than the usage of electricity the grid does not work as intended. The current can for example change direction and reach higher values than the cables are built for. Another issue is that this can lead to voltage transients on the grid due to e.g. clouds covering the sun. Higher currents leads to higher voltage differences in the grid, especially at the nodes producing solar power. If the voltage deviates to much from the nominal voltage (230V in Sweden) consumers electronics do not work and might get damaged. The Swedish government also imposes laws on grid owners where the grid owners must make sure that voltages are within ±10% of the nominal voltage. Tekniska verken have seen these issues in various low-voltage grids, and as of today the standard solution to these issues is to strengthen the distribution grid by either adding new cables, strengthening existing cables, adding new network stations or completely rerouting the grid. This is called reinforcing the grid.

Another way to reinforce a grid is handling excess power using battery storage systems (BSS). This is used to store excess power and utilise this when the power demand in the grid is higher. Depending on the situation this may be more cost-efficient than reinforcing using cables. Another potential usage of BSS is using them for frequency regulation, where there may be another potential economic incentive for the BSS.

However there are factors to batteries that have significant drawbacks in comparison to cables. For example according to Tekniska verken, the life length of cables is around 40 years whereas battery life is expected to be much shorter.

As stated previously there are limits set by the Swedish government, however, Tekniska verken has set their own limits (lower) on how high the cable loading ($I_{measured}/I_{max,allowed}$) and the voltage deviation in any part of the grid can be. These limits are a cable loading of 80% and a maximum voltage deviation of 7% from the nominal voltage; therefore these limits will be considered in this thesis.

This is the fourth piece of work done in collaboration with Linköpings University and Tekniska verken, where problems on the distribution grid caused mostly by solar panels are discussed.

1.1 Related Research

Two master's thesis have been done on the subject, [16] the first thesis focus was to understand the effects of adding solar panels to the grid, especially to observe the voltage variations. The thesis also contains a small analyse of how energy storage systems can minimise these variations. The second thesis [10] looked at the problems of implementing solar panels described in previous thesis, and discussed if this could be solved by using Battery Storage Systems (BSS) and the batteries in electric vehicles to minimise voltage variations. Another master's thesis from Uppsala University [12] also studied the impact on the low-voltage grid by integrating EVs and PVs, especially focusing on voltage drops, limits and energy losses.

A project group [7] later investigated how smart charging of electric vehicles can minimise voltage variations using different price models and optimisation. Where dynamic programming for individual household was used based on households models from [20] and [18] and the cost function of the dynamic programming was for the EV-owners to save as much money possible and see if this could affect the stability of the grid. These models were then used to see how many solar panels and electric vehicles a specific grid can handle, with and without smart charging, where the specific demand was keeping the grid within the boundaries $\pm 10\%$ of the nominal voltage.

A lot of research has been done on optimal battery placement and sizing in distribution grids. Especially focusing on the problems that can occur with multiple production sources, and solving these optimal flow problems. In [19], a full cost analysis on optimal placement of batteries in a IEEE 13 bus test feeder is done. This uses a hybrid solver of a genetic algorithm and an optimal power flow problem to find the optimal placement and sizing of batteries.

Battery aging is also an area where significant research has been done. This due to batteries becoming more popular, especially in vehicles. In [14], studies are done on what State of Charge (SoC) ranges are good to use for longer battery length, also combining this with factors such as temperature.

Research has been done on the impacts of batteries vs cables previously. In a master thesis at Chalmers, an economic comparison between cables and batteries was made [9]. This study was focused on the effects that Electric Vehicles had on the low-voltage distribution grid. Two different cases were studied using the software General Algebraic Modeling System (GAMS), and an optimal flow problem was studied. The results here varied, and in one case it was economically beneficial to make an investment in a BSS.

1.2 Purpose and goal

The authors of this report have carried out this thesis in cooperation with Tekniska verken.

The purpose with this thesis is to find out what type of solution is most efficient to eliminate high voltages caused by solar panels on the low-voltage grid. This by figuring out when it is more cost-efficient to implement BSS's in the grid compared to the traditional way of switching cables.

Unlike [9] and [19] the main focus is minimising the size of the batteries instead of minimising power losses and currents. Instead, current levels and voltage deviations will be set as constraints. This is because it is of greater interest of Tekniska verken for grid stability.

The goal of this thesis is to develop an optimisation tool, that finds where batteries should be placed in the grid to minimise how large they have to be to make sure that peak voltages and currents never become too large. The goal is also to compare the cost of this solution to traditional cable reinforcements that give similar results.

1.3 Problem

Based on the purpose and goal, the problem can be summarised as following.

- Analyse when it is more cost effective to use batteries than cables to limit maximum voltages and cable loading.

To do this, the following problems need to be solved.

- Create a simulation tool using consumption data and validate in comparison to actual voltages on a real grid.
- Evaluate how long a stationary battery can last when used to reinforce a low voltage grid, based on how many cycles the battery can last before losing capacity and before the installed power on the grid is too large.
- Create an optimisation algorithm for controlling stationary batteries.
- Evaluate the performance of one and multiple batteries.
- Find the minimum battery capacity needed to give the same results as cable-reinforcing the grid.
- Find out which grid-characteristics that lead to batteries being a more cost efficient solution.

- Investigate how cables and batteries can be placed most efficiently to keep the grid from reaching $\pm 7\% V$ of the nominal voltage and 80% of the cable loading.

1.4 Scope

The scope of this thesis is the economic evaluation of reinforcing the grid with batteries or cables. This is done mainly by studying one case, where the issues were solved with cables. This case is then analysed to draw general conclusions on when batteries or cables can be beneficial.

Hourly data for production and consumption is known and provided by Tekniska verken for most points. However, in specific cases some physical or statistical modeling is done to compensate for the lack of data.

Due to optimisations being very performance intensive and time-consuming, the simulations will be performed during specific time periods. These time periods are periods where Tekniska verken have experienced issues due to the large amounts of produced electricity by prosumers, which in turn coincide with dates where the solar irradiance is especially large.

In the cost analysis, mostly investment costs and lifetime costs are analysed. The cost analysis is done purely from a grid owner point of view.

1.5 Approach

In 2019, Tekniska verken have had problems in a low-voltage grid, grid A, where the solar production has been too large. This case was solved by attaching a large part of the production to another grid, grid B, where the production was lower. In this way strengthening grid A.

An approach to handle the problem formulation described in Section 1.3 is described below. This will be done using grid A as a basis.

Firstly the grid is to be modeled. This is done in the same manner as in [16], but for the new grid that is observed in this thesis. This is then combined with battery models that can be placed throughout the grid.

The nodes on the grid represent households, cable connections and transformers, and these are non-controllable. The batteries can then be placed throughout the grid, the sizes are adjustable and they are controllable.

1.5.1 Optimisation and Simulation

The batteries will be controlled with optimal control theory, where the goal function is to decrease the needed battery size and the main constraints are peak voltages and peak cable loadings.

The next step of the optimisation is finding the placement or combination of placements that minimise the size of the batteries. The goal is to find the optimal placement and amounts of batteries that is still able to keep the grid from reaching $\pm 7\% V$ of the nominal voltage and 80% of the cable loading.

When the grid is modeled with all free components and optimisations are added, the grid is then simulated to compute all voltages. The solver used is the FBSM-solver developed in [16].

1.5.2 Analysis

The goal of the thesis is to find out when batteries or cables are more optimal to use to eliminate the problems caused by PV-systems on the grid. The various solutions that are seen while simulating will be compared both cost-wise and efficiency-wise to the real case. Some new cases will be created from the original case to be able to solve all parts of the problem formulation. These cases can for example be increasing the length of the cables required to reinforce the grid and removing the possibility to connect to grid B.

1.6 Thesis outline

- Chapter 2: Information on grid reinforcements. Background and information gathered during the literature study.
- Chapter 3: The used method in the thesis, a description of the modeling, optimisation, simulation, validation and the analysis.
- Chapter 4: Results and analysis, a work through of the results of the modeling, simulation, validation, optimisation and an analysis throughout the chapter.
- Chapter 5: A discussion of the findings in the Results and analysis chapter and how they stand in comparison to the problem formulation.
- Chapter 6: Conclusions on the problem formulation and example of future work.

2

Background and Information

In this chapter the theoretical background needed to understand and analyse the results, as well as being able draw conclusions are described. First, models and equations used to simulate the grid are brought up. Then different ways of reinforcing a grid combined with their cost estimates are presented together with some background on the reinforcement done in the studied case. Lastly, a background on batteries and some factors that affect the cost of reinforcing a grid with a battery is given.

2.1 Grid modelling and simulation

A model for cables in a low voltage grid as well as a transformer model have previously been done in [16]. These models describe how currents through cables and transformers result in power losses and voltage drops. The model used for cables are described by the following equations.

$$I_c = \frac{S}{\sqrt{3}U_h} \tag{2.1}$$

$$S_{loss} = 3Z_c|I_c^2| = 3Z_cI_cI_c^* \tag{2.2}$$

Where I_c is the current through the cable, S the power, U_h the voltage line to line. S_{loss} is the power loss, I_c^* represents the complex conjugate of I_c, and Z_c is the cables impedance. These equations are described in [16] and [21] a simple way of modelling a transformer is to use the same equations as for cables.

Derived from the cable equations a voltage drop between the two ends of the cable is introduced.

$$\Delta U = U_e - U_s = -\sqrt{3}I_cZ_c \tag{2.3}$$

Where the current goes from Node s two Node e and I_c is always positive.

Also, currents can be added up according to Kirchhoff's current law, which means that the sum of the currents going into a node equals the sum of the currents going out from the same node.

$$\sum I_{in} = \sum I_{out} \tag{2.4}$$

An example grid will be used to explain how these models give rise to increased voltages in a grid with solar panels and why these voltages can be reduced using a battery. The example grid is illustrated in Figure 2.1, 2.2 and 2.3.

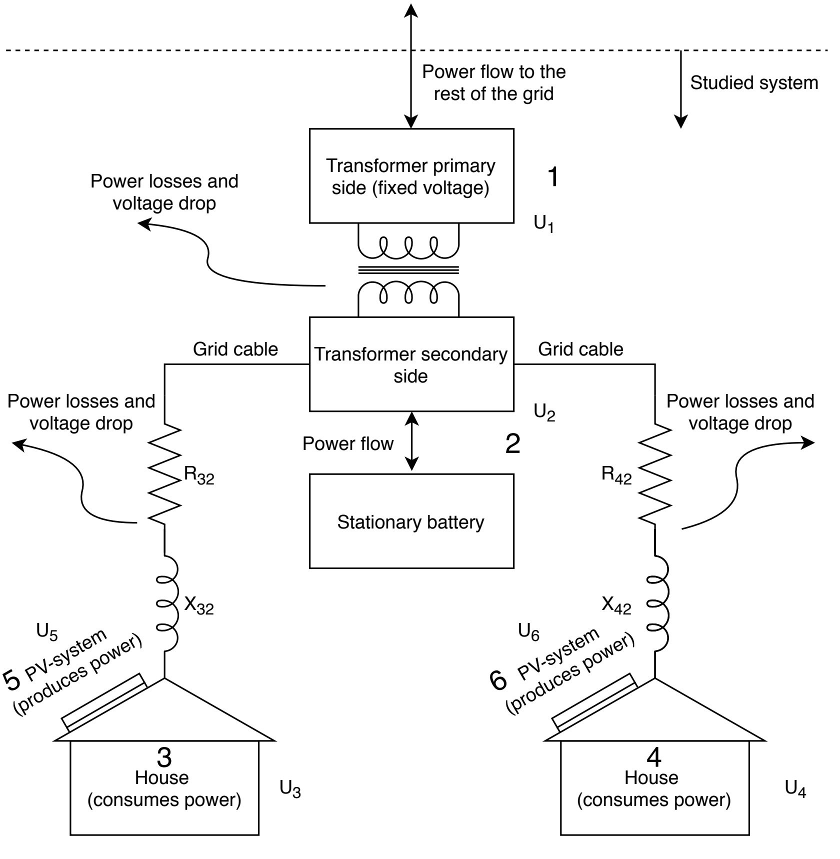


Figure 2.1: *An example of what a simple grid could look like. This grid contains the different components/models that will be studied in this thesis. The numbers shown in the figure are the node numbers and these are the same as in Figure 2.2. Note that Node 2 is both the secondary side of the transformer and contains in this case a stationary battery.*

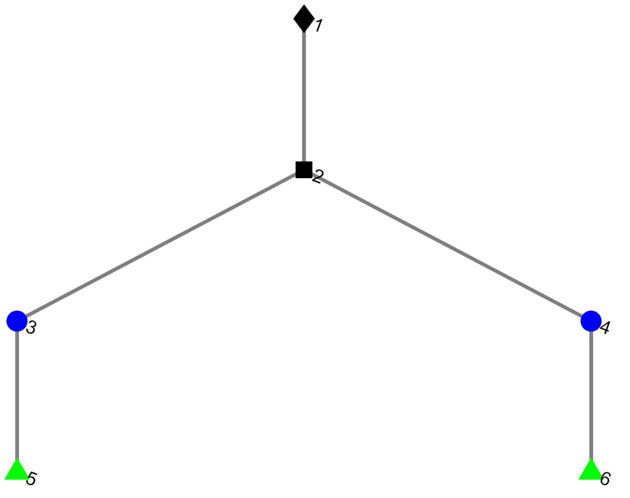


Figure 2.2: Another illustration of the grid shown in Figure 2.1. This way of illustrating grids will be used throughout the thesis.

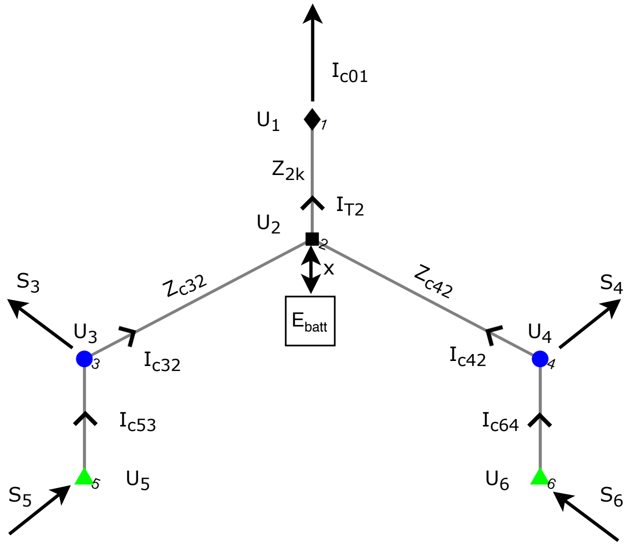


Figure 2.3: Another illustration of the grid shown in Figure 2.1. It is the same as 2.2 but also including the currents, voltages, powers and impedances, as well as the battery's charge and power exchange with the grid. These parameters shown are the primary parameters used in the modelling and the solver described in Chapter 3. The color scheme is also described in 4.1

By studying the current directions in Figure 2.3 and Equation 2.3 it can be seen that the voltages further down in the tree must be higher than the voltage in Node 1 and 2. This is always the case when prosumers are producing more energy than they consume and the opposite is true when the consumption is higher than the production. These equations also mean that the higher the current through the cables and the higher impedance's, the greater the voltage drops. To decrease the voltages further down in the tree one could either decrease the impedance, using cable reinforcements, or decrease the current going through the cables. Decreasing the current can be done in several ways but one way could be charging and discharging the battery in Node 2 so that $I_{T2} \rightarrow 0$ (see Equation 2.4) which leads to a decreased voltage drop between Node 1 and 2. This is the theory of how batteries are being used to reinforce the grid in this thesis.

The individual parameters used in the cable models as well as in the simulations can also be written as matrices in the following way.

$$U_{bus} = \begin{bmatrix} U_{1,1} & U_{1,2} & U_{1,3} & \dots & U_{1,n} \\ U_{2,1} & U_{2,2} & U_{2,3} & \dots & U_{2,n} \\ U_{3,1} & U_{3,2} & U_{3,3} & \dots & U_{3,n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ U_{m,1} & U_{m,2} & U_{m,3} & \dots & U_{m,n} \end{bmatrix} \tag{2.5}$$

Where each row describes the voltages for a certain node and each column represent a time-step in the simulation. Writing all the voltages on matrix form for the grid in Figure 2.1 with a simulation of 24 hours (one hour time-steps) would lead to $m = 24$ and $n = 6$. The matrices S_{bus} and I_{bus} are structured the same way as U_{bus}.

2.1.1 Modeling households

In this specific case, and in the case of many grid companies in general [24], when doing grid modeling usually type curves called BETTY-curves are used to estimate household consumption. These curves were developed by Svenska Elverksföreningen in 1991 [11] for around 50 types of consumers. These type curves, take into consideration seasonal changes, weekends or workdays, and also approximate a typical day consumption wise. However, today much more information is known, and it is possible to retrieve hourly data for all customers on a grid. This means that it should be possible to more accurately do future modeling and simulations on the grid. With demands from the Swedish government on the grid companies replacing all power meters and starting measuring power values every fifteen minutes [22], and with more and better data, better modeling can be made.

2.2 Grid reinforcements

In grid reinforcements, according to Tekniska verken, standard is to do this using cables. Reinforcing grids using cables can be done in several different ways, some of these are:

- Adding parallel cable/cables.
- Changing to a thicker cable/cables that has a lower impedance.
- Rerouting parts of the grid to another nearby grid that has a lower load.
- Rerouting parts of the grid to a new transformer.

In the studied case the third presented option was chosen since there was another nearby grid with low loads.

The costs of these reinforcements have been provided by Tekniska verken [24] and are presented in Table 2.1 and Figure 2.4.

Table 2.1: *Average prices for grid reinforcement components.*

Component	Price	Description
Cable, 240mm^2	598,2 kSEK/km	Ground cable in studied case
Cable, 95mm^2	227,9 kSEK/km	Ground cable in countryside
Cable, 240mm^2	577,7 kSEK/km	Ground cable in urban area
Cable, 240mm^2	937,5 kSEK/km	Ground cable in city centre
Network station 100kVA	44,0 kSEK	Excluding transformer
Network station 800kVA	340,7kSEK	Excluding transformer
Net. sta. urban area or city	101,7 kSEK	Additional cost
Net. sta. under ground	3091,9 kSEK	Additional cost
Transformer 100kVA	42,1 kSEK	From 12kV to 0,4 kV
Transformer 500kVA	111,3 kSEK	From 12kV to 0,4 kV
Transformer 800kVA	147,6 kSEK	From 12kV to 0,4 kV

These costs include cost such as shutting down roads or parts of the construction area, digging etc, which is a significant part of the cost, however these may vary depending on how difficult the reinforcement is. In some cases, it may not be possible to perform some reinforcements at certain time points in populated areas. In these cases batteries might instead be a better solution as a grid reinforcement.

2.2.1 Grid reinforcement cost in studied case

The grid that is studied in this thesis was reaching voltage levels above Tekniska verken's internal limit of +7%, therefore they decided to reinforce the grid. Eight buildings and six PV-systems connected to a cable station (Node 67 in Figure 3.1.) were connected to another, nearby transformer with a new cable. The total cost of this reinforcement was 225 000 SEK while the cable itself cost 42 000 SEK, 18% of the total cost. Other substantial costs were the cost of digging, approximately 65 000 SEK and restoration, approximately 45 000 SEK. According to Tekniska verken, [24] this was a rather simple reinforcement and the cost of the actual cable is usually a smaller fraction of the total cost.

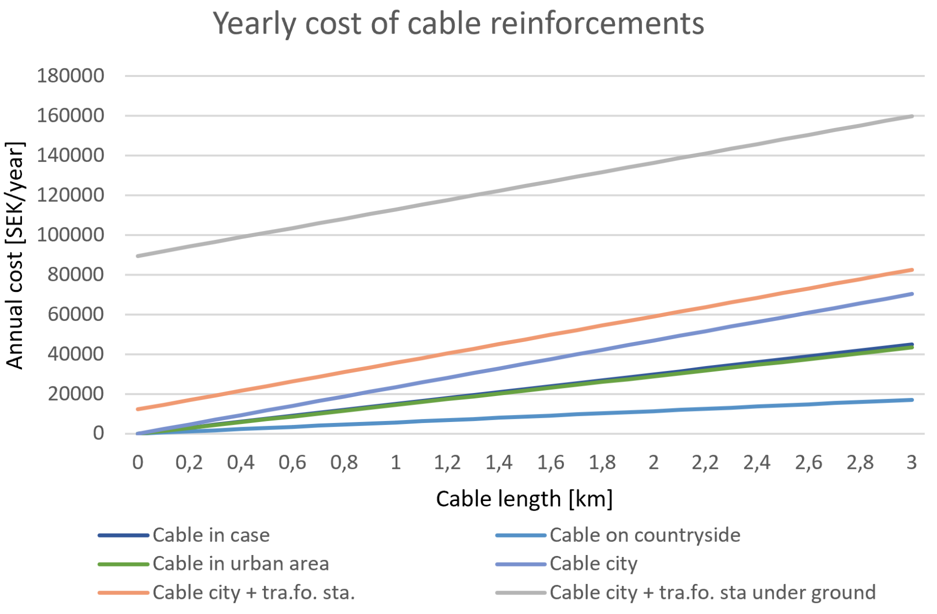


Figure 2.4: *Graph showing the annual cost of different cable reinforcements. Calculated based on the table above, and with a life length of 40 years. These include different combinations of cables and transformers etc. in different types of landscapes.*

2.3 Battery Storage Systems in the distribution grid

The overall power increase in decentralised power production in the distribution grid means that energy storage systems could work well in decreasing high voltages while storing excess power, therefore leading to possible economic advantages compared to traditional reinforcements using cables. This due to being able to utilise the excess power in the grid. Using a stationary battery for these purposes will be studied as an alternative way of reinforcing a grid.

2.3.1 Battery types

Batteries are used in all types of industries and a comparison between batteries for grid-level large-scale electrical storage is done in [23], and the results can be seen in Table 2.2.

Table 2.2: *Battery data, data from [23].*

Battery type	Energy density [Wh/kg]	Usage life [years]	Cycles
Lead-Acid	30-50	2-3	500-1000
Ni-Cd	50-75	>10	2000-2500
Ni-MH	40-110	>5	300-500
Na-S	150-240	10-15	2500
Li-ion	100-250	5-6	>1000
Zinc-bromine	75-85	5-10	>2000
Vanadium redox	10-50	5-15	12000-14000
Polysulfide bromide	30	15	>2000

Due to the large amount of research in Lithium-ion batteries, future potential with them, along with Lithium-Ion having some specific qualities that work very well for grid purposes. These include them having a low self discharge rate of around 1.5-2% per month. With these batteries possibly not being used for long amounts of time this is a significant advantage over for example Ni-Cd and Ni-MH [3]. For these reasons Lithium-ion batteries, and to lessen the scope of the thesis, focus will be on Lithium-ion batteries.

Lithium-ion

In battery solutions the past years there has been a large increase in the usage of lithium-ion batteries. These batteries compared to other commonly used batteries have high energy density, high power density and long life [17]. These batteries have become especially common in the automobile industry. From the list above it can be observed that Li-Ion have all of the wanted characteristics to be used in the grid. The issue is that the price is high however, with increased demand, research and economies of scales advantages the prices of lithium Ion batteries is dropping. With prices now at $156/kWh and projected to drop to $100/kWh by 2024 and $62/kWh by 2029 [5] and [4], these batteries are becoming more affordable. In Figure 2.5, this price drop is illustrated. With the drawbacks of the high prices of Li-Ion being improved and the fact that these batteries seem promising in the future, these batteries will be evaluated further.

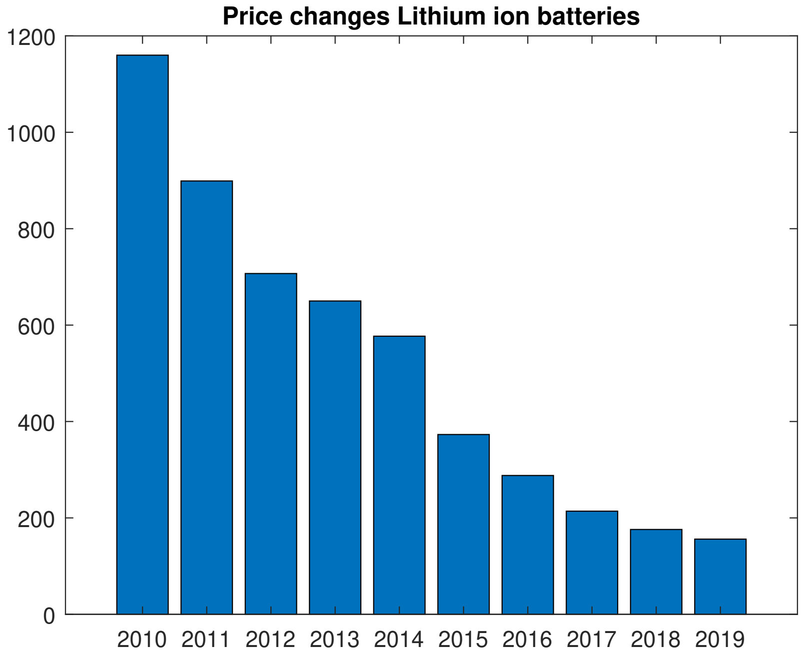


Figure 2.5: *Price changes in average prices for lithium-ion batteries during this decade [5]. The prices on the Y-axis are in USD/kWh.*

2.3.2 Battery life length

An important factor in the economic viability of batteries is the life length of batteries. As cable reinforcements have an economic life length of 40 years, and a technical life length of at least 50 years, cables can often stay in the grid for a longer time than 60 years as well.

The significant drawback with batteries, is degradation of batteries, and expected life length [6]. There is also a large drawback with Li-Ion batteries in there still not being any good alternatives for recycling and end of cycle processes. If battery storage systems are supposed to be used as a substitute for cables, these factors are important. However, these factors are not the focus area of this thesis, and will therefore not be discussed.

The life length of a battery is affected by several factors, some being elevated temperature, charging peaks and amount of cycles. To keep the number of possible cycles for a battery large, the batteries should never be fully charged or fully discharged. When letting SoC near the end points of the range $SoC \in [0\%, 100\%]$, it degrades a lot faster than ranges of $SoC \in [40\%, 60\%]$ [10], [1]. This means that there can be some benefit in having a quite large battery, by sizing the battery for example the worst day of the year can be a good strategy for keeping the life length of the battery high, due to the larger size needed than for most days, which keeps cycles relatively small. The difference in amount of cycles can vary from about 600 cycles at worst case to around 15000 cycles when only using about 10% depth of discharge, [8]. Another range showed is $SoC \in [25\%, 85\%]$, which would lead to the batteries reaching end of life at around 5000 cycles [8]. However, [8] is based on data gathered for the automotive industry, where the energy density is of greater importance. The end of life for a battery in this is considered to be when the battery reaches around 80% of its total capacity and data is rarely gathered beyond this point. A stationary battery might still be of great use after this point so its end of life could therefore be after more cycles than shown in this data.

2.3.3 Battery usages

Something to consider when comparing battery reinforcements to cable reinforcements is that batteries can provide other services. According to [13] energy storage systems can be used for 13 different use cases including Energy Arbitrage, Frequency Regulation and Voltage Support. These use cases are split into three categories customers, utilities or system operators/transmission organisations. These services can be used on three different levels of the grid; behind the meter, at the distribution level or at the transmission level. In this thesis, the two potential interesting solutions are behind the meter or at a distribution level.

Below the use cases from [13] most relevant to this thesis are presented.

- Energy arbitrage, purchase of electricity when marginal price of energy is low.
- Voltage support, regulating the continuous electricity flow across the power grid.
- Increased PV Self-consumption by minimising electricity export to maximise the financial benefit for the owner of the PV-system.

Where these categories are especially interesting in regards to prosumers and consumers having stationary batteries at their homes. In this case this could be beneficial for both the grid companies as the prosumers also help with voltage stability, and for the prosumers and consumers as they are able to take advantage of the increased self-consumption and energy arbitrage for financial gain.

2.3.4 Battery control

When using batteries, there are different ways of controlling them. The easiest way of controlling a battery would be setting a limit of in this case ±7%, and if these ranges are reached, the battery would start either charging or discharging until the voltage range is at acceptable levels again. A drawback with this is how the voltages would be measured, should the voltages be measured at all nodes in the grid, or should the voltage only be measured at the assumed worst point in the network, and then only be activated to decrease this point. More sophisticated regulators could also be used. For example, prognosis models based off of weather and known usual consumption for different parts of the year could be added, and then these prognosis models could be used with for example an Model Predictive Controller (MPC).

For this thesis the control of battery is done through optimisations. This is chosen due to the purpose of the thesis, that is to evaluate placement and sizing of batteries. By using an optimal control based solution, where the goal function of the algorithm is to minimise the size of the battery, an optimal size for batteries will be found. This optimal size can in turn give an optimal placement as well, due to the battery varying in size based on where it is placed. When placing a battery in an actual grid like this, the battery size needed may actually be larger, however the placement of the battery found with this method should be optimal, and the size should give an indication of which size is necessary.

2.3.5 Battery placement

To completely take advantage of all the positive utilities of using energy storage systems placement of batteries is important. According to [13], to gain most benefit the battery storage should be placed as close to the customer as possible. This is an aspect that will be thoroughly evaluated in this thesis, especially from a grid stability stand point. This means, that there could be a point for grid stability to give an incentive for stationary batteries customers.

2.3.6 Batteries in the future

Batteries are a constant evolving technology and many of the drawbacks just 10 years ago are not as significant today. With research in the subject the drawbacks will most likely lessen and the advantages of having batteries in the grid may be more apparent in the future.

3

Method

This chapter describes all the used methods to produce the results. As mentioned in Chapter 1, information and data from a specific low-voltage grid in Linköping will be used as a reference case to draw conclusions about other scenarios and grids. This grid is used since it was recently reinforced by a cable and a lot of data is available, both before and after this was done. This grid combined with all of its customers (both households and solar production) is modeled and used in the simulation tool described in this chapter.

To describe the methods used in a structured manner these are divided into five parts; modelling, optimization, simulation, validation and analysis. The purpose of the Modelling, Optimisation and Simulation stages are to create a tool that can output parameters such as node voltages, power losses and optimal battery placement and sizing etc. Later, in the validation stage, the voltages from this tool are compared to actual measured voltages to see if the tool is reliable. In the fifth stage (Section 3.5 Analysis) it is described how the output from this tool is analysed to answer this thesis's problem.

As stated previously, quite a bit of work has been done on the subject previously (see [16] and [10]). Therefore some work is used and built upon. These parts are the modeling of cables and transformers, the FBSM-algorithm and a way to implement the optimisation algorithm. However, all these parts are briefly explained to assist the reader.

3.1 Modelling

The modeled components used in the grid are cables and transformers, modeled as in [16] and batteries modeled as in [10]. However, as the goal of the batteries differs in this thesis, the control algorithm for the batteries will be quite different in comparison to [10] where they minimised voltage and power variations, more on this in Section 3.2 Optimisation. In addition to these models, power consumers and producers are modeled using power-data, and for the cases where this is missing, the consumption and production is modeled. The modeled grid is visualised in Figure 3.1.

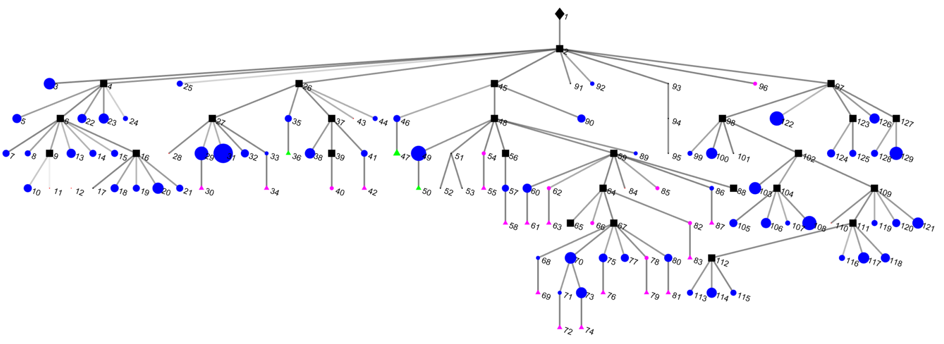


Figure 3.1: *Figure showing the grid after the modelling is complete. Node 1, in the top of the picture is the primary side of the transformer and Node 2 is the secondary. All the lines are different cables connecting the nodes to each other (not scaled according to actual length). Circular nodes are nodes where there is power consumption (households etc.) and they are scaled according to their amount of consumption. Square-shaped nodes are connection nodes and triangular-shaped nodes are nodes with solar production. The blue circular nodes have known hour based consumption and the green triangular nodes have known hour based solar production. Nodes that are purple have modeled consumption/production.*

3.1.1 Grid and cables

The first step of the modelling is modelling the grid. The grids are modeled in the same way as for [16] and [10]. It is found reasonable to neglect the shunt admittance in this case as well since the longest cable in the grid is only 198 m. The grids include one or two transformers and multiple cables connecting the buses in the grid in a radial (tree-structured) way. How each bus is connected is provided by data from Tekniska verken, [24]. For each cable the following data is given, see table 3.1.

Table 3.1: Cable parameters

Parameter	Abbrev.	Unit	Description
Name	-	-	Name of the cable
Area	A	mm^2	Cross section of the area
Type	-	-	Underground or overhead
Resistance	R	Ω/km	Resistance per km
Reactance	X	Ω/km	Reactance per km
Length	L	m	Length of the installed cable
Start node	s	-	The node closest to the transformer
End node	e	-	The node furthest away the transformer
Max current	I_{max}	A	Maximum current allowed

Parallel cables

All nodes in the grid were connected with single cables except between node 2 and 45 and node 45 and 46. In these two cases two identical cables were connected in parallel (see Figure 3.2).

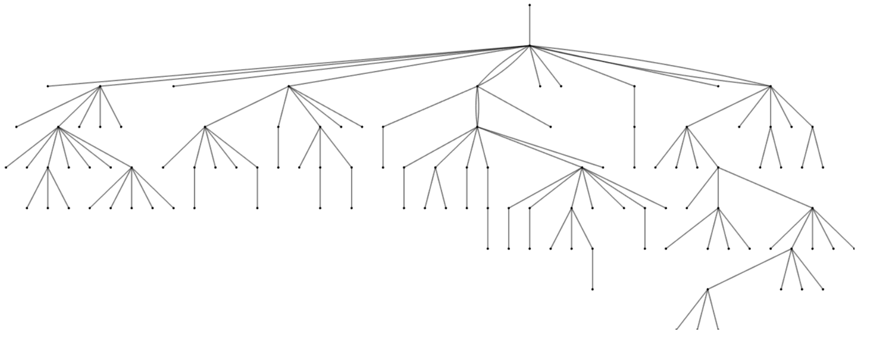


Figure 3.2: Figure showing the grid before the four parallel cables (in the center of the figure) were modeled as two thicker cables.

The solver (described in Section 3.3) in not built to work with parallel cables so these cables were instead modeled as one thicker cable using the following equations.

$$R_2 = \frac{R_1 R_1}{R_1 + R_1} \tag{3.1}$$

$$X_2 = \frac{X_1 X_1}{X_1 + X_1} \tag{3.2}$$

$$I_{max2} = I_{max1} + I_{max1} \tag{3.3}$$

Where index 1 means one of the two parallel cables and index 2 means that it is the modeled, thicker cable. Variables are described in Table 3.1.

3.1.2 Transformers

The grid is connected to one transformer-station. In this station there are two identical transformers. Data on these transformers was received from Tekniska verken and is shown in Table 3.2. The transformers are modeled in the same way as for [16] and [10] but with the modification done in Section 3.1.2 Parallel transformers. The parameters in Table 3.2 are the ones given by Tekniska verken.

Table 3.2: *Transformer parameters.*

Parameter	Abbrev.	Unit	Description	Value
Name	-	-	Name of transformer	Tra.fo. 1/2
Impedance	Z_{base1}	Ω	Primary impedance	100
Impedance	Z_{base2}	Ω	Secondary impedance	0.16
Voltage	U_{prim}	V	Volt. on primary side	10000
Voltage	U_{sec}	V	Volt. on secondary side	410
Power	S_{tot}	kVA	Max power usage	500

Parallel transformers

As stated before the transformer station in this specific case consists of two identical, parallel transformers. The FBSM-solver (described in Section 3.3) can not handle two transformers (i.e. slack busses). These two identical transformers (index 1 in equations) are therefore modeled as one, larger transformer (index 2 in equations) using the following equations.

$$S_{tot2} = S_{tot1} + S_{tot1} \tag{3.4}$$

$$R_2 = \frac{R_1 R_1}{R_1 + R_1} \tag{3.5}$$

$$Z_2 = \frac{Z_1 Z_1}{Z_1 + Z_1} \tag{3.6}$$

$$U_{prim2} = U_{prim1} \tag{3.7}$$

$$U_{sec2} = U_{sec1} \tag{3.8}$$

Where R and Z are calculated from R_s and Z_s the same way as in [16] and [10]. Other parameters are found in Table 3.2.

3.1.3 Adding power data and modelling missing data

Most customers in the grid have power data containing the average power used per hour, which is the chosen time-step of the simulation. This data is added to the nodes where each customer is located. In some nodes there are more than one customer, in these cases the power consumption by each customer in the node is summed.

Not all customers power usage is known for every hour (see Table 3.3), however, there is data on how much power usage they have per year. To match the time-step of one hour the yearly consumption has to be modelled into hourly consumption. This is done differently depending on the type of customer and other factors and is described in the following sections: Households, Solar production and Street lights.

Table 3.3: Number of different types of power consumption and production and number of customers with missing data on an hourly basis.

Type of customers in node	Number of nodes	Lacks hour based data
Households	97	4
Solar	18	15
Streetlights	3	3

Households

The households that are missing hour based-data are modeled using its own yearly power consumption as well as the average power consumption per hour and the yearly consumption of a reference household. By using the following equation, the modeled data gets its characteristics from the reference house and is scaled using the yearly consumption of both the reference house and the house that is to be modeled.

$$S_{ModelledHouse}(t) = S_{ReferenceHouse}(t) \cdot \frac{E_{ModelledHouse}(t)}{E_{ReferenceHouse}(t)} \tag{3.9}$$

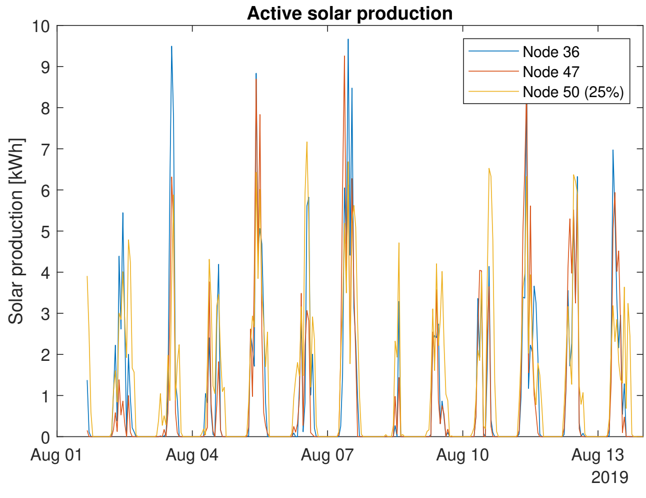
Where S is the average power consumption per hour and E is the yearly power consumption. The reference household used for each model is chosen by finding a house with similar size as the house where the household to be modeled is located.

Solar production

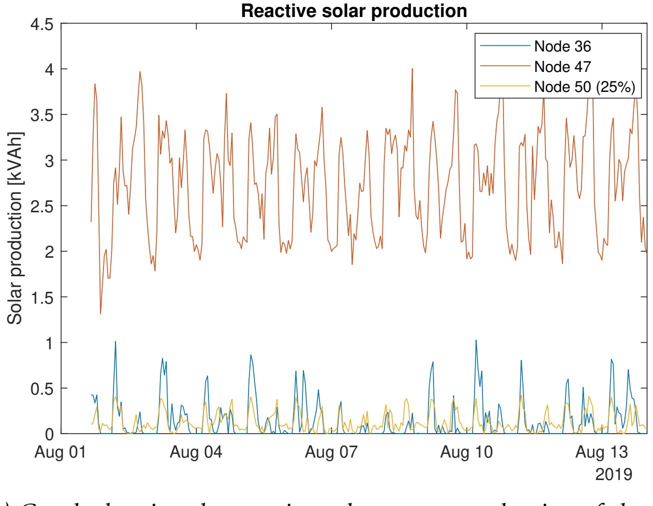
The solar production systems (PV-systems) that have missing hour based data is modeled with the same strategy as the households (see Section Households) and therefore the same equation can be used.

$$S_{ModelledSolar}(t) = S_{ReferenceSolar}(t) \cdot \frac{E_{ModelledSolar}(t)}{E_{ReferenceSolar}(t)} \tag{3.10}$$

The reference PV-system for modeling a PV-system that is missing hour based data is chosen by looking at the angle of the panels and find the most similar angle of the available reference systems. There are only three PV-systems that have hour based data, these three are further analysed to determine in which case these should be used as a reference which be seen in Figure 3.3.



(a) Graph showing the active solar power production of the three PV-systems which has hour based data.



(b) Graph showing the reactive solar power production of the three PV-systems which has hour based data.

Figure 3.3: *Graphs showing the solar production of the three available reference PV-systems. The power production of Node 50 is divided by 4 to more easily read the graph. Note the high reactive solar power production of Node 47.*

As can be seen in Figure 3.3b the reactive power production of the PV-system in Node 47 is quite different from the other nodes production (much higher and not reaching zero during the night). However, the active power production in

Node 47 (shown in 3.3a) does not look that different from the others. Since no reasonable explanation of why the reactive power production in Node 47 was so high this node was not included as an available reference PV-system when modelling other PV-systems.

The two remaining PV-systems were the ones in Node 36 and 50. The panels in Node 36 were facing south and were therefore used as the reference PV-system when modelling a system facing south. The panels in Node 50 were facing south and west and were used as a reference when modeling the rest of the PV-systems (these systems were facing south-west and west).

Street lights

The street lights are modeled in a very simple way because its effect on the grid is considered to be close to neglectable with 3 nodes and their power consumption low compared to other customers in the grid. These models are built so the lights are turned on from 18:00 to 06:00 every day, all year. The power consumption is constant for every hour when the lights are turned on and is based on yearly consumption data from Tekniska verken. To calculate the power consumption for each hour, the following equation is used.

$$S_{StreetLights} = \frac{E_{StreetLights}}{n} \tag{3.11}$$

Where n is the number of hours the street lights are turned on in one year.

3.1.4 Batteries

The main measurement of the battery is its current charge (E_{batt}). The used model is the following.

$$E_{batt}(t+1) = E_{batt}(t) + \eta_{batt} \cdot P_{batt}(t) \cdot \Delta t \tag{3.12}$$

Where η_{batt} is the battery's charging and discharging efficiency, P_{batt} is the power going into the battery and Δt is the time-step, in this case one hour. The efficiency, η_{batt} is set to 100% which is a reasonable estimation with li-ion batteries generally having almost 100% according to [23]. The converter is also assumed to be 100% for the sake of simplicity.

3.2 Optimisation

The idea of the optimisation is finding the minimal battery capacity, for each location in the grid, that can still keep the grid voltages and cable loadings inside the set boundaries/constraints, ±7% of the voltage and ≤ 80% of the cable loading. This is done by minimising an optimal flow problem using an optimisation algorithm and by finding and testing the combinations of locations of the batteries. This can be described as a hybrid algorithm, illustrated in Figure 3.4, where the primary outputs are the optimal location/locations and minimum sizes of the batteries.

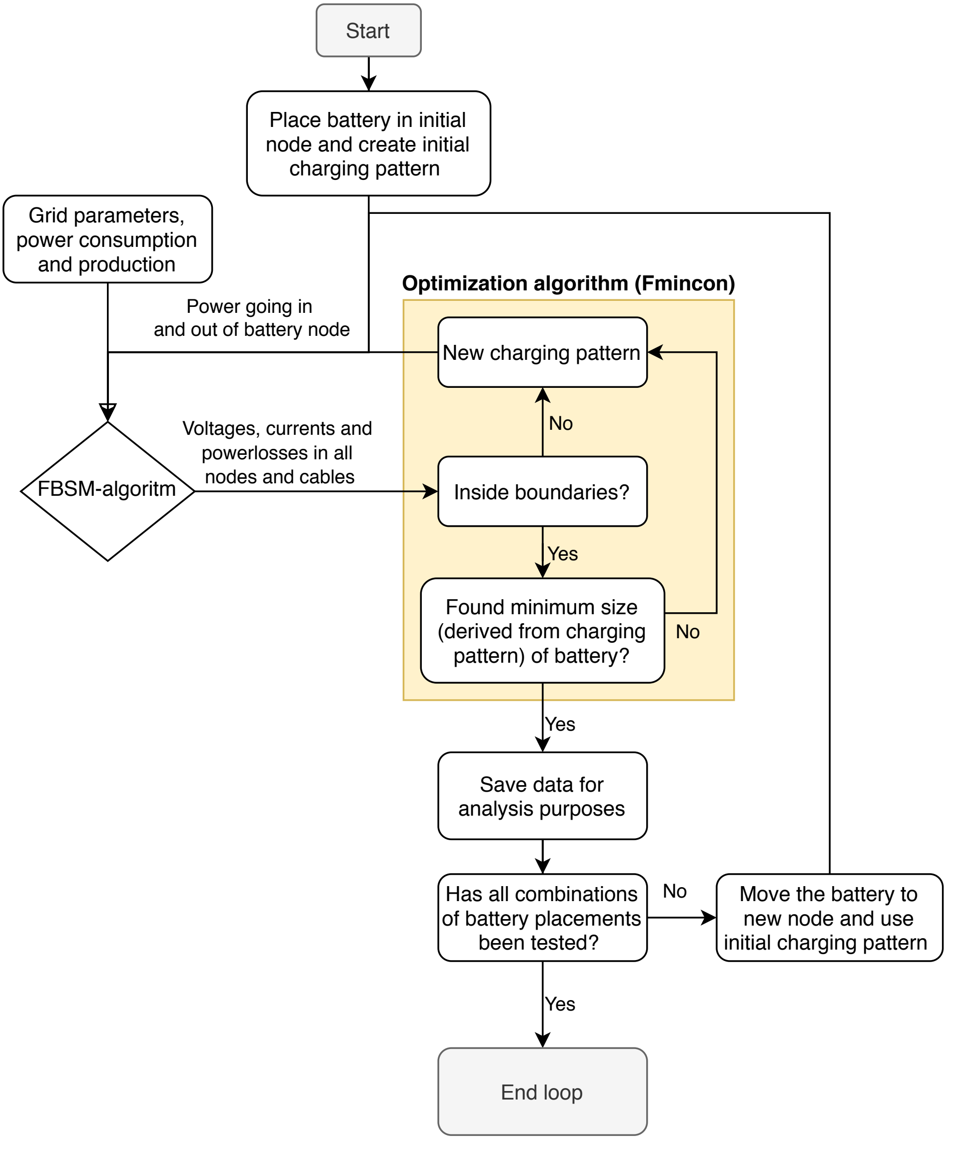


Figure 3.4: *Figure showing how the different algorithms are used together to find the optimal placement and sizing of one or more batteries in a grid. The Optimisation algorithm is described in Section 3.2.1 Battery size optimisation algorithm and the FBSM-algorithm is described in Section 3.3 Simulation*

3.2.1 Battery size optimisation algorithm

The goal with the optimal flow problem is finding the smallest battery capacity possible to keep the grid inside the constraints that can be found further down. In words, this is done by thoughtfully charging the batteries in a way that minimises the difference between the highest peak and the lowest valley of contained charge. This is an optimal flow problem and can be formulated as following.

$$\mathbf{min}\,|\,\mathbf{max}(E_{batt}(t)) - \mathbf{min}(E_{batt}(t))| \tag{3.13}$$

Where $E_{batt,t}$ is the battery's charge at time step t , which goes from hour 1 to hour n. $E_{batt,t+1}$ can be described as following.

$$E_{batt}(t+1) = E_{batt}(t) + (x(t) \cdot \Delta t) \tag{3.14}$$

Where x_t is the power going into the battery at time step t and Δt is the time-step, in this case 1 hour.

The constraints of the optimisation can be formulated as following.

$$0.93U_n \leq U_{bus}(t) \leq 1.07U_n \tag{3.15}$$

$$I_{bus}(t) \leq 0.8I_{cab,max} \tag{3.16}$$

$$E_{batt}(0) = E_{batt}(t_{end}) \tag{3.17}$$

Where U_n is the nominal voltage, 230 V

For deeper understanding of how U_{bus} and I_{bus} are structured, see Section 2.1. To solve the optimal power flow problem the Matlab function `fmincon` [15] is used. This strategy is also used in [19] but with another cost function and constraints for another type of grid and situation. Due to the fast nature of the optimisation, batteries in every node is tested, and how good the placement is based on how large the battery from the cost function is. How the placements are chosen for multiple batteries is based on the results of simulating one battery, where interesting placements based on the performance of one battery are chosen, this is described further in Chapter 4.

3.3 Simulation

The simulation is done using the FBSM-solver created previously in [16] and [10]. This solver is an iterative solver which outputs all voltages, currents and power flow in every node, given the power usage in every node, grid structure and its impedances and the slack bus voltage (on the transformers primary side) as inputs. The algorithm's inputs and outputs are described as an equation below.

$$[U_{bus}(t), I_{bus}(t), P_{bus}(t)] = FBSM(Z_{bus}, P_{use}(t), U_{slackBus}(t)) \tag{3.18}$$

Where $U_{slackBus}$ is the slack bus voltage on the primary side. This voltage is a fixed voltage of 10 kV, see Table 3.2. This voltage needs to be known since it is used as a reference voltage to calculate the other voltages in the grid.

This is done for every time-step in the simulation. The outputs from the FBSM-solver are the central results to be analysed.

If one or more batteries are present in the simulation, the FBSM-solver is used in a loop with the Optimisation algorithm (see Figure 3.4). Then the batteries charging and discharging power gets included in the input P_{use}, which goes into the FBSM-solver.

3.4 Validation

Since the goal of this thesis is to draw conclusions about how a battery could be used in a real grid, it is crucial to know how well the simulated grid agrees with the real one. To determine this the output values from the simulation algorithm are compared to measured values given by Tekniska verken. These measured values are the average voltages every hour in the transformer and Node 33, the same year as the simulation is based on. The measured values and the simulation values are plotted together and compared. This is covered in Section 4.2 Validation.

3.5 Analysis

The results from the simulations are gathered and analysed. These simulations include cases where there is no reinforcement, a cable reinforcement and different battery reinforcements. An economic analysis of battery- and cable-reinforced grids is later done. This is done using results from the simulations and the information presented in Chapter 2. This means including aspects as battery size, cable length, time to implement changes, environmental issues, battery lifetime and other aspects in the complete comparison of batteries vs cables. This is covered in Chapter 4 and Chapter 5.

4

Results and analysis

In this chapter, results are presented and analysed. The structure of the chapter is firstly presenting the grid, then the data validation, then the results of the simulation and optimisation, and lastly the economic results.

4.1 Grid with no reinforcement

The grid as of before the cable-reinforcement was done is presented in Figure 4.1. The result from a simulation of a full year is presented in Figure 4.2. To get a better understanding of the nodes that are actually above the limits of ±7% of the nominal voltage, a color scheme where only these nodes are colored red is presented in Figure 4.3.

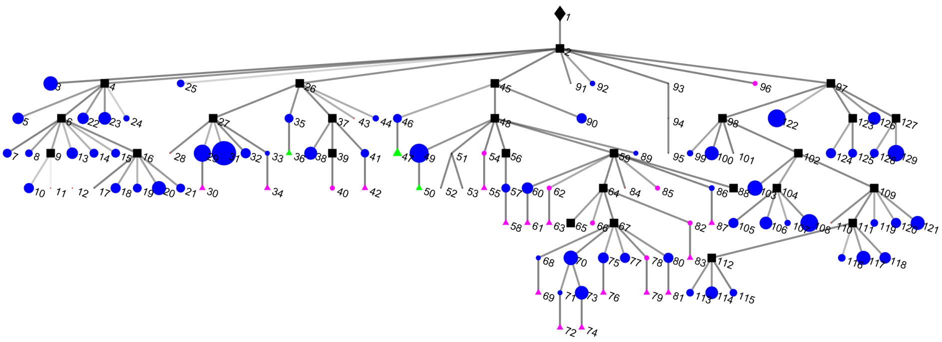


Figure 4.1: *A modeled version of the grid. The color blue represents known consumption, green known production, purple modeled data and black represents connection points. Circles represent consumption loads and triangles represent production, while the diamond is the transformer, and the sizes represent the sizes of consumption and production. The lines in between the nodes are cables which are darker if the impedance is lower and at higher impedance they become lighter until they are completely white.*

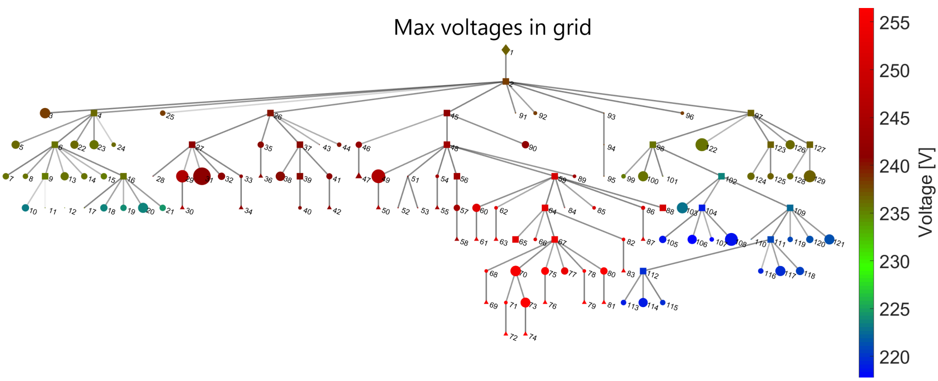


Figure 4.2: *The grid where nodes colored according to the color bar on the right. The values are the voltages in each node that deviates the most from the nominal voltage (230 V) during one year.*

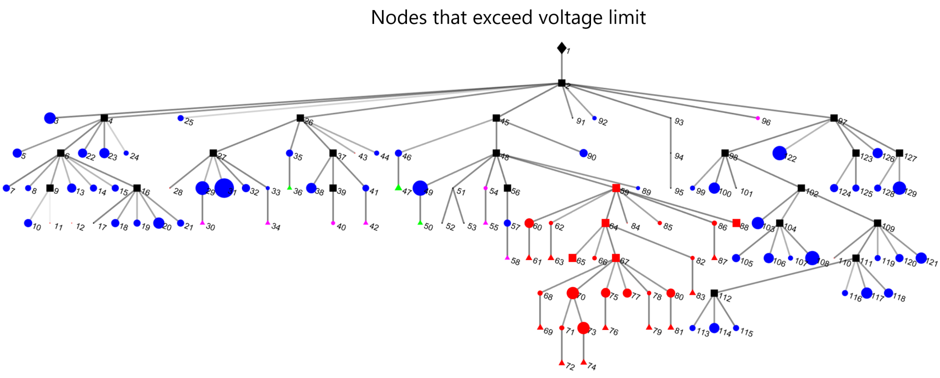


Figure 4.3: *Shows voltages of +7% of 230 V during a year as red. These nodes are all nodes from Node 59 to Node 88. Note that out of these nodes there are 10 PV-systems, these are illustrated as red triangles.*

The node from the simulations experienced the highest voltage during the entire year was Node 72. This voltage was 256,8 V.

4.2 Validation

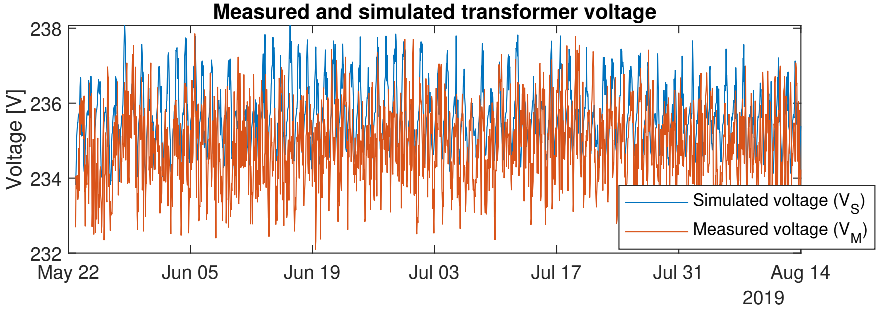
Voltage data (measured in the actual grid) is given by Tekniska verken for the transformer and Node 33, in the grid. These are the two nodes in the grid where voltages are measured and known. The idea of the validation is to make a comparison between these measured voltages and the ones received from the simulation. The voltages in both nodes have hourly voltage data for one year, which gives a maximum of 17520 data points to compare to the same amount of data points given by the simulation. However, the transformer settings were changed once during this year, May 22, and the cable reinforcement took place on August 14, so only the data gathered in-between these dates is used during this validation (3992 data points).

4.2.1 Voltage differences

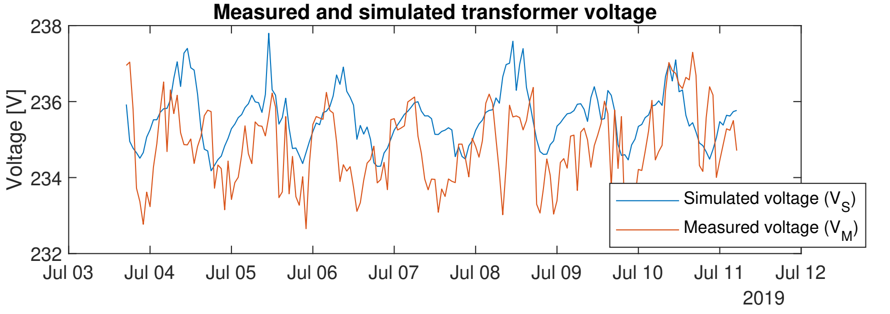
The voltages are the main output of the simulation and is therefore the most important value to validate.

Transformer

When comparing the variation of the voltage in the transformer in the actual data and the simulated data, the voltage is rarely exactly the same, see Figure 4.4. However the simulated and the measured voltages seem to follow a similar trend trough out the days and the deviation/error is rarely greater than two volts, see Figure 4.5. Other interesting measures are in this case that the simulated max voltage is only 0.22 volts higher than the measured and that one can expect an error of 1.79 volts in any time-step (RMSE-value), see Table 4.1.

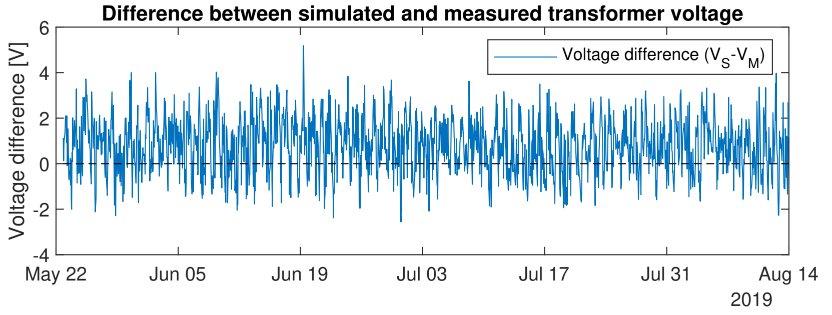


***(a)** The simulated voltages and the voltages measured by Tekniska verken. The interval is the chosen interval for validation.*

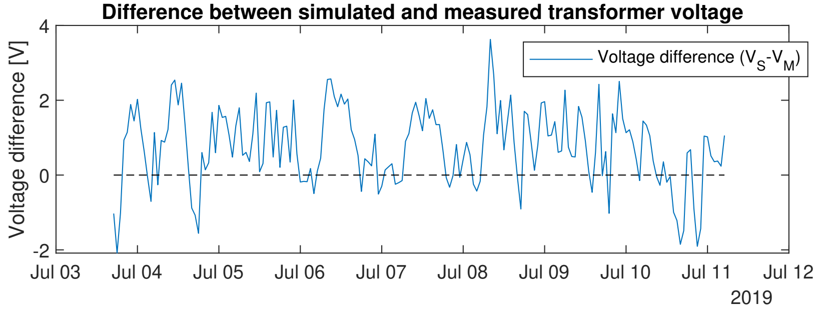


***(b)** A zoomed in version of the graph above.*

***Figure 4.4:** Plot of simulated voltage and measured voltage for the transformer.*



(a) *The difference between the simulated voltages and the voltages measured by Tekniska verken. The interval is the chosen interval for validation.*

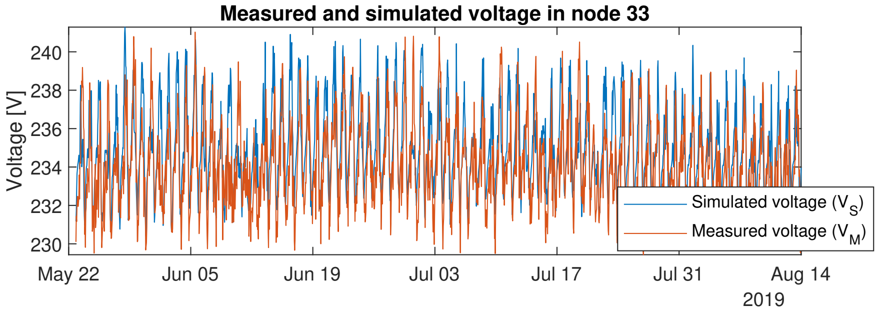


(b) *A zoomed in version of the graph above.*

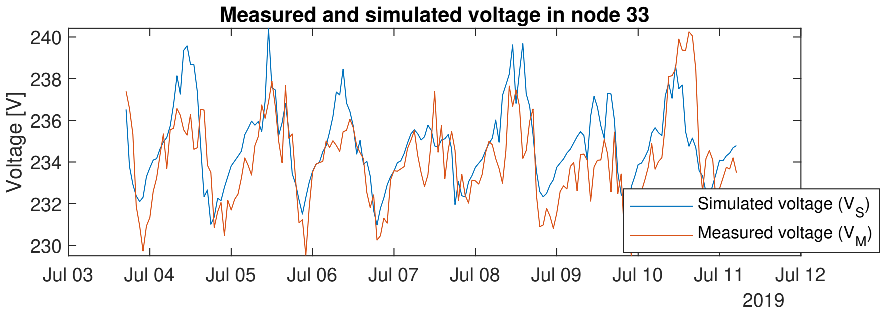
Figure 4.5: *Plot of difference between simulated voltage and measured voltage for the transformer.* V_S *and* V_M *can be seen in figure 4.4*

Node 33

Node 33 is quite far from the transformer and has a modeled PV-system connected to it. This is a PV-system that exists in real life, but no production data is measured from this node. This PV-system affects the simulated voltage in this node greatly. However, even though the real data is not known, the simulated voltage in this node seem to follow the measured value quite well, see Figure 4.6. The difference between the simulated and measured voltage is mostly within 3 volts but there are a few high peaks, see Figure 4.7. Some other interesting measures are in this case that the simulated max voltage is only 0.26 volts higher than the measured and that one can expect an error of 1.3 volts in any time-step (RMSE-value), see Table 4.1. Note that this is lower than for the transformer.

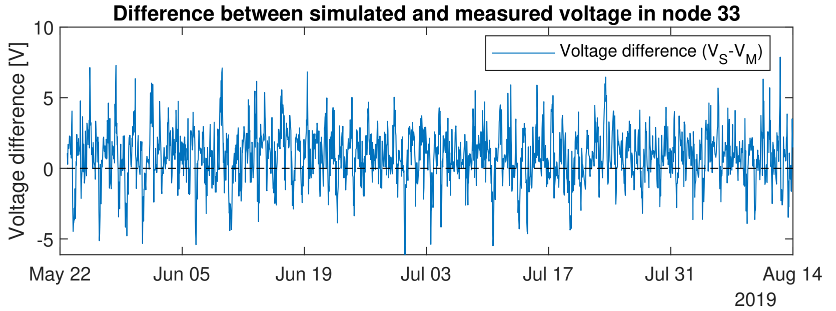


(a) *The simulated voltages and the voltages measured by Tekniska verken. The interval is the chosen interval for validation.*

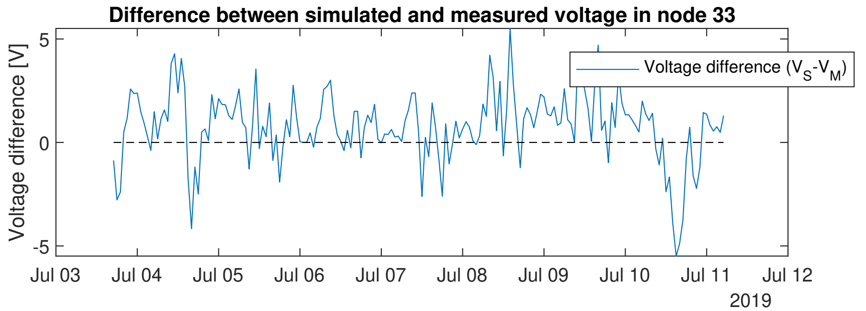


(b) *A zoomed in version of the graph above.*

Figure 4.6: *Plot of simulated voltage and measured voltage for Node 33.*



***(a)** The difference between the simulated voltages and the voltages measured by Tekniska verken. The interval is the chosen interval for validation.*



***(b)** A zoomed in version of the graph above.*

***Figure 4.7:** Plot of the difference between simulated voltage and measured voltage for Node 33. V_S and V_M can be seen in figure 4.6*

4.2.2 Statistical validation results

Some statistical measures are calculated in order to analyze how well the modeled grid compares to the actual grid. These measures can be seen in Figure 4.1.

Table 4.1: Statistical comparison of modeled and measured values for Node 33 and for the transformer node (Node 2).

		Transformer	
	Measured	**Simulated**	**Difference**
Min Voltage [V]	231.01	233.04	2.03
Max Voltage [V]	237.85	238.07	0.22
Max difference [V]			5.19
Variance [%]	1.16	0.83	
		Node 33	
	Measured	**Simulated**	**Difference**
Min Voltage [V]	225.74	226.74	1.02
Max Voltage [V]	241.03	241.29	0.26
Max difference [V]			7.88
Variance [%]	5.25	6.59	
		Mean Squared Error	
		Transformer	**Node 33**
MSE [ ]		3.19	1.69
RMSE []		1.79	1.3

Analysis of validation values

As stated before, the purpose of this validation is to see how well the used models compare with the actual grid, as this will tell to what extent conclusions can be drawn from the simulations. Both the simulated transformer voltages and the simulated voltages in Node 33 follow the trend of the measured values but are a bit off, where the transformer voltages are slightly worse. The reason for this could be that the voltage on the primary side of the transformer varies (modeled as fixed) and this has a greater impact on the voltages on the primary side of the transformer than the voltages in Node 33.

The voltages that are studied the most in this thesis are voltages nearby solar panels, the voltage errors in the transformer is of a little less importance than the voltages in Node 33. This due to the fact that the most accurate representation of the voltages should be in the nodes where problems are expected to exist. Optimally, if it would have been possible (no available data), a validation of a node in the branch that experience the highest voltages would have been of greater interest, following the same reasoning.

What can be seen though is that the max voltage in Node 33 is just 0.26 volts higher than the measured and the RMSE value is lower for Node 33 than for the transformer. This could indicate that both the modeling of the PV-systems and the voltage drop caused by the currents through the cables are good ways of modeling the real components. Since these components are the most crucial in this study, the results from the simulations are deemed a good enough representation to the extent where conclusions can be drawn on the real system.

4.3 Cable reinforcement results

To be able to compare the cable reinforcement that Tekniska verken did with a reinforcement using a battery the cable reinforced grid was simulated. As mentioned earlier, this reinforcement was to disconnect Node 67 (and the nodes below this node) and connect this to another nearby grid. The cost of this reinforcement was 225 000 SEK. This was then modeled and simulated. The results from this simulation showed that if the reinforced grid would have operated throughout 2019 it would have reached its highest voltage on April 23 with a voltage of 246.6 V (in Node 63). This voltage is +7.23% of 230 V, slightly higher than the given constraint of +7%. Since this difference is so small it is found reasonable to economically compare this cable reinforcement with the results from simulations of a battery-reinforced grid, where the constraint is set to +7% of 230 V.

Another scenario where there is no nearby grid is simulated as well. In this case the reinforcement is instead a parallel cable going all the way from the transformer and Node 67, a distance of 395 meters. The cable used has an area of $240mm^2$ and its price is calculated to 228 192 SEK, using data from Table 3.1. This reinforcement is however not enough to get all nodes below the limit of +7% of 230 V, instead the maximum voltage with this reinforcement would reach 249.2 V, +8.4% of 230 V. In this case, a new transformer is the only way of reinforcing this type of grid with conventional methods, and the cost in this case is estimated at least at 500 000 SEK, also using data from Table 3.1. However, no simulation of this is done.

4.4 Battery reinforcement results

The battery reinforcement results are gathered using the simulation tool and include a large amount of tests. In these tests, different number of batteries and locations are set and the purpose is to find which constellation that leads to the minimal total battery size for different cases. These results are then further analysed to find how much and often the batteries are used throughout the year.

4.4.1 Reinforcing with one battery

The first test is seeing where a single battery can be placed and how large its capacity has to be in order to fulfill the set constraints of ±7% of 230 V and less than 80% in cable loading. One battery is placed in every node of the grid and the optimisation algorithm (see Section 3.2) finds the minimum size of the battery that still leads to fulfilled constraints. In some cases the constraints can not be fulfilled and this means that only placing one battery in this node can solve the problems that the grid is experiencing, this is called a *not possible placement*. To reduce the computing power necessary this optimisation is only done for one day. The chosen day is June 16, 2019 since this day is the day that requires the largest battery (can be seen in Figure 4.18). Here a battery placed in node 70 is simulated for an entire year, and the day with the highest energy needed was found to be June 16.

Possible placements

The results of this simulation is that quite few different battery placements of a single battery are possible. These and their calculated minimum size are presented in Figure 4.8 and Table 4.2

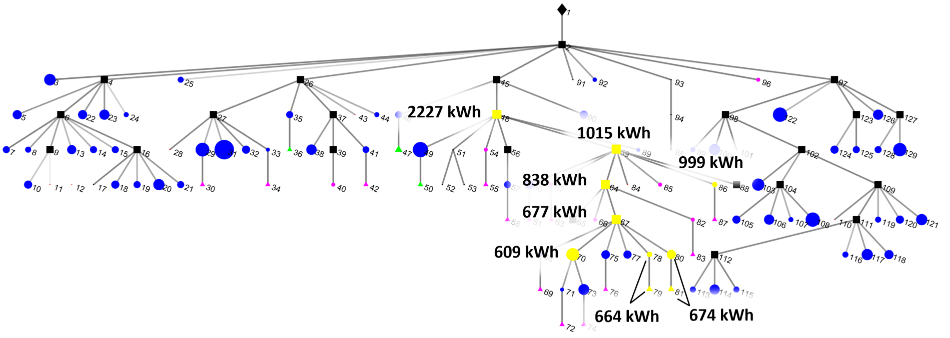


Figure 4.8: *The grid and the different nodes where a single battery can be placed to stabilise the grid enough (marked in yellow). Next to these nodes the least amount of battery capacity needed is stated. These numbers and nodes can also be seen in Table 4.2. Note that the battery capacity needed when a battery is placed in Node 88 is slightly lower than when placed in Node 59. This can be explained with increased power losses in the additional cable, see Section 2.1.*

Table 4.2: *Nodes where a placement of one stationary battery is possible, and the minimum size it can be to fulfill the constraints.*

Node	Size [kWh]
48	2226
59	1015
64	839
67	677
70	609
78	675
79	674
80	665
81	664
88	999

Not possible placements

When looking at Figure 4.2 and Figure 4.8 it can be seen that only battery placements in the branch that reaches the highest voltages are possible. There are two reasons for this, these can be observed by looking at two cases where a placement of the batteries does not work. Theses are illustrated in Figure 4.9 and Figure 4.10.

Firstly, if the batteries are placed too far away from the problem zones, a lot more energy is needed to be able to decrease the voltage spikes. This instead leads to too much power being used in certain parts of the grid, and in this case leading to voltage drops below -7% of 230 V, see Figure 4.9.

The second reason is that in some cases the cables are too weak, and often in these cases that all power flow goes through just one cable. This leads to large cable loading, and in that case leads to this constraint not being fulfilled, see Figure 4.10.

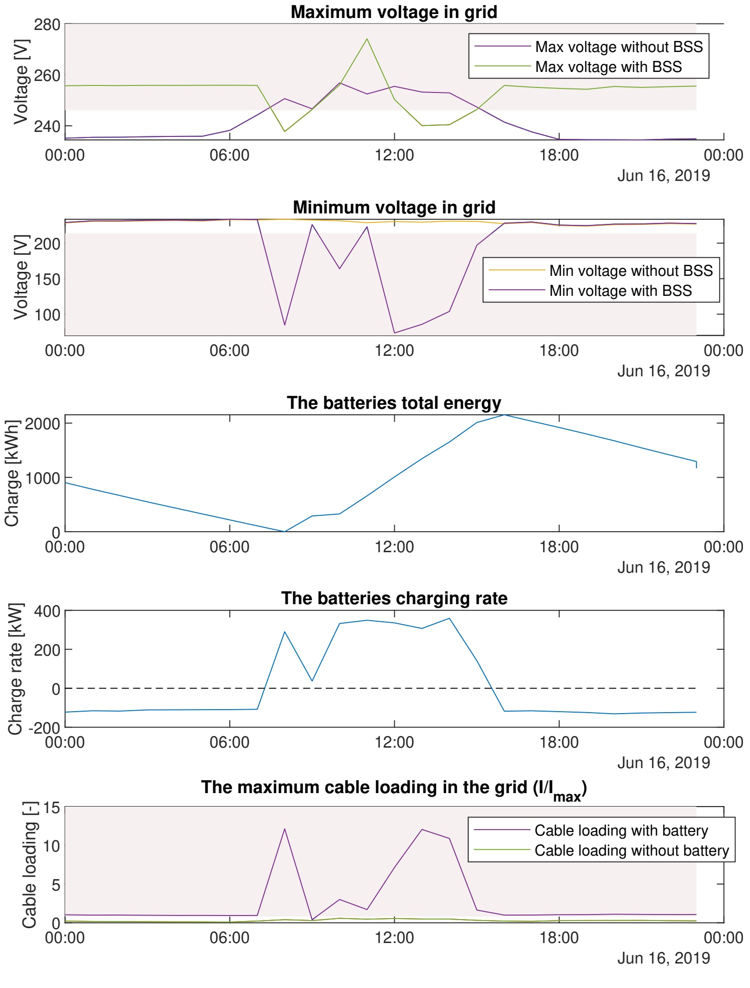


Figure 4.9: *Illustration of maximum and minimum voltage, SoC variations and cable loading for a stationary battery in node 15, far away from the nodes that exceed the maximum allowed voltage. The graph of the maximum voltage show the maximum voltage of all the nodes in each time step, same goes for the minimum voltage and the maximum cable loading (but for all the cables instead). Note that during the time-steps when the battery is charging, between 07:00 and 16:00, trying to reduce the maximum voltage in the grid, the minimum voltage in the grid gets reduced far below the limit of −7% of 230 V.*

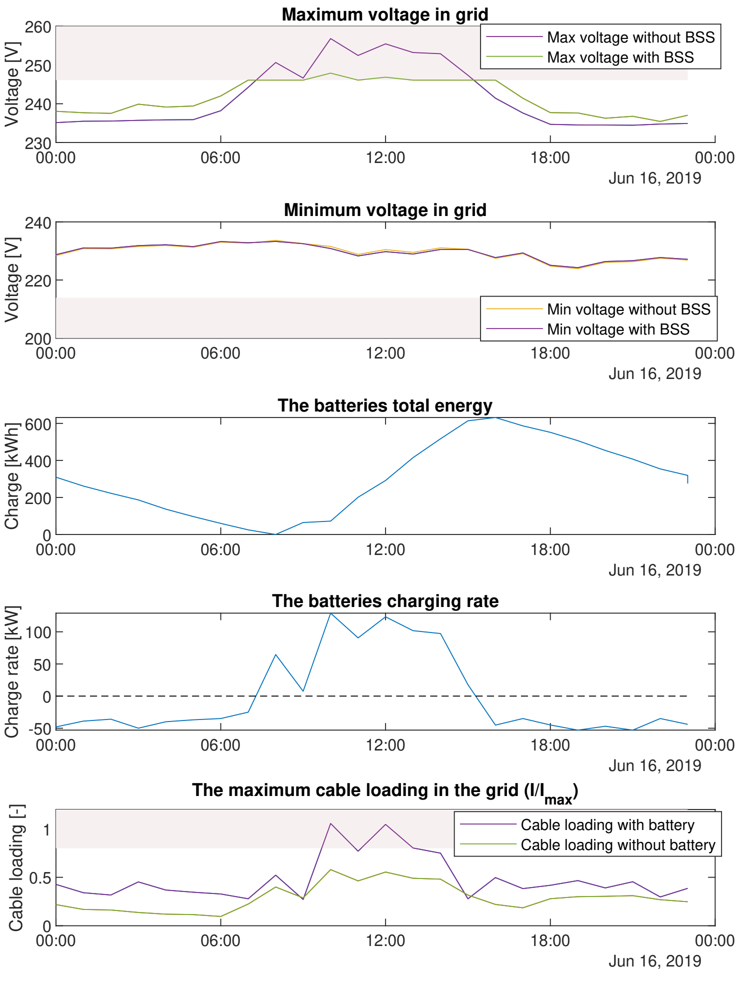


Figure 4.10: *Illustration of maximum and minimum voltage, SoC variations and cable loading for a stationary battery in node 68. Note that the maximum voltage is almost below the maximum allowed voltage in all time steps with BSS. The reason why these voltages can not be brought down is that the cables are too weak and the maximum cable loading is exceeded in the same time steps.*

Where Node 15 is situated far away from the solar panels, which leads to the large power needed and the large drop in voltage. In case of Node 68, this is situated in the part of the grid with a lot of solar panels, but the cable loading becomes too large due to the power flows it needs to charge the battery going through the cable being larger than the cable can handle.

Optimal placement

From Section 3.2, the optimisation strategy is to keep the battery size as small as possible while still keeping the grid within the limits of ±7% of the voltage and z80% of the cable loading. This optimisation was tested with one battery in every node in the grid and the results can be seen in Figure 4.8. According to the optimisation results the optimal placement of one battery is Node 70. This, as well as the trend that the closer to the transformer the battery is, the larger it has to be, can be seen in Figure 4.8 and Table 4.2. To understand why a battery further away from the transformer is a more optimal placement in this case, an analysis is carried out.

Firstly, if any node in the grid exceeds the voltage constraints, there has to be a voltage reduction in the node that the battery is placed in in order to reduce the voltage in the exceeding nodes. This behaviour can be seen in Figure 4.11. The decrease of voltage in the battery node seems to be independent on where the battery is placed, as seen in Figure 4.12. On the other hand, when studying Figure 4.13 observe that the current going into the battery has to be greater when the battery is placed closer to the transformer. The reason for the need of a higher current in order to achieve the same voltage reduction can be mathematically explained from the equation in Section 2.1 and presented below.

$$\Delta U = U_e - U_s = -\sqrt{3} I_c Z_c \tag{4.1}$$

If the battery is placed further away from the transformer, the impedance of the cable between the battery and the transformer is increased. Since an induced current to the battery also runs through this cable, the impedance of this cable, as well as the current through it is what gives rise to the voltage drop. When studying Equation 4.1 a higher impedance increases the sensitivity of the voltage drop when the current through the cable is changed. This means that it is the cable-impedance that determines how high the current going into the battery has to be in order to create a change in voltage to a certain magnitude. The size of the battery is a direct consequence of the size of the current and it is therefore also the cable-impedance that determines the battery size needed in each node.

However, these results are just gathered from the studied case. If the locations of the PV-systems were more spread out a battery closer to the transformer could be a better option. Figure 4.14 shows that a battery closer to the transformer lowers the voltage more evenly throughout the grid, this might be more beneficial in those cases.

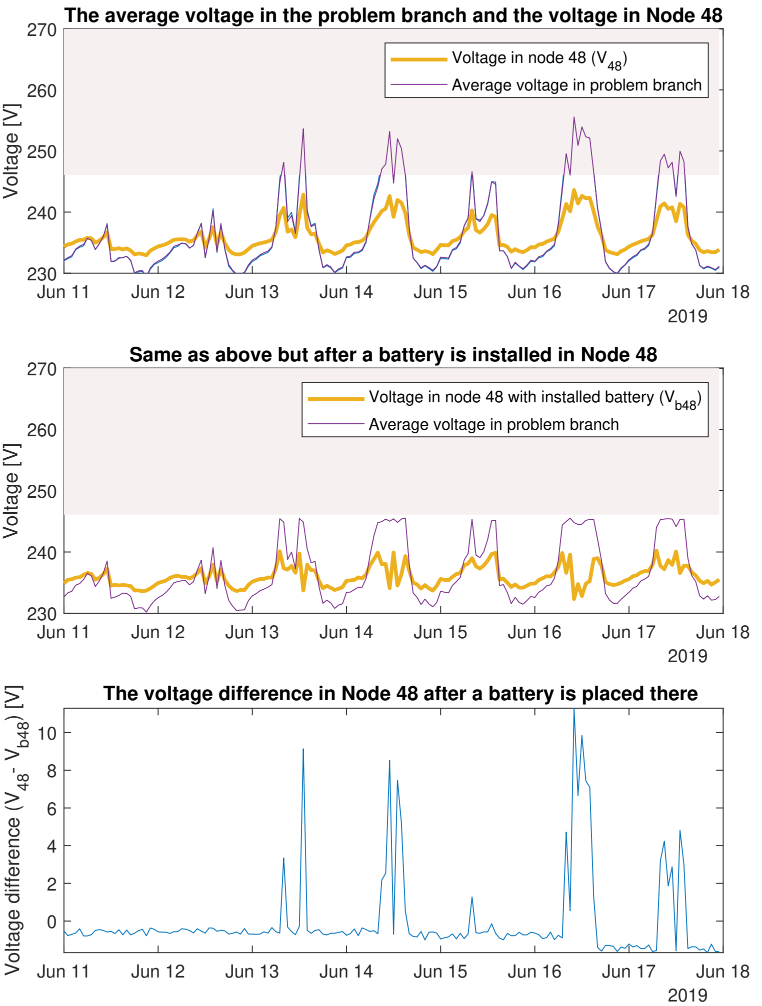


Figure 4.11: *Illustration of the average voltage in the branch with the highest voltages (where most PV-systems are, Node 67-81) and Node 48, both before and after the battery is placed in that node. It can also be seen that the voltage difference in Node 48 (lowest graph) has similar characteristics as the peaks without a battery (voltages in the red area of the top graph). The third graph for different battery placements can be seen in Figure 4.12*

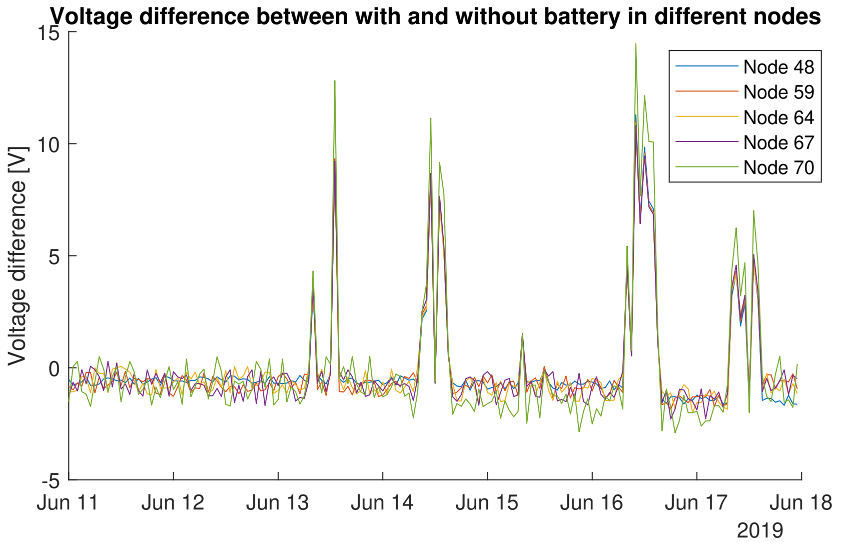


Figure 4.12: *Graph showing the voltage difference in the battery node caused by the battery charging and discharging. Each line comes from a simulation where that node is the battery node. Note that the voltage difference peaks all have similar magnitudes no matter where the battery is placed, except when the battery is placed in the most optimal node, Node 70.*

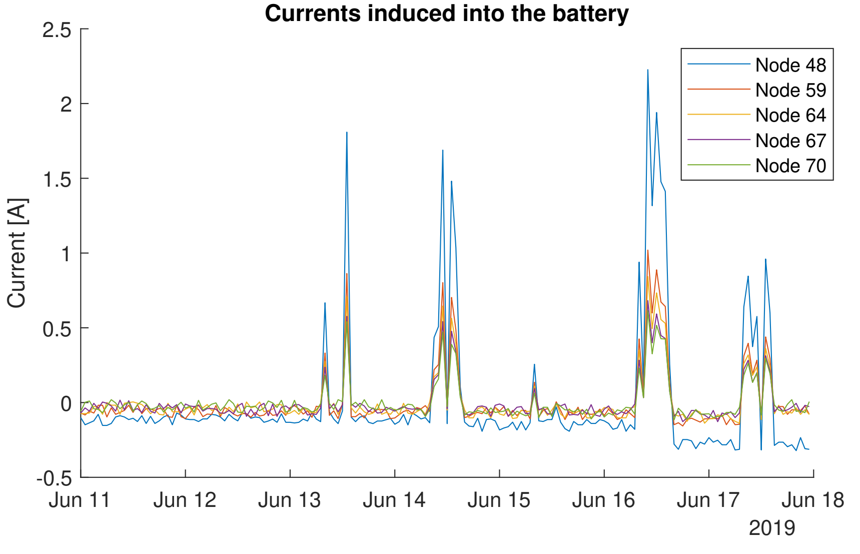
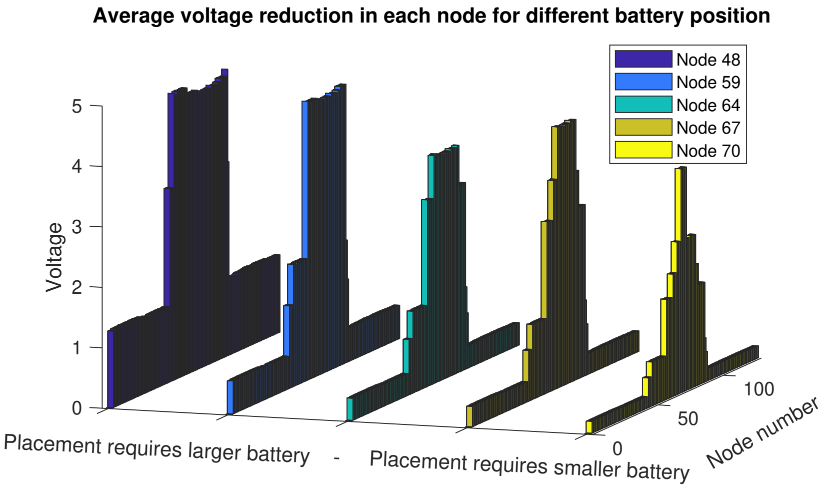
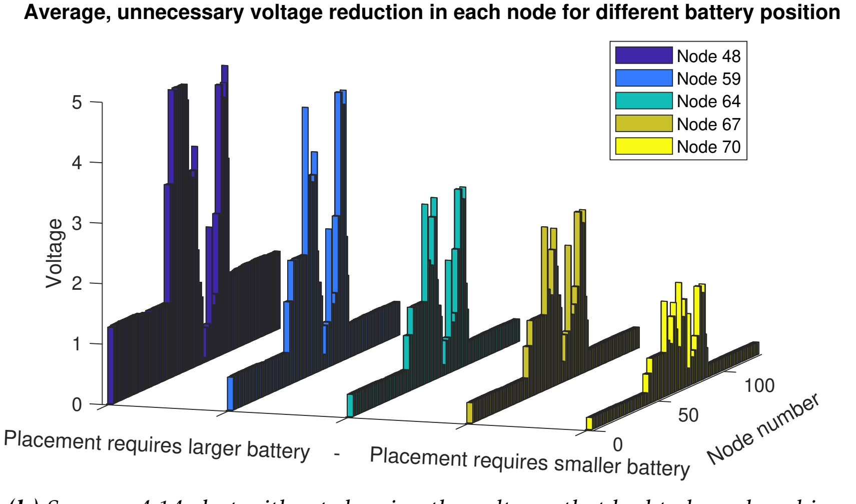


Figure 4.13: *Graph showing the current going in and out of the battery for different battery placements. Note that the peak currents are higher when the battery is placed in a node closer to the transformer.*



(a) *The average voltage reduction caused by the battery's charging during one week. Each bar represents the voltage reduction for that node. The voltage reduction results for each different battery placement are grouped together using different colors and placements along the z-axis. As can be seen in Figure 4.8 a battery in all of these cases leads to stabilised grid, with a battery in Node 70 being the most optimal and a battery in Node 48 the least optimal, i.e. requiring a larger battery (cases in-between these are sorted accordingly on the axis).*



(b) *Same as 4.14a but without showing the voltages that had to be reduced in order to stay under the voltage constraints. This means that the voltage reductions shown are reductions that were not necessary to make for the individual nodes. However, there might always have to be unnecessary reductions unless only one battery can lower the voltage in all nodes to just below +7% of 230 V.*

Figure 4.14: *Two bar-graphs showing the voltage reduction for every node in the grid caused by placing a battery in different nodes.*

4.4.2 Reinforcing with two batteries

From the previous examples, one can observe that only a few nodes are possible to place batteries in. Firstly it is established that batteries really need to be placed in the problem area. However, even in the problem area cables can be too weak to handle the size of the currents needed if only one battery can be used to lower the voltages. When instead doing evaluations with two batteries in the problem area, 210 combinations were tested and only 19 failed. This means that in the problem area the most important part of the placement was especially trying to keep the current flows in certain cables lower. Results of one of the best combinations can be seen in Figure 4.15. The lowest total battery capacity needed when two batteries were placed in the grid was 581 kWh with placements in node 73 and node 76, 28 kWh lower than when only one battery is placed in the grid.

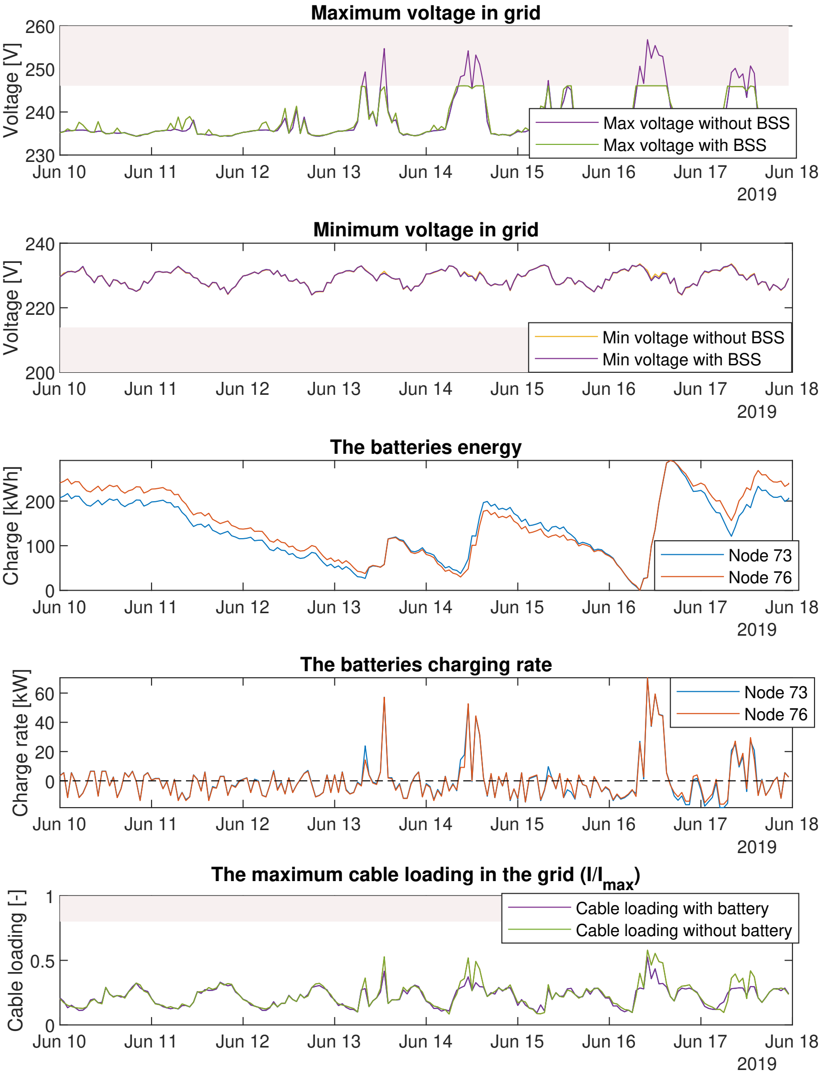


Figure 4.15: *One week simulation with batteries in node 73 and node 76.*

4.4.3 Batteries at every PV-system

From the previous sections, the most significant problem areas have been found. Based on the assumption that optimal battery placements are close to the problem areas. To see how much excess power there is in June 16, a battery is placed in every solar panel for this branch. This is illustrated in Figure 4.16. These batteries are controlled the same way as for one battery but the goal function value is the total battery capacity of all batteries combined, see Section 3.2.

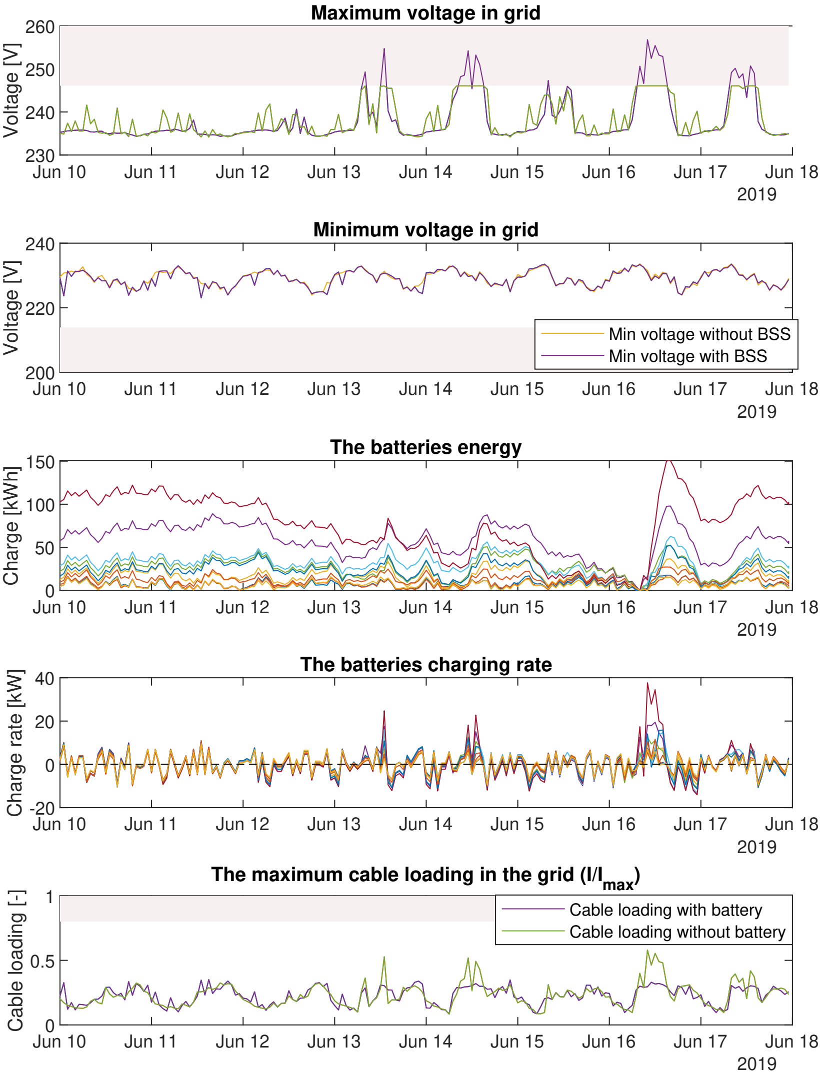


Figure 4.16: *Placement of 10 batteries in the grid.*

The function value is retrieved by adding the highest peak of charge for each battery for a value of 530kWh. This combined battery size is not a significantly different from the battery size of 609kWh, with one battery. However, what this means is that by placing batteries closer to the individual problem sources, this leads to less needed battery capacity, and means that the assumption of placing batteries close to the problem source is true.

4.4.4 Need of battery capacity each day

One trend that shows up when studying all previous results in Section 4.4 as well as Figure 4.17 is how significant the day the 16 of June is for the size of the battery. More specifically this is because the maximum voltage is very high over a longer than usual amount of time. If this day is not included, the battery sizes needed to stabilise the high voltages on the grid are much smaller. Instead of needing a battery of about 600 kWh, if only using one stationary battery, a normal day usually a battery of between 250-400kWh of extra energy is needed. This trend is shown in Figure 4.18. This trend is illustrated further in 4.19, where there is a clear diminishing return in the amount of energy saved in comparison to battery size needed.

To compensate for extreme days, two things could be done. One of them is to "burn" energy, in some way to compensate for extreme peaks and dimension the size of the batteries more based on average days. The second way is to limit the PV-systems so that they do not produce electricity when the voltage in that node passes a certain threshold. In this case every node from the branch starting in node 59 and downward passes the limit of +7% of 230 V, so if using this strategy, the PV-systems in this branch would have to be limited, see Figure 4.3.

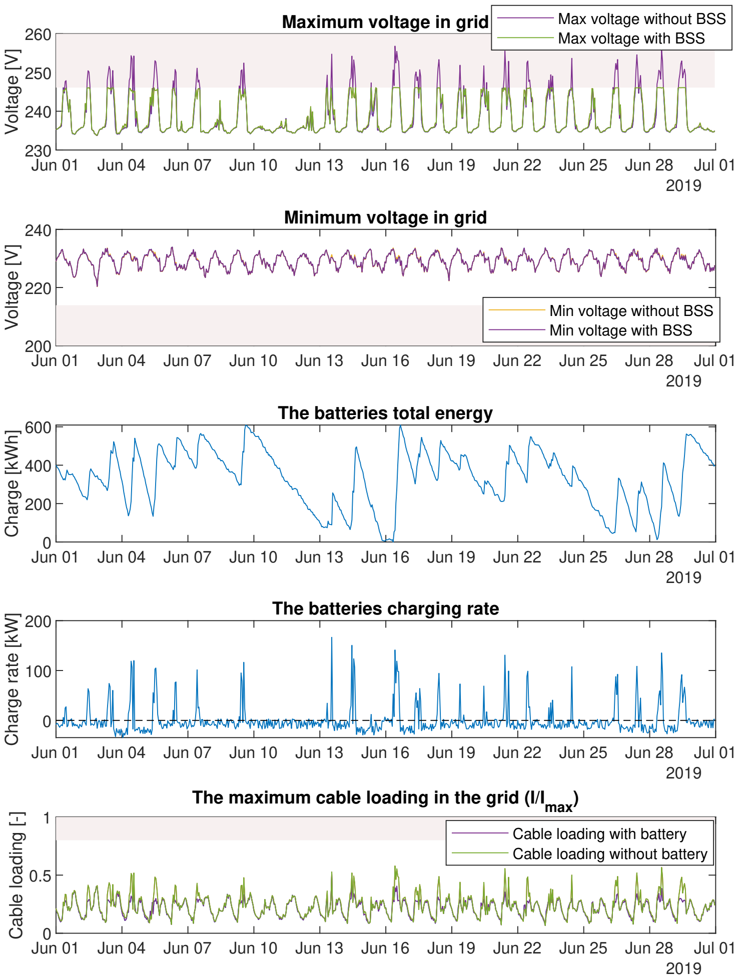


Figure 4.17: *Illustration of maximum and minimum voltage, SoC variations and cable loading for a stationary battery in node 70. Note that the day that dimensions the size of the battery capacity is June 16 (the charge reaches both the top and and the bottom during this day) and that the battery reinforced grid behaves similarly to the cable reinforced grid, in terms of cable loading as well as maximum and minimum voltage.*

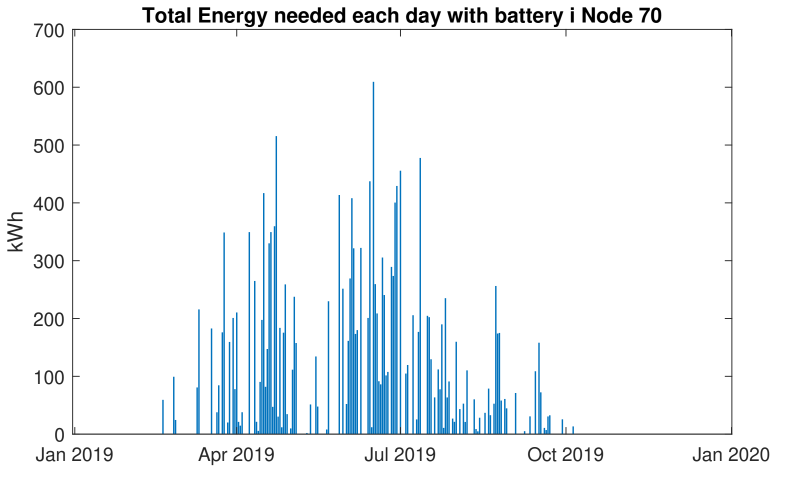


Figure 4.18: *Histogram, showing energy needed each day in the system to keep all voltages in between ±7% of 230 V and the cable loading below 80%. The total numbers of days the battery is needed is 125, which is shown in the figure as the number of bars.*

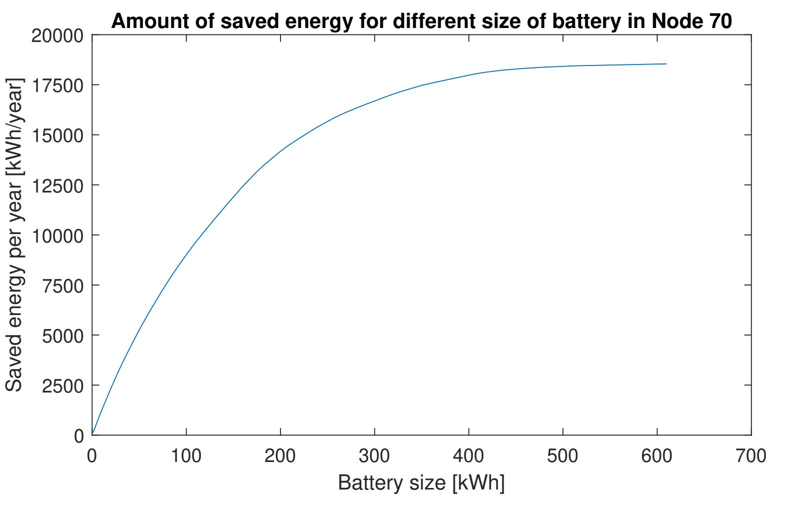


Figure 4.19: *Graph showing how the amount of energy that can be saved per year using different battery capacity. In this simulation the battery was placed in the most optimal place, Node 70. Since this is highly non-linear a smaller battery might be a better option than a larger one. For example a battery of 300 kWh can save as much as 90% of what a battery of twice that size can. For further understanding of why this is not linear, see Figure 4.18*

4.5 Evaluation of future grid problems

In all of the above cases, an actual grid was used and the figures everything is based on is the real grid. However, in the future, problems may arise on other parts of the grid. With increased electrification, the observed grid will most likely have more solar panels in ten years than it does right now. The grid right now only has one branch with real problems. To simulate another branch on the grid with problems solar panels are added in nodes 10, 13, 14, 15, 18 and 20. The size of these are all set at 30kW which is a reasonable size in comparison to the other solar panels in the grid, and all with the same direction. Which gives a new total installed power of 180kW. The amount of solar panels is chosen so that another part of the grid also had nodes that passes the limit of ±7% of the nominal voltage. Firstly this entire grid is looped through with just one battery, but no solutions are found.

4.5.1 Solution with two batteries

As no solutions is found with one battery, instead two batteries are evaluated. For simplicity one case was tried with a battery in node 70, which was the optimal placement for the original grid. A battery was also tested in the new problem branch, in node 6. In Figure 4.20 the results from this can be seen.

The problem is solvable with a battery placed in the new problem zone since it is possible to keep the voltages within allowed range. However, the battery in node 70 is significantly larger than it is when simulating the original grid. The reason for this is that the voltages are increased in the original problem branch when increasing the production in another branch. This also means that in the future, if a new branch starts causing problems it would not be enough just by placing a battery in this branch. However, when reinforcing the grid one could in the future only place a battery in a new problem zone.

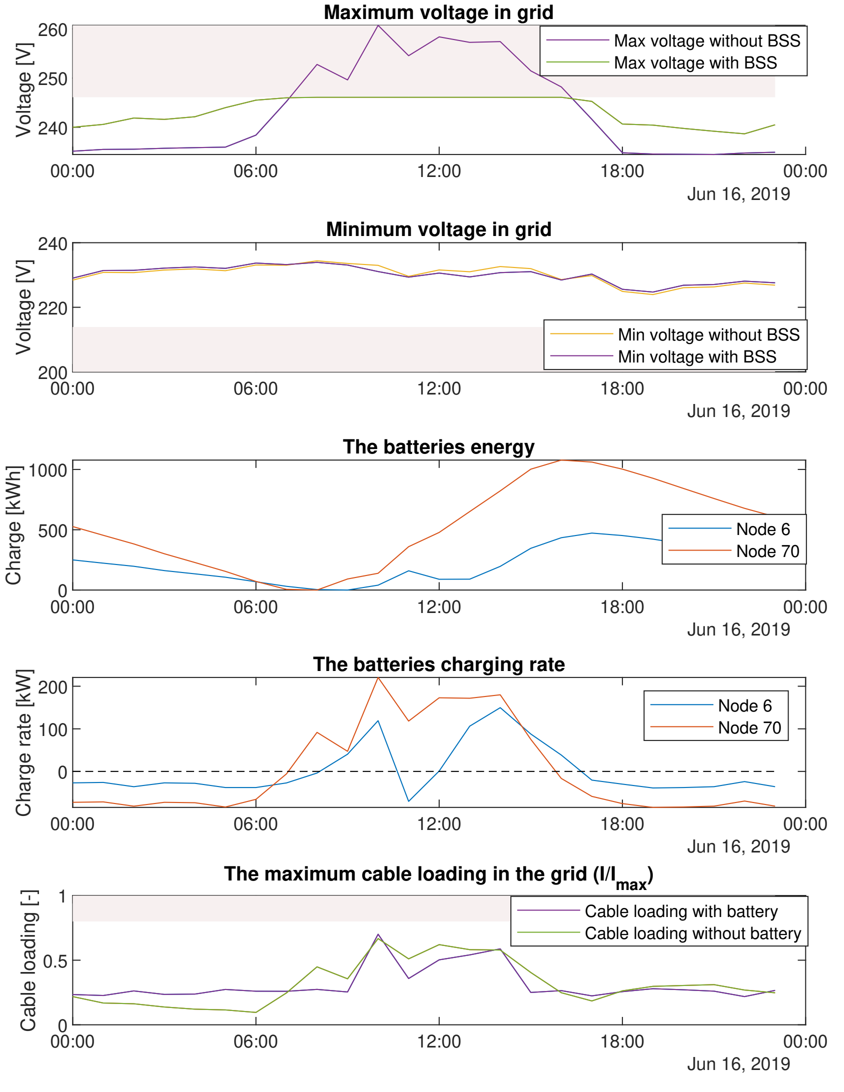


Figure 4.20: *The grid with added PV-systems simulated with a battery in node 6 and node 70*

4.6 Economic comparison of cable and battery reinforcements

From the previous sections, a few different battery- and cable-solutions have been found. The cost of these and some further analysis will be covered in this section.

4.6.1 Reinforcing with one battery

As can be seen in Figure 4.8 and Table 4.2 the smallest possible size of a battery that can save all excess power, i.e. keep the highest voltage in the grid just below the limit of +7% of 230 V, is 609 kWh. Using the costs of a lithium-ion battery presented in Section 2.3.1 the price of such battery would be 935 504 SEK with the average price of 156$/kWh$ for batteries year 2019 and the USD/SEK exchange rate 9.847 for May 6 2020, [2].

4.6.2 Future batteries

Batteries are projected to drop in price quite significantly in the future. This might lead to batteries becoming more viable in the future, a cost comparison between a 300kWh battery and a 600 kWh battery is done in Figure 4.21, where projected prices from 2024 and 2029 are forecasts from [5], and 2019-2024, and 2025-2029 are both assumed to have a linear drop.

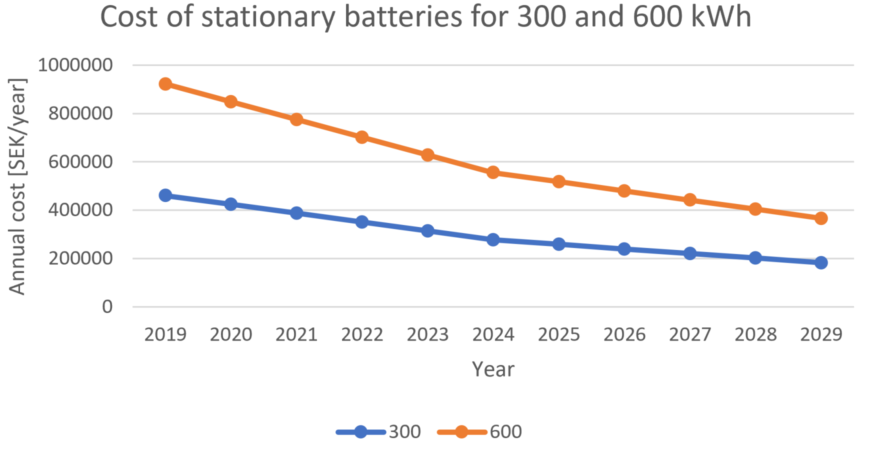
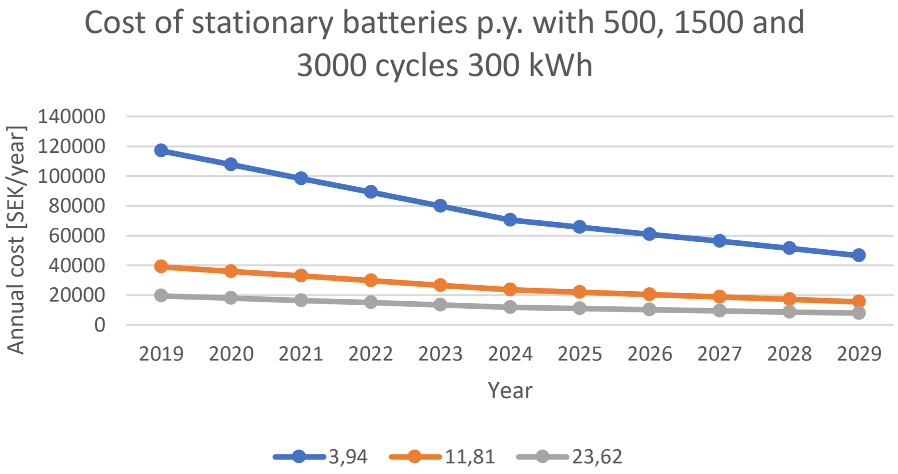
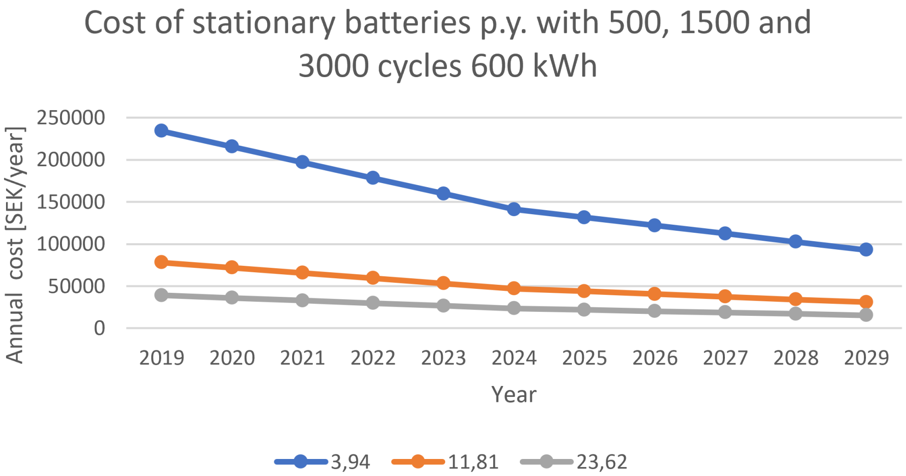


Figure 4.21: Cost comparison between a 300 and 600 kWh battery price evolution from 2019-2029

Another important factor in regards to cost for batteries is how long a battery can last. From the analysis in Section 4.4.4 it is known that for 2019, the battery needs to be used 129 times where a cycle is defined as the usage of the battery for one day. This mainly due to the fact that usually when the battery is used in a day it is both charged and discharged. This is an indication of how many cycles a battery in a grid needs to run each year. Using this as cycle amount a year, we can then use this result to calculate how many years a battery can last. Since no precise and reliable data on many cycles a battery can run, three cases in a reasonable interval was created. These three cases where that a battery lasts either 500, 1500 or 3000 cycles. The results from the above mentioned calculation in the three cases can be seen in two figures, see Figure 4.22, where the yearly cost of the batteries are compared.



(a) Comparison done for a 300kWh sized battery



(b) Comparison done for a 600kWh sized battery above.

Figure 4.22: *Yearly costs of three different cases where the expected number of cycles a battery lasts differs; 500, 1500 and 3000 cycles. Where the lifetime of these are 3.94, 11.81 and 23.62 years respectively. The years on the y-axis represent projections for price drops in li-ion batteries.*

To see how economically viable a battery reinforcement would be to compare to a cable reinforcement in the future, some examples of the annual cost of different battery configurations are put in the same graph as the cost of some cable configurations, see figure 4.23. Two battery configurations were chosen, the 600kWh battery that can completely keep the grid within allowed ranges, and the 300kWh battery that could save a lot of energy and be beneficial for the system but has the assumption that sometimes the production in the grid needs to be turned off in some way. The life length chosen for these batteries is 1500 cycles. The cycle amount is an assumption of how the SoC variations affect the number of cycles the battery. In Section 2.3.2 the amount of cycles vary based on how large the SoC range is. For the simulations made in this thesis, the cycles are not known for longer than one year in the future, which means that if the battery starts varying in the range of $SoC \in [0\%, 100\%]$ in the future, the battery will degrade faster. For this reason a significantly smaller cycle figure is now assumed of 1500, in comparison to the 5000 cycles discussed in the Section 2.3.2 is assumed. The cable configurations were chosen due to the high cost in reinforcing infrastructure in urban and city environments, these are the cases where batteries are most likely to be able to compete, see Figure 4.23.

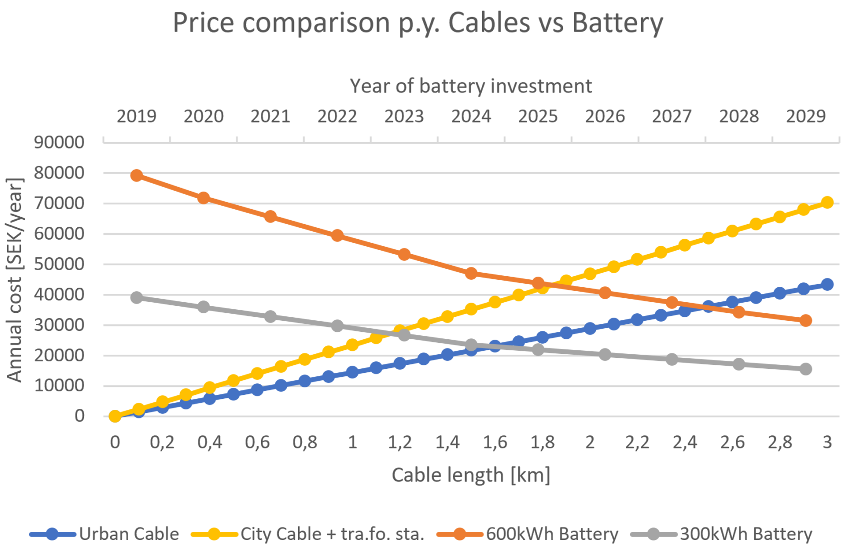


Figure 4.23: *A per year price comparison between the cost of a cable and a 600kWh battery with a lifetime of 11.81 years. The projected price changes of the batteries are from Bloomberg, and distance of cables is in kilometers.*

In this case, in the future, based on how much infrastructure needs to be changed. There may be cases both in urban areas and in city areas where batteries could be a better economic choice then changing infrastructure. From Figure 4.23 the smaller battery might be a better solution already by 2023 in a city environment. As mentioned previously in Section 4.3, in some cases, it would not be possible to only reinforce cables. Instead a transformer would likely need to be added, the cost of this in comparison to the cost of batteries can be seen in Figure 4.24. For more examples of annual cost of cable reinforcements, see Figure 4.25.

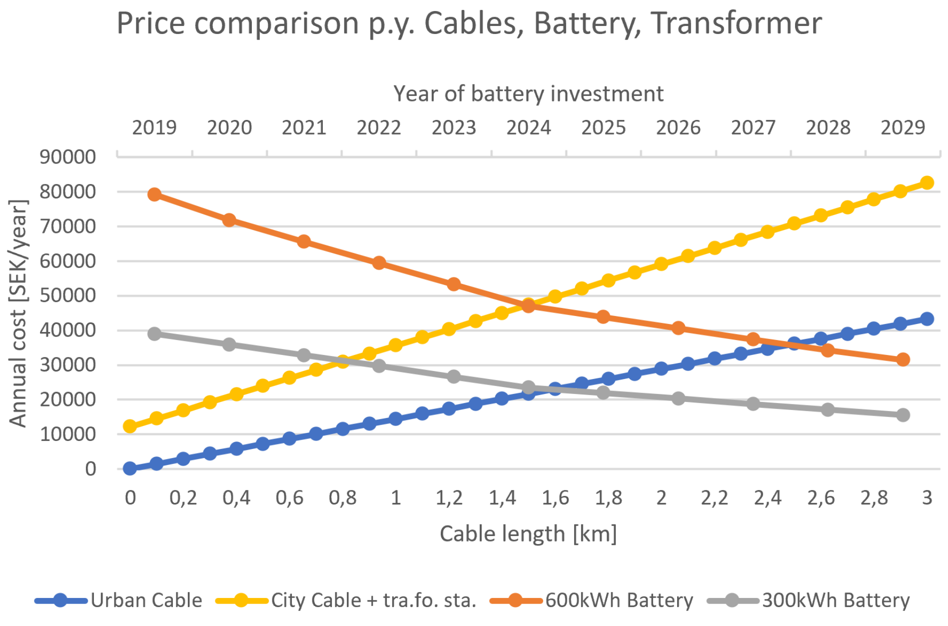


Figure 4.24: *A comparison of the yearly cost of batteries compared to a transformer with cable reinforcements.*

4.6.3 The real case

The basis for the thesis was a real case, where a real solution was made. In this case the problem branch, shown in Section 4.3 is reconnected with a 395 meter cable for a price of 224 887 SEK. This lead to the voltage in the grid always being in accepted ranges, as most of the production was moved to a network station with less production in it. When testing this case with our simulation models, a few other solutions were tested.

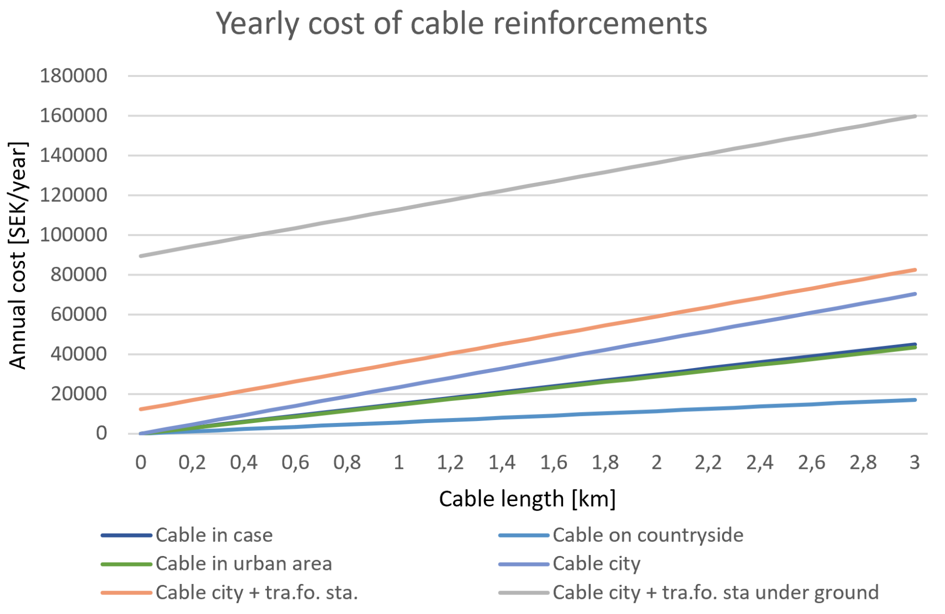


Figure 4.25: *Copy of figure 2.4 placed here for simplicity purposes.*

To completely keep all grid voltages under the limit of 7% of the nominal voltage, when using one battery a battery sized 609kWh was needed. By also taking into account of keeping the battery in the range of $SoC \in [10\%, 90\%]$ for the sake of keeping the battery life long, the battery would need to be 760kWh. This is of course problematic, as the battery in this case is only sized based on the worst day of the year, all other days the batteries is not close to leaving this range. And stepping outside of the recommended SoC once will not have that large of an impact for only one day. So for the sake of simplicity, a battery of 300kWh is used with the assumption that it in some way will be possible to either regulate solar panels, when they produce too much electricity, or in some way to "burn" electricity. The SoC analysis of 1500 cycles is for this case reasonable, as the battery size is a lot smaller now, the cycles will often be in the entirety of the SoC-range. Therefore, the much smaller cycle value than the tests in Section 2.3.2 show is used. This would lead to a price of 460 840 SEK in 2019, 39 018 SEK annually, and 183 154 SEK in 2029, 15 507 SEK annually. In comparison to the real cost of 224 887 SEK, a battery solution could definitely be competitive in 10 years time if the complexity of the cables were today. However with reinforcements today assuming a battery of 300kWh the reinforcement would have to cost 1 600 000 SEK for it to be worth to invest in batteries instead.

A common solution to these sorts of voltage problems as mentioned in the background of this thesis is to strengthen the grid by either adding new cables or switching cables. This was tested in Section 4.3, and not able to keep the battery required voltage range. What this means is that for this specific case, there was a near enough grid where the problem zone could be rerouted. This may not always be the case, and in these cases, where you are not able to rebuild the infrastructure of the grid there are three solutions. Either add a new network station to the grid, create a new low distribution grid with a new network station including the most problematic zone or add a stationary battery. The cost of these network stations vary from about 80 kSEK to 500 kSEK, and in this case according to [24], the cost would be 500 kSEK for a new transformer in an urban area. Adding this cost, and a battery solution could definitely be competitive in the future.

5
Discussion

In this chapter a discussion is carried out regarding the problem formulation. The problem formulation from Chapter 1 is presented below to assist the reader and is sorted to follow the structure of the discussion.

- Create a simulation tool using consumption data and validate in comparison to actual voltages on a real grid.
- Create an optimisation algorithm for controlling stationary batteries.
- Investigate how batteries can be placed most efficiently to keep the grid from reaching $\pm 7\% V$ of the nominal voltage and 80% of the cable loading.
- Find the minimum battery capacity needed to give the same results as cable-reinforcing the grid.
- Find out which grid-characteristics lead to batteries being a more cost efficient solution.
- Evaluate the performance of one and multiple batteries.
- Evaluate how long a stationary battery can last when used to reinforce a low voltage grid, based on how many cycles the battery can last before losing capacity and before the installed power on the grid is too large.
- Analyse when it is more cost effective to use batteries than cables to limit maximum voltages and cable loading.

5.1 Building simulation tool and validating

For the modeling of the grid a lot of data was available. However, not all data was available and a few assumptions had to be made. A discussion on the validity of these assumptions is made below.

The most missing data was solar panels. However, due to the quite simple behaviour of solar panels, these were the easiest to model. Data from PV-systems on three (two being used) houses were known, and due to the known geographic location of the grid; it was possible with Google Earth to approximate both angle of roof and direction of the solar panels on these houses. Due to this factor, when modeling, no information on solar conditions were needed and no approximation of local weather conditions needed to be made. These could then be scaled to the other parts of the grid where there were solar production units, and by using the models as a base, combined with the annual solar production per year and the orientation of the solar panels, a quite good approximation of the unknown data was possible to make. Apart from the solar production, data was also missing for street lights, and for a few households. Both of these were easy to approximate with help of knowing the annual production.

Lastly, the validation of the models was done in comparison to voltages retrieved from Tekniska verken. This was done to truly test if the modeling was accurate enough to draw conclusions, and from the results section these results were concluded to be good enough. When grid companies usually do grid modeling, it is based on standard-curves, in shape of BETTY-curves. With new measuring devices being rolled out, and grid companies spending resources on using more data, the data-driven approach in this report in regards to modeling feels more future-oriented. Especially considering the fact that the grid keeps getting more and more complex.

5.2 Optimisation algorithm and minimum battery capacity

The different battery sizes mentioned are all retrieved from the optimisation algorithm. The constraint of the maximum voltage is set to +7% of 230 V in the optimisation. When the cable reinforcement was made, the maximum voltage happened to be almost the same as the constraints set for the battery optimisation. For this reason, the battery size needed to give the same results as reinforcing the grid with a cable was the same size as keeping it in accepted constraints, see Section 4.4. However, the battery sizes given by the optimisation algorithm are not necessarily what would be advised to use in the real grid. First of all the optimisation algorithm may not find the global minimum, i.e. the smallest possible battery size for that node. Instead, the algorithm tries to find the global minimum and stops when the value is good enough. Since the same algorithm is used for every location, comparing the results is instead a very good way of finding the *location* that needs the smallest battery size.

Another thing to consider when in regards to optimal battery sizes is that they are obtained by an optimisation algorithm and not from a control algorithm; which would likely be used to control the battery in real life. How well a control algorithm would perform compared to the optimisation algorithm used in this work is outside the scope of this thesis. However, since a control algorithm makes decisions based on only historical and present data and the optimisation algorithm also receives data about what is going to happen in the future, it is reasonable to assume that the control algorithm would not perform as well as this optimisation algorithm. In this case, a larger battery would be needed than the sizes that are mentioned in this thesis.

5.3 Grid characteristics and how they affect the cost of batteries and cables

Grid characteristics could mean a lot of different things, but what has been covered, or partly covered in this thesis are the following:

- Distance between the transformer and nodes that exceed the maximum allowed voltage.
- Number of branches that contain nodes that exceed the maximum allowed voltage.
- Distance from nodes that exceed the maximum allowed voltage and another grid.

How these characteristics affect the cost of a cable reinforcement and the size and cost of a battery used in a battery reinforcement is discussed below.

When a node experiences a voltage higher than the maximum allowed voltage, that node-voltage has to be brought down. This can be done by lowering the voltage in the specific node or in any other node in between it an the transformer, since this indirectly lowers the voltage in the specific node the same amount. If a battery is used to bring this voltage down, the optimal placement of it would be in the node that experiences too high voltages. This is because batteries are more efficient the further away from the transformer they are, or more precisely, the higher the impedance is between it and the transformer, see Section 4.4.1.

If one would construct a case where a battery is a very efficient way of lowering the voltage, the node or nodes that exceed the allowed voltage limit would be placed very far away from the transformer. This would lead to a smaller needed battery size per reduced amount of voltage and also make a cable reinforcement more costly, since a longer cable would have to be installed. This cost of a longer cable could however be avoided if there is another transformer which is closer. So ideally, a grid where one would be more likely to benefit of choosing to make a battery reinforcement would be in an isolated grid where too many PV-systems were placed very far from the transformer.

If there are more branches containing nodes with exceeded voltages the case gets more complicated. According to the results in Section 4.5.1 there are situations where more than one battery is needed to lower exceeded voltages in all branches. What this leads to is that the initial battery, that was large enough to cover the initial problem branch no longer is large enough to cover the voltages in this branch. This due to the fact that the voltages are increased throughout the entire grid when a new problem branch arises. Since increased voltages in one branch also affect other branches voltage, it is no longer as clear where the optimal placement of batteries would be. The results of this show in a way that if it is possible to completely change the infrastructure of the grid, long term this will often be better than installing a battery in a grid where the infrastructure is not dimensioned for photovoltaics. A comparison between the cost of the minimum battery sizes needed in a situation with several problem branches and the cost of solving this using cable reinforcements would have been an interesting analysis, however this was outside the scope of this thesis.

5.4 How long does a stationary battery last

One of the significant aspects in the cost-comparison between cables and batteries is the life length of them. How the battery is used also has a large impact on the lifetime of the battery. For this reason when choosing battery size based on the needs of the grid, the battery was sized in a way that the SoC values rarely differ that much. By also retrieving an approximate value on how often the battery needed to used during an entire year, an approximation of the life length of the battery could be made. One factor that is not taken account to here, is that the production in these types of grids could likely increase. This would in turn lead to the battery being used more aggressively, and increasing both the range of SoC of the battery. This would lead to the batteries having a shorter life length than the tests discussed in the background section.

There were a few significant assumptions made in regards to battery life length. No own study was made on this, but instead available research was used, and then conservative guesses were used based off of this research. In reality, how the battery is used will have a significant outcome on the life length of the batteries. What would be interesting but was outside the scope of this thesis, would be to include this in the simulation tool in some shape or form.

5.5 When is it cheaper to use batteries than cables

This is the main research question of this thesis, all other problems were handled to be able to solve this question. Most of the time, it is cheaper to use cables than batteries and situations where batteries are most beneficial are discussed in Section 5.3. However, as mentioned in Section 4.6, there are still some cases where it not only is cheaper to use batteries than cables, but where it may be necessary. This is especially for infrastructural reasons, where it is simply either very hard to rebuild the grid or maybe even impossible in few years span. In these cases the portability of moving a stationary battery while planning a major rebuild of the grid may be the only possible solution. One result that is also especially positive, is that by increasing the amounts of batteries the size of the batteries necessary to keep the grid within allowed limits is lower. This means that there is a large incentive for prosumers and consumers owning batteries, both for financial gains for them, with energy arbitrages and increased self-sufficiency, and for the grid companies, where this may be a way of getting higher grid stability.

A lot of assumptions were however made in the economic analysis of batteries. Firstly, a fixed rate in USD per kWh for batteries was found, these prices may vary a lot depending on size of battery, manufacturer and company. A consumer buying a stationary battery in their household will not be able to buy batteries at the same rates as grid companies buying stationary battery stations for hundreds of kWh. The entire future analysis is also built on projections, and these projections may not at all be true. Prices might be significantly higher due to higher demand for precious metals, or significantly lower due to technological progress. The only battery type used in the economical analysis was lithium-ion batteries, and in 10 years time, new innovations for batteries might be possible. As stated in Section 5.4, the guesses made for how many DST-cycles the battery could handle were all quite conservative guesses, which may have either inflated or deflated the prices p.y. discussed in Section 4.6.

6 Conclusions and future work

6.1 Conclusions

A simulation tool using data from Tekniska verken was created and after validation it can be reasonable to think that its output represent actual voltages quite well. This simulation tool also included an optimisation algorithm that could find the optimal placement and minimum size of a battery that can reinforce the grid so that all voltages are kept in between ±7% of 230 V and the cable loading of all cables never exceeds 80% of the maximum cable loading.

According to the results from the simulation tool, the optimal placement of one battery in the grid is to place it close to the nodes that are experiencing the highest voltages.

To keep the studied grid within these constraints mentioned above a battery capacity of 609 kWh was needed. However a battery of 300 kWh combined with a voltage limit that stops the solar production at specific time points would still save 90% of the energy of what a 609 kWh battery can save. Since the cable reinforcement performed by Tekniska verken resulted in a new maximum voltage of about the same as the constraint used in the optimisation, the same battery sizes can be used when comparing the two types of reinforcements, see Section 4.3.

In general, batteries are as most efficient at lowering voltages when they are placed close to nodes that experience the highest voltage and when this node is located far away from the transformer. A situation like this would lead to a smaller needed battery size.

If one battery is used to reinforce the studied grid, it would go through 129 charging cycles per year in this specific case. Using this number combined with information gathered about life lengths it is concluded that a battery would last in between 4 and 23,5 years, approximately.

According to the results, the lowest calculated annual cost of a battery reinforcement put in the studied grid today is 39 018 SEK, where as the annual cost of the cable reinforcement done is calculated to 5 622 SEK. The battery would have a size of 300 kWh and have an expected life length of 11.81 years. If the same battery was to be put in place in the future by 2029 the cost of this battery would instead be 15 507 SEK annually.

To summarise, from the results in this thesis, using the cost of toady's Lithium-Ion batteries, one would consider a battery reinforcement over a cable reinforcement when, for example

- The battery size needed is smaller than 300 kWh and the cost of a cable reinforcement would be around 1 600 000 SEK.
- When other factors such as installation time of cables is too high.

This can however change in the near future since the price of batteries are expected to drop rapidly the upcoming years.

6.2 Future Work

There are still many different subjects possible to investigate in this subject.

- Implementing an actual control system with the same goal as the optimisation problem solved in this thesis. Potentially using weather forecasts and forecasts on consumption rates, by using historical data to predict future consumption.
- Adding battery health to the simulation and optimisation. For example adding stricter limitations on power flow, or changing the optimisation function in a way so that the battery is used in a way that promotes battery life length. Using the actual cycles from the simulation to predict how long a battery would last if used this way.
- Further analyse of how the size of the minimum battery size changes when nodes in different branches exceed the maximum voltage.
- Other usages of battery reinforcements in the low voltage grid to make them more economically viable.

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