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Industrial Electrical Engineering and Automation

Energy Storage for Voltage Control in LV Grids

Sizing, Control Strategies and Economic Benefits

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Abstract

This thesis addresses overvoltage issues in weak low voltage grids caused by large solar power production. The suggested method is using PI controllers to control voltage. This is done by using battery energy storage systems (BESS), designed to absorb active power during these times and thereby limiting the voltage rise. This could enable faster integration of solar power and a reduced demand for network reinforcement. A case study was conducted on a rural part of a grid owned by Kraftringen in southern Sweden. The network was modeled in Simulink with hourly load data from 2017-2020. Furthermore, solar power installations based on solar data from the same time period were added. Power and energy storage capacity of the BESS needed to keep voltage within acceptable limits were determined, as well as the impact of PV penetration, battery placement and line types on these dimensions. Furthermore, it was investigated during which times the BESS had to be reserved for voltage control, and whether the BESS could be used to provide other services during the remaining time. Results showed that with 30 kW installed solar power at each one of the four customers, a BESS placed at the customer most sensitive to voltage rise required 13 kW/62 kWh battery capacity. The BESS was used about 50 % of the days between mid-April and mid-August and unused the rest of the year. During the days needed, it was used for a maximum of 9 hours per day. This enabled the opportunity to use the BESS for other services such as frequency control during night time and winter, as well as for load and production peak shaving. These additional services could play an important role in making the solution economically viable.

Preface

This master's thesis was carried out in the fall semester of 2020 at Lund University, Faculty of Engineering (LTH), Division of Industrial Electrical Engineering and Automation (IEA), in collaboration with Kraftringen.

I would like to thank my supervisor at LTH, Olof Samuelsson for great support in both theoretical and practical issues throughout my work with this thesis. I would also like to thank Martin Lundberg, who in collaboration with Olof Samuelsson proposed the topic of this thesis. Martin has provided great input throughout the work and has spent a lot of time helping me with the simulation model.

Furthermore, I would like to thank Kraftringen for showing interest in my thesis and allowing me to carry out the work there. A special thank you to my supervisor at Kraftringen, Håkan Skarrie, who with his wide knowledge of network planning and operation has helped me understand the many factors that have to be taken into account for a solution to be successfully implemented. Lastly I would like to thank Andreas Vikström at Kraftringen for helping me to extract and understand the network data that I used for simulations, as well as for providing valuable input throughout the work.

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1 Introduction

This section provides a background of the topic and introduces the research questions, limitations and related works.

1.1 Background

As a result of ambitious climate goals, the incentives to invest in renewable energy sources (RES) have increased. RES such as wind and solar power represent a growing part of the electricity production, reducing the climate impact of the electricity system.

Traditionally, power grids are designed to transport electricity from large producing plants, through high voltage (HV) transmission grids, medium voltage (MV) regional distribution grids and low voltage (LV) local grids to finally reach the end consumers [1]. However, this is changing with an increasing amount of RES in the power system. Small scale wind and solar power is usually produced further out in the grid, connected to low- and medium voltage grids, meaning that the production is shifted from centralized to a distributed generation (DG). Furthermore, the production from these energy sources is highly weather dependent and therefore varies during the day and year. This is creating new demands on the design of the system [2]. In LV grids, photovoltaics (PV) is the dominating type of RES [3] and this thesis will focus on LV networks with high PV penetration.

When high PV production coincides with low load, power flow reverses in the LV (less than 1 kV [4]) grid, and power is fed from the outermost part of the grid, towards the LV/MV substation (in Sweden usually 0.4 kV/10 kV or 0.4 kV/20 kV). This can lead to voltages exceeding the maximum acceptable voltage levels in the point where the PV is connected. Methods for resolving the overvoltage issue include the use of tap changers, reactive power control, load control and grid reinforcement. In the case when no other method is available, active power curtailment could be used. This means that the power output of the PV system is reduced, resulting in lower utilization of the installed capacity. The method is however often cheaper than grid reinforcement on a system level and more simple than other methods which is an incentive to use it despite the mentioned disadvantages [2]. Another method used by distribution system operators (DSOs) to avoid the overvoltage problem is simply limiting the amount of PV power allowed to be installed in the system, either at all times or when overvoltage occurs [5]. In Sweden the grid owner is obligated to accept installations of new power generation devices unless special circumstances exist [6]. The owner of the PV system has to pay for the costs directly related to the connection and the grid owner might have further expenses related to the PV installation for example from grid reinforcements in the overlying grid. If the choice of connection is not the most cost effective for the connecting customer, the grid owner has to pay for the difference [7].

Active network management (ANM) refers to solutions where control systems and communication technology are used to create a flexible power system that allows a large integration of RES while keeping the grid utilization high. Avoiding curtailment of RES is therefore an important issue within the ANM research area [8]. This thesis was conducted with the grid owner Kraftringen in Lund. In Kraftringen's grid, active power curtailment is not used today.

Instead, network reinforcement is the standard solution. Overvoltages due to large solar installations are uncommon since most of Kraftringen's grids are relatively strong. In weak parts of the grid, however, large solar installations can take long time to implement due to the need of network reinforcements. ANM solutions designed to reduce the overvoltage issues can therefore be used to avoid reinforcement and to enable more solar power to be installed in the electricity grid at a faster rate.

One possible ANM solution for reducing the need of RES curtailment while handling the overvoltage issue would be to install a battery energy storage system (BESS), designed to relieve the network by absorbing power when the production is high and the consumption is low. Since changes in active power flow have a large impact on voltage in low voltage grids [3], this method should be able to limit the overvoltages, assuming it has large enough power and energy capacity. The BESS can be discharged later in the day, when the PV installation produces less and overvoltage is no longer an issue. The charging and discharging behavior of the BESS can be controlled by a dedicated controller.

Batteries are fast to integrate, compared to grid reinforcements, and can easily be moved to where and when they are needed. In that way, they can be used to avoid or delay grid reinforcements, while still fulfilling consumer demands [9]. Using BESS for voltage control purposes could potentially decrease the need of RES curtailment and improve utilization of the grid. BESS are already in use in the power system today, in Sweden mainly placed behind the electricity meter of customers with PV who want to maximize their self-sufficiency of electricity. There are also some large BESS in operation, designed for purposes such as delay of network reinforcement, peak shaving, frequency control and backup [9].

1.2 Purpose and Research Questions

The purpose of this master's thesis is to investigate whether batteries can play a role in solving the overvoltage issue caused by high PV penetration in LV grids. Furthermore, it aims to investigate how these batteries should be dimensioned and operated, as well as whether they can provide any additional services when not needed for voltage regulation. The research questions that are aimed to be answered are listed below.

- To what extent can batteries help solving overvoltage issues in LV grids with high PV penetration?
- What would be suitable power and energy dimensions for a battery energy storage system with this purpose, and where should it be placed?
- What are the economic benefits of the solution and can the BESS be used for other purposes when no overvoltages are predicted to occur?

1.3 Limitations

This work mainly focuses on the impact on the grid by BESS designed to limit overvoltage. A three-phase symmetric load is assumed and only slow changes in voltage will be examined. Furthermore, the degradation of the battery over time and its impact on the BESS performance are not assessed.

The voltage simulations are performed on an existing part of Kraftringens grid and historical load data of the customers in the grid. In this thesis, the change of different parameters such as line types and BESS placement is examined. However, the results of these simulations can vary depending on the layout of the grid, and future load profiles might look different. Consequently, the results are not necessarily representative for all grids.

Regarding the PV production, it is assumed to be proportional to the incoming solar irradiation on a horizontal surface in Växjö. The actual solar production of a PV unit depends on shading, direction and inclination of the panels as well as location. This is not taken into account in this thesis.

1.4 Related Work

The topic of PV integration in LV grids is popular in research. This work aims to build upon previous work in the area; both Swedish and international.

The interest organization Power Circle has conducted a study aiming to show the potential role of batteries in the future power grid. They identify some barriers such as legislation and a conservative electricity industry but also enlight the benefits of batteries in the electricity grid. These include flexibility in placement and size and possibility to shift load flow [9].

In a master's thesis from LTH, the impact of a large PV penetration in low voltage grids is examined. Simulations show that the outermost buses of a weak network are most sensitive to overvoltages. In 2013 when this thesis was conducted, the asymmetry between phases was an important issue to consider [10]. In Kraftringen's grid, 3-phase connections are recommended [11], which eliminates this problem. Equation 1 is a simplification of the voltage drop along a line in a distribution network, $\overline{\Delta V}$, and its dependency on the active power, P, reactive power, Q, resistance, R, and reactance, X. V_r is the voltage at the receiving end of the line [12]. This simplification is valid for lightly loaded lines, assuming a small phase angle difference between sending and receiving end voltage and $R \approx X$.

$$\Delta V \approx -\frac{RP + XQ}{V_r} \tag{1}$$

As equation 1 shows, the voltage in a node is affected by changes in both active and reactive power. Reactive power control is a common way to handle voltage issues in transmission grids [13]. However, LV networks generally have a low X/R-ratio, which makes the voltage less dependent on reactive power than in higher voltage grids [14]. Reactive power as a tool for voltage control in LV networks has been examined in multiple works, however often combined with other methods [2] [14] [15].

In the doctoral thesis [2], a coordinated voltage control is suggested to deal with overvoltage issues. This method combines an on load tap changer (OLTC) at the transformer station with active power curtailment and reactive power consumption at the PV side of the feeder. The author concludes that reactive power consumption has to be relatively large compared to the active power to have an impact on the voltage in distribution networks, since they have a low X/R ratio. A large flow of reactive power may lead to increased losses in the feeder. The simulations show that active power curtailment can be reduced with the coordinated voltage control methods suggested [2]. However, this requires communication between the network nodes and the substation and the on load tap changer is limited to control voltage for all buses in a feeder at once.

Another study [16] shows promising results of introducing BESS to avoid voltage rise in LV networks. Reactive power control supplied by the PV inverters is suggested to be used combined with BESS in the most critical nodes. The optimal placement and sizing of the storage systems is not taken into account, however is suggested as further research.

In [17], simulations show that batteries in a power system with high PV penetration both has the ability to mitigate voltage rise, as well as undervoltage during the peak load that usually occurs in the evenings in residential areas.

2 Theory

In this section, the theory behind the topic is described in detail. Grid codes, system characteristics, control, battery technology and economic aspects are studied.

2.1 Grid Codes

According to European Standard EN 50160, the feeding voltage in LV grids is allowed to vary ±10 % from nominal voltage. These limits are allowed to be exceeded during a maximum of 5 % of all 10 minute mean RMS values each week [2]. National regulations in Sweden are even stricter, requiring power to be within ±10 % of nominal voltage during all 10 minute mean RMS values in a week. Furthermore, for nominal voltages up to 1000 V, the voltage is not allowed to exceed 135 % of nominal voltage for any time period longer than 10 ms and not allowed to exceed 115 % of nominal voltage during more than 5 s [18].

2.2 Load and Generation in LV Grids

Electricity distribution in Sweden has traditionally been done in a single direction, producing electricity in large power plants such as hydro and nuclear plants. The electricity has been distributed via high voltage lines, through distribution networks and local grids to the end consumer which could be a household for example. This has changed gradually when production changes from large centralized power plants to distributed generation such as PV [2]. In 2019, Sweden had a total installed solar power capacity of 700 MW consisting of 44 000 installations, of which 38 000 had an installed power of 20 kW or below [19]. This size of solar panels are commonly used in residential areas and are connected to the low voltage grid. The prices of grid connected residential solar power systems decreased rapidly from around 60 SEK/W in 2010 to 15 SEK/W in 2015 [20].

The solar irradiation, and consequently the solar power production, varies during the day, as can be seen in Figure 1. The peak power that the solar panels can produce is referred to as the installed capacity and the unit is written as kWp, where the p stands for peak. The production pattern of PV systems can be compared to the consumption pattern of a typical household. The solar power production peaks around noon while the consumption is generally higher in the morning and in the afternoon, mainly due to cooking. As a result, the household owning the PV usually has to buy electricity during morning and evenings and sell during mid-day, assuming they have no BESS installed. The temporal mismatch in consumption and production occurs on a yearly basis as well, which can be seen in Figure 2. When production in a radial network is higher than consumption, the power flow in the feeder will be reversed, and this is when the overvoltage issue can occur.

According to prognoses by the Swedish Energy Agency, the solar power production in Sweden is expected to increase from 0.3 TWh in 2018 to 1.3 TWh in 2022 and possibly 25 TWh by 2040, assuming necessary policy changes are carried out. This means that the points in which overvoltage occurs may increase [9].

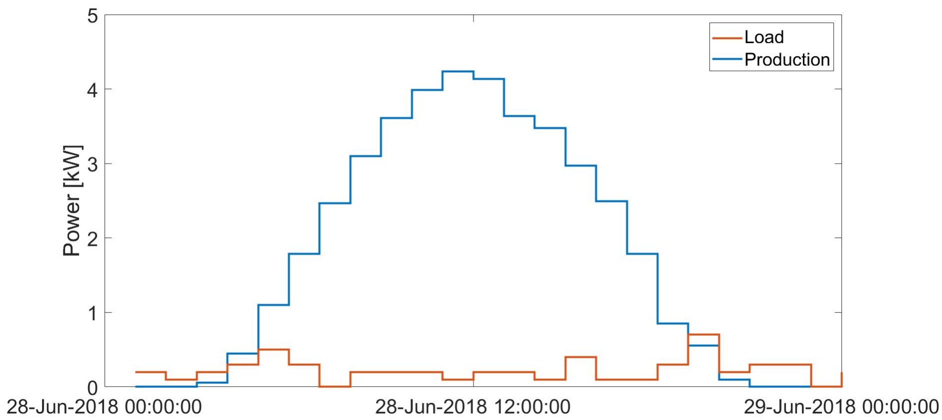

Figure 1: Hourly load and production power profiles for a customer with 5 kWp installed solar power on a sunny day.

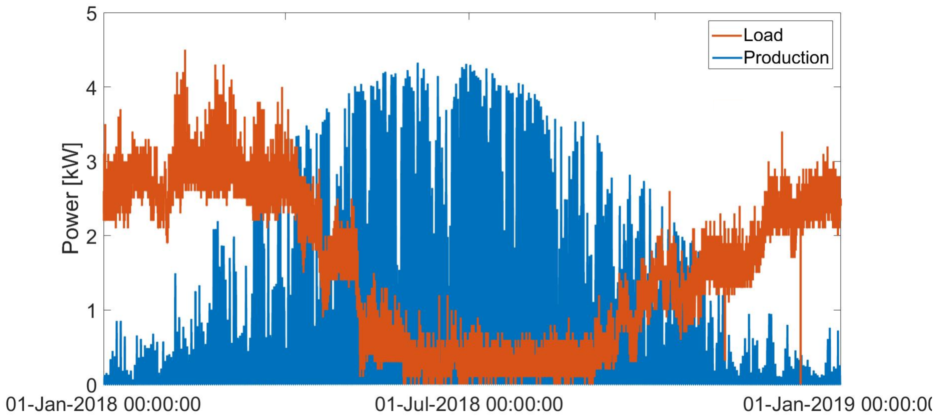

Figure 2: Hourly load and production power profiles for a customer with 5 kWp installed solar power during the year 2018.

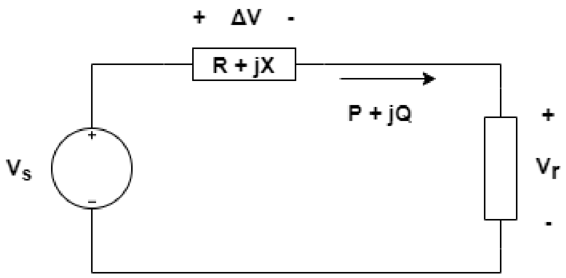

Figure 3: Thévenin equivalent of LV line.

2.3 Voltage Characteristics of LV Grids

A LV line can be represented by a Thévenin equivalent, shown in figure 3 [2]. The voltage V_s at the sending end is assumed to be constant and equal to V_{Th}, one impedance represents the line and one represents the load at the receiving end.

Equation 2 [2] shows the voltage drop, $\overline{\Delta V}$, along the line. This is the non-simplified version of equation 1 introduced earlier. In this equation, the phase angle between voltages at the two ends is taken into account, resulting in a complex expression.

$$\overline{\Delta V} = \frac{1}{\overline{V_r}}((RP_{net} + XQ_{net}) + j(XP_{net} - RQ_{net})) \tag{2}$$

Where R [Ω] and X [Ω] is the resistance and reactance of the line respectively, Q_{net} [var] is the reactive power transfer and P_{net} [W] is the net active power. P_{net} is defined in equation 3, where P_{prod} is the active power production by the PV units and P_{cons} is the active power consumption. The corresponding definition of Q_{ref} is shown in equation 4.

$$P_{net} = P_{cons} - P_{prod} \tag{3}$$

$$Q_{net} = Q_{cons} - Q_{prod} \tag{4}$$

The resulting voltage profile along a line can be seen in Figure 4. The voltage level on the transformer side is usually kept fixed to a value above nominal voltage to compensate for the voltage reduction due to load. This has historically been a reasonable choice since distributed generation used to be less common. Another reason to keep voltage levels close to the upper voltage limit is to reduce losses [2]. However, this choice decreases the margin to the upper voltage limit, leaving only little room for voltage increase caused by reverse power flows (P_{net}<0). By instead adjusting the LV/MV substation (secondary substation) voltage to a value below nominal voltage, it is possible to install more PV without violating the upper voltage limit. Nonetheless, one should be careful not to go below the lower voltage limit during periods of high load and low PV production. Furthermore, the adjustment of setpoint voltage can not be done while the system is energized unless the tap changer is an on load tap changer, which is uncommon today [2].

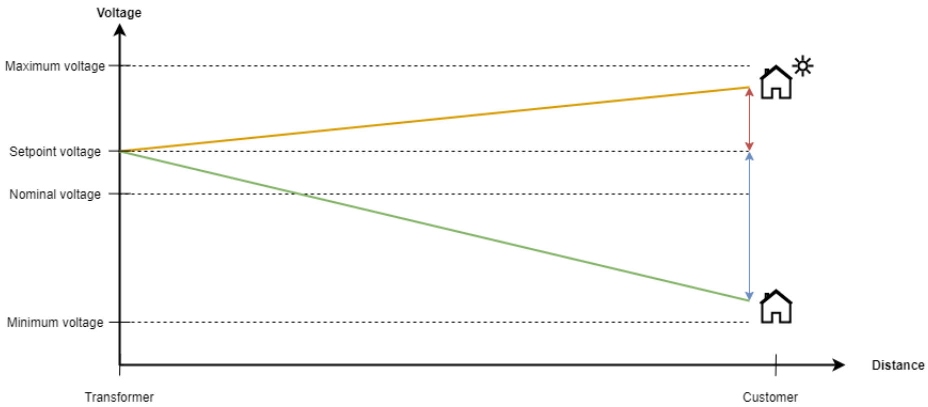

Figure 4: Voltage profile of a distribution line. The yellow line shows the case where P_{net}<0, i.e. when the production is larger than the consumption at the customer and the green line shows the traditional case where P_{net}>0, i.e. when the consumption is larger than the production.

The effect on voltage by a change in active power in a certain node of the network can be represented by a voltage sensitivity factor, $\frac{\partial V}{\partial P}$. The derivation is based on a Thévenin equivalent of the grid connected to the node studied, i.e. $V_s = V_{Th}$. The voltage at the receiving end, $V_R = V$, is the phase reference, meaning it is always real. The voltage sensitivity factor can then be derived from equation 2 according to equations 5 through 11, resulting in equation 12 [2].

$$\overline{\Delta V} = \overline{V_s} - V_r = \overline{V_{Th}} - V \tag{5}$$

$$\implies \overline{V_{Th}} = V + \frac{(RP_{net} + XQ_{net}) + j(XP_{net} - RQ_{net})}{V} \tag{6}$$

assuming a small phase angle we can neglect the imaginary part and get:

$$\implies V_{Th} = V + \frac{(RP_{net} + XQ_{net})}{V} \tag{7}$$

$$\Leftrightarrow V = \frac{V_{Th}}{2} \pm \sqrt{\frac{V_{Th}^2}{4} - (RP_{net} + XQ_{net})} \tag{8}$$

$$\implies \frac{\partial V}{\partial P_{net}} = \pm\frac{1}{2}\frac{-R}{\sqrt{\frac{V_{Th}^2}{4} - (RP_{net} + XQ_{net})}} \tag{9}$$

assuming that $V \approx V_{Th}$, equation 2 and 5 give that $RP_{net} + XQ_{net}$ is small, which simplifies equation 9 to:

(10)

$$\frac{\partial V}{\partial P_{net}} \approx \pm\frac{1}{2}\frac{-R}{\sqrt{\frac{V_{Th}^2}{4}}} \tag{11}$$

$$\Leftrightarrow \frac{\partial V}{\partial P_{net}} \approx \pm\frac{R}{V_{Th}} \tag{12}$$

The voltage sensitivity factors can be calculated for each couple of nodes and can then be combined into a voltage sensitivity matrix shown in equation 13, with elements numbered according to equation 14 [21], where the negative solution of equation 12 was chosen and $P_i = P_{net}$ in node i.

$$\mathbf{S} = \begin{bmatrix} \frac{\partial V_1}{\partial P_1} & \cdots & \frac{\partial V_1}{\partial P_j} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_i}{\partial P_1} & \cdots & \frac{\partial V_i}{\partial P_j} \end{bmatrix} \tag{13}$$

$$S_{ij} = \frac{\partial V_i}{\partial P_j} = -\frac{R_{ij}}{V_{Th}} \tag{14}$$

Where R_{ij} is the resistance between node i and the reference node for $i = j$. For $i \neq j$, R_{ij} is the resistance between the reference node and the first common node of the paths from node i to the reference node and node j to the reference node respectively.

Each element S_{ij} of the voltage sensitivity matrix **S** represents the impact of a change in active power in node j on the voltage in node i. A similar voltage sensitivity matrix can be derived for the impact of reactive power on node voltages [21]. The effect of reactive power on node voltages will not be treated in this thesis.

As a result of equations 13 and 14, the change in active power affects the voltage more for lines or cables with larger resistance. Since resistance depends on line length, nodes that are placed far out in radial grids are more sensitive to both over- and undervoltages (when they overproduce or overconsume respectively). Consequently, a BESS designed to control overvoltage in a weak part of the grid is expected to require smaller power capacity the further out in the grid it is placed.

The X/R ratio is a common way of describing the characteristic properties of lines and cables. The X/R ratio is small for LV grids compared to higher voltage grids. Furthermore, the X/R ratio is usually smaller for cables than for overhead lines [2].

2.4 Avoiding Overvoltage

One of the most simple and common solutions for overvoltage issues is network reinforcement. Network reinforcement means a thicker conductor which reduces the impedance of the feeder, resulting in lower impact from active power injection on voltage. The solution includes both existing feeders and transformers that are reinforced, as well as new ones being built [3].

The OLTC that has been mentioned previously is another solution with large potential to solve voltage issues. The OLTC can adjust the lower voltage level of a transformer without having to de-energize the system. The solution works well if all feeders connected to the transformer have similar loads. Since the secondary substation usually connects to multiple feeders, the control system has to change the set point for all feeders at once, and not only the most critical one. This could lead to overvoltages in some parts of the network at the same time as undervoltages occur in other parts of the network, and is therefore not optimal [3]. Another disadvantage of this method is that the OLTC is exposed to stress causing decreased lifetime of the device [22].

Active power curtailment simply means that some energy is spilled for the purpose to reduce the active power flow from the PV unit and consequently the voltage rise in the connection point. The use of active power curtailment should be limited since it leads to lower utilization of the installed PV capacity. However, the method does come with some benefits. For example, it allows PV and other DG to be installed without delay caused by network reinforcement or other installations. It could even be cost-effective from the PV owners' point of view [2].

The method proposed in this thesis aims to take advantage of the many benefits of active power curtailment, however not by spilling the energy but by storing it for later use.

2.5 Automatic Control

Droop control is a commonly used grid frequency control method for the sharing of load between generation units. The frequency can be controlled through active power and the voltage can be controlled through reactive power. However, as reactive power has less impact on voltage in LV grids, more advanced droop based methods are often developed for use in LV grids [14].

In this thesis, a PI control method is used as an alternative to droop control, to control voltage. The PI controller is the most common type of controller in industry application. It is known to deal well with oscillations and leaves no stationary error. The PI controller has a proportional and an integral feedback term, resulting in the control signal, u, defined in equation 15 [23].

$$u = K_p e(t) + K_i \int e(\tau) d\tau \tag{15}$$

Where K_p and K_i are proportional and integral gain respectively and e is the error term, i.e. the difference between measured voltage and setpoint voltage. The input to the PI controller could in this application be a node voltage (V_r in equation 2) and the output a signal telling a battery to charge or discharge at a certain power, changing P in equation 2 which in turn will affect the voltage drop along the line and restore the voltage to the setpoint value.

2.6 Battery Energy Storage Systems

Battery energy storage systems are fast power resources. Studies have shown that batteries can respond as fast as within 0.1 seconds, and reach maximum power output within 0.2 seconds [24]. Today, BESS are primarily used by private customers for backup or electric mobility. In Germany, BESS also play a role on the frequency control market. The role of BESS in the power system is predicted to increase due to the many services they can provide, such as frequency reserves and voltage control. Some of these potentials are however limited due to legislation not being adapted to the new technologies [24].

Commonly used types of batteries for private energy storage from PV are Li-ion batteries such as the lithium iron phosphate ($LiFePO_4$) type manufactured by German company sonnenBatterie that is offered to customers of Kraftringen [25]. Li-ion batteries are preferable since they have large energy density and high efficiency (80-90 %) compared to other battery types [26]. In 2016 the Swedish Energy Agency supported the construction of a large scale Li-ion battery factory in Sweden by SGF Energy AB (now re-branded as Northvolt) by offering a loan of 19 MSEK. They identify the technology as an important part of future electromobility, storage of renewable energy as well as ancillary grid services [27].

A company in the forefront of electromobility combined with renewable energy storage is Tesla, offering the product Tesla Powerwall which is a home BESS solution designed to store PV output and use for smart charge of electrical vehicles. The system has a storage capacity of 13.5 kWh and a rated power of 7 kW (peak) / 5 kW (continuous) [28]. This is considerably larger than the common storage capacity of residential BESS in Sweden (which is around 4-9 kWh) [29]. This can be compared to the batteries of electric vehicles which have capacities of up to 100 kWh [30].

The number of electric vehicles in Sweden is expected to increase from 100 000 in 2020 to 2.5 million in 2030. The power consumption peaks occurring when these are charged can lead to problems in LV networks, however the large battery capacity that these sum up to might also be a valuable resource regarding flexibility [9].

Battery prices have decreased significantly during the past years. In 2007, the price per kWh was above 1 000 USD and in 2020 this has decreased to around 150 USD/kWh. According to forecasts, the prices will go below 100 USD/kWh in 2025, assuming a global fleet of 60 000 000 electric vehicles [31]. Other predictions are more restrictive, predicting a decrease from 375 USD/kWh in 2020 to between 75 and 300 USD/kWh in 2050. That prediction is based on 4-hour Li-ion batteries, i.e. batteries that take 4 hours to discharge at full capacity [32].

Li-ion batteries degrade over time at a rate depending on many factors. These include ambient temperature, charging patterns and depth of discharge. It has been shown that their lifetime can be significantly increased if they are not exposed to very low SOC levels [33].

In the simulations of this thesis, BESS will be used to store energy in order to keep the voltage within the allowed interval. In order for this to work, both the energy rating and the power rating of the BESS have to be large enough. This is to ensure that the BESS is never fully charged when it is needed for downregulation of voltage (energy capacity), and to make sure that the BESS can charge at a fast enough rate in these situations (power capacity). Both power and energy dimensions influence the cost of the BESS, which is why these two key properties should be minimized.

2.7 Economy and Swedish regulations

2.7.1 Key players

To understand the potential economic benefits of installing BESS in a LV grid, one has to understand the roles of the different parties involved in the pricing of electricity and ancillary services. Some of these roles are transmission system operator, balance responsible parties, provider of balance services, aggregator, electricity retailer, distribution system operator (grid owner), customers, and microproducers.

- The transmission system operator in Sweden is Svenska kraftnät. In addition to operating the transmission grid, they have overall system responsibility, which includes managing the physical power balance [34].

- The balance responsible party has a responsibility to buy the same amount of energy that their consumers use. The trading of electricity takes place on the marketplace NordPool where the main part of electricity trade is done the day before consumption, on the day-ahead market. Mismatch between consumption and production affects the system frequency. Therefore, the balance responsible party has to pay a fee to Svenska kraftnät proportional to the difference between bought and sold electricity if they fail to balance these. The balance responsible party can also place bids on Svenska kraftnät's balance market to provide balance services.

- A new role, provider of balance services, will be introduced in 2021 [24]. This will make it possible for parties, such as aggregators, who are not balance responsible parties to place bids on the balance market of Svenska kraftnät without going through the balance responsible party. This opens up for aggregated balancing services from different bidding areas and balance responsible parties.

- An aggregator is a company that collects multiple flexible resources, such as BESS, and sell the services that these resources can provide. The aggregator opens up the possibility for small flexibility resources such as small scale BESS to indirectly be part of the balance market, even though they are too small to make up an entire bid themselves. Aggegators can also collect and provide voltage control services.

- The electricity retailer buys electricity on NordPool and sells it to the customers. The electricity retailer does not consider grid capacities and has the right to sell electricity to any customer in Sweden, regardless of physical location. The electricity trading company are obligated to have the role of balance responsible party, or to have a contract with an external company who serves as balance responsible party.

- The grid owner or DSO refers to the owner of the grid connecting to the customer. The grid owner in the case of this project is Kraftringen Nät. The grid owner has a responsibility to connect all consumers or producers who apply for connection unless special circumstances exist.

- The customer is an individual or a company who produces or consumes electricity. A customer doing both of these is sometimes called a prosumer. The customer can own grid connected PV installations and BESS.

- A microproducer is an electricity producer who has a fuse size of a maximum of 63 A, produce at a maximum power of 43.5 kW and whose net electricity consumption during a year is larger than the net electricity production [35].

2.7.2 Ownership

An important aspect to consider when determining the economic benefits of a BESS is ownership, i.e. if the BESS is owned by a consumer, the DSO or a third party. Currently, DSOs in Sweden are only allowed to own and operate BESS if they are fully integrated network components [9]. These regulations are set up with the purpose to avoid that BESS become part of the natural monopoly that the grid owners have. It has been suggested that grid owners buy the ancillary services that BESS can provide instead of buying the physical BESS. However, the incentives of investing in physical solutions rather than services are still dominating [9]. The ownership of the battery is also an important factor to the safety aspect. It is yet to be clarified who is responsible for how the battery should be operated when the grid is not in normal operation.

2.7.3 Grid connection

When a new connection is made to the grid, the connecting customer has to pay a fee to the grid owner corresponding to the fuse size they need and the distance to the closest secondary substation. The fuse size has a rating corresponding to the maximum current allowed to flow through it. Therefore the customer needs a larger fuse size if they at any time plan to use power corresponding to a current exceeding the fuse size. The fuse size may be changed when consumption and/or production patterns change [36]. The change in fuse size might result in a need for network reinforcement. The costs of this directly related to the connected customer will be paid by the customer. Costs related to reinforcement further upstream in the grid which are of benefit for multiple customers are paid by the grid owner [7]. A larger fuse size also means a higher yearly cost to the grid owner [37]. This makes fuse size an important aspect to consider when dimensioning solar power installations.

2.7.4 Electricity price

The price that a customer pays for their electricity in Sweden can generally be divided into market costs, grid costs and taxes. The market cost covers production and trade of electricity and is controlled by supply and demand [38]. Electricity retailers buy electricity from the NordPool market and sell to their customers [39]. The market is de-regulated which means that the electricity retailers compete and can sell to any customer in the country regardless of geographical location [40]. However, the prices can differ between the four bidding areas that Sweden is divided into due to transmission bottlenecks. The market costs cover about 30 % of the total costs paid by the customer [38].

The grid costs are paid to the owner of the physical grid where the customer is located. This cost covers operation, maintenance and reinforcement of the grid and makes up about 25 % of the total costs paid by the customer. The grid price is monitored by the Swedish Energy Markets Inspectorate to make sure that no grid owner takes advantage of their monopoly situation [38]. In Kraftringen's grid, the grid tariff is based on fuse size [41].

The tax part of the electricity price consists of a value-added tax and energy tax. The energy tax for 2020 is 35.3 öre/kWh, with a few exceptions in the north of Sweden where the energy taxes are reduced [42]. The value-added tax is 25% of the sum of market costs, grid costs and energy tax. In total, the price that consumers pay consists of about 45 % fees and taxes [38]. In essence, all parts of the electricity price are based on energy consumption, i.e. the total consumption in kWh. Some parts are based on hourly rates or seasonal rates

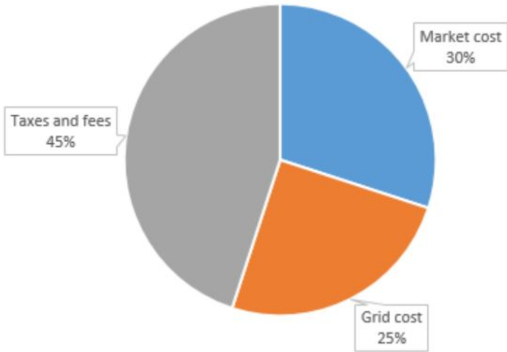

Figure 5: The approximate ratio between the different parts of the electricity price paid by private electricity consumers in Sweden.

while others are constant throughout the year. The approximate ratio of the different costs can be seen in Figure 5 [38].

As for the selling of surplus energy by consumers with PV installations, the income consists of one part from the grid owner and one from the electricity trading company. The electricity retailer usually pays the microproducer hourly NordPool spot prices and sometimes adds a bonus to encourage people to invest in solar power [43]. Kraftringen does this when the customer has bought the solar installation through Kraftringen. They pay spot price plus 50 öre/kWh for installations smaller than 10 kW, spot price plus 25 öre/kWh for installations between 10 kW and 20 kW and spot price for installations exceeding 20 kW, all including value-added tax [44].

The grid owner compensates the PV producer for the losses avoided by producing electricity locally instead of transporting it long distances, as well as for the transmission of electricity that no longer has to be bought by the regional grid owner. As a microproducer, one could also receive a tax reduction of 60 öre/kWh of the sold electricity [43]. The tax reduction is applicable for producers of renewable energy with production and consumption in a common grid connection point and a maximum fuse size of 100 A. The tax reduction is only applicable for a maximum production of 30 000 kWh/year and where the net consumption is larger than the net production on a yearly basis [35].

Another possible income for PV owners is through electricity certificates. The market for electricity certificates has existed in Sweden since 2003 [45], and since 2012 Sweden and Norway have a common market for electricity certificates [46]. The system was introduced to promote renewable power generation by giving out electricity certificates to producers of renewable energy who are then able to sell the certificates on an open market. The buyers are electricity trading companies, energy-intense industries and other parties with quota obligation. The quota obligation means they are obligated to buy a certain amount of electricity certificates depending on their electricity sales or electricity use. The producer has the opportunity to get one electricity certificate for each MWh of produced and measured electricity [45]. The prices are set by supply and demand and have decreased significantly since the launch of the system [47]. According to the Swedish Energy Agency, an average household PV installation can generate electricity certificates corresponding to 220 SEK/year [48]. Because of the low market prices, it is uncommon that owners of small scale PV installations apply for electricity certificates. Most electricity meters only measure net power, meaning that the share of solar power that the household consumes itself is not recorded. Adding a meter able to measure the total production comes with an extra cost, resulting in even lower profitability [43].

2.7.5 Avoided Expenses and Additional Benefits

Active power curtailment is not used in the grid owned by Kraftringen today. The economic benefit of BESS as a solution for overvoltages for Kraftringen would rather be to avoid or postpone network reinforcement. This is particularly interesting when a line or grid component has to be replaced before reaching its technical and economical lifetime, due to new connections of PV installations. [37]

Since voltage control by active power absorption by BESS is mostly needed on days with large PV production and low consumption, a BESS installed for this purpose might be unused during large parts of the year. Therefore, the possibilities of additional services that the BESS can provide during periods of uncritical voltage levels should be considered. Frequency control is one of the most promising of these services.

To keep frequency within the accepted range of 49.9-50.1 Hz, the power system has to be balanced, i.e. the total production and consumption in the system has to be equal at any given time. With a larger ratio of non-dispatchable power generation in the system, this task is increasing in complexity [13]. The TSO Svenska kraftnät is responsible for the overall balance of the Swedish transmission system, however the balance responsible party is responsible of not selling more electricity than they are buying [34]. Svenska kraftnät has several markets for ancillary services such as frequency restoration where balance responsible parties can place bids where they offer the service of either increasing or decreasing the net power flow from the transmission system. There are different markets for different purposes, such as fast or slow responding resources [13].

The most realistic scenario for small scale BESS owners to participate in the frequency control market is by selling the service of an available BESS to an aggregating party, who in turn will place an aggregated bid, for example on the FCR-N market. The benefit of involving an aggregator is that the bids on the FCR-N market have to exceed 100 kW (in both directions, so a BESS would have to be 200 kW), which is larger than most residential BESS [43]. As of today, only balance responsible parties are allowed to place these bids, however the new role of provider of balancing services will allow aggregating parties not entitled balance responsible to place bids on the market. As participant on the FCR-N market, one has to be able to decrease or increase production within 1 minute, at a certain power for a certain time [13]. Both power and energy dimensions therefore play a role. The FCR-N market is open during the two days before the day of operation [49] and bids are placed in hourly intervals. The resolution time is planned to be decreased to 15 minute intervals in 2023. This is thought to lead to a more fair pricing of ancillary services [13]. The payment to the actor delivering the service is divided into one part for the called capacity and another for the actual energy used [49]. Svenska kraftnät has identified the need of a frequency reserve that can respond even faster than the FCR. The service is called fast frequency reserve (FFR) and came into operation in 2020. The FFR is designed to handle low frequencies that often occur during nights in the summer [13]. This could also be an option in order to gain additional income from the BESS when it is not needed for voltage control.

Energy arbitrage, i.e. to take advantage of changes in the NordPool spot price is an option that is not very profitable for small scale BESS with the pricing model of today. It could however be an option for the scenario when a BESS is installed but is not being used for any other service at the time [43].

As mentioned before, the grid costs for Kraftringens' customers are based on fuse size, up to 200 A. Installing a BESS in the system could lead to the possibility of lowering the fuse size and thereby get a lower grid cost [50]. In the future, the fuse size-based billing is planned to change in to a peak power-based billing instead. This would result in lower grid costs for customers using a BESS for power peak shaving, without the need of changing fuse size. [37]

2.8 Measurements and Communication

In order to control the voltage, it has to be measured. Voltage measurements at each customer are not standard in Kraftringen's grid today. However, within the upcoming years all electricity meters will be replaced by more capable ones able to measure both power and voltage at a much higher sample rate than the older meters as well as with a standard interface for real-time data. In the case where the controlled quantity is measured in the same network node as a BESS is placed in, no external communication will be needed, which simplifies the situation further [51].

3 Method

In this section, the methods used to build a case study model in Simulink and to conduct simulations are described.

3.1 Case Study Network

In order to determine whether BESS as a solution for overvoltage could be viable, a section of Kraftringen's grid was chosen to conduct simulations upon. In this section, this model network is introduced in detail. The case study network is located in a rural part of Kraftringen's grid and has four customers referred to as customer A, B, C and D, connected by underground cables. The customers have no PV installations or BESS today, meaning their load profiles represent electricity consumption only. Different combinations of PV installations and BESS are added and the impact on the grid will is examined. The layout of the grid is shown in Figure 6.

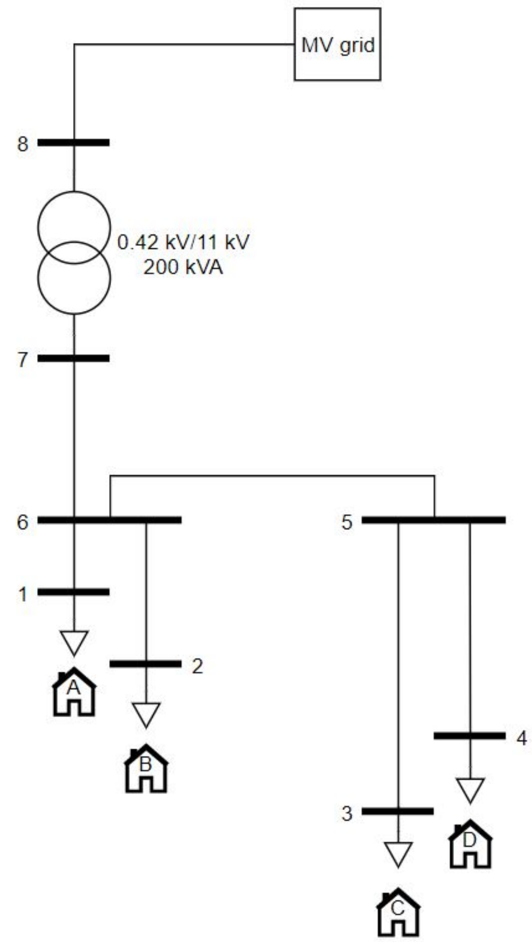

Figure 6: Layout of case study network.

The known parameters of the grid are:

- Rated voltage levels of transformer (0.42 kV/11.0 kV).
- Rated power of transformer (200 kVA).
- Cable resistances of all LV lines (see table 1).
- Cable inductances of all lines at the LV side of transformer (see table 1).
- Cable capacitances of all lines at the LV side of transformer (see table 1).
- Line lengths of all lines at the LV side of transformer (see table 1).
- Customer load profiles (hourly values) for customer A, B, C and D for the time period 2017-01-01 - 2020-10-31.
- Hourly values of solar irradiation at nearest SMHI measurement station (Växjö, station 64565) [52] for the time period 2017-01-01 - 2020-10-31.

Table 1: Cable data for the case study network.

From bus	**To bus**	**Cable type**	**L [mH/km]**	**C [μF/km]**	**R [Ω/km]**	**Length [m]**
7	6	N1XE 4G150Al	0.23	0.63	0.206	295
6	1	N1XV 4G10Cu	0.29	0.32	1.83	17
6	1	N1XE 4G50Al	0.24	0.56	0.641	79
6	5	N1XE 4G95Al	0.23	0.65	0.32	227
6	2	N1XE 4G50Al	0.24	0.56	0.641	46
5	3	N1XV 4G10Cu	0.29	0.32	1.83	97
5	3	N1XE 4G10Cu	0.29	0.32	1.83	23
5	4	N1XE 4G50Al	0.24	0.56	0.641	82

3.2 Implementation in Simulink

3.2.1 Model

The simulation model was implemented in Simulink as a compilation of work by Ahmet Elmas [53] and Jonathan LeSage [54], combined with the author's own work. The PV block is created by Ahmet Elmas and modified by the author. The bus measurements and MV grid representation are also inspired by Ahmet Elmas. The BESS and load blocks are created by Jonathan LeSage. The assembly of these blocks as well as other parts of the system are the author's own work.

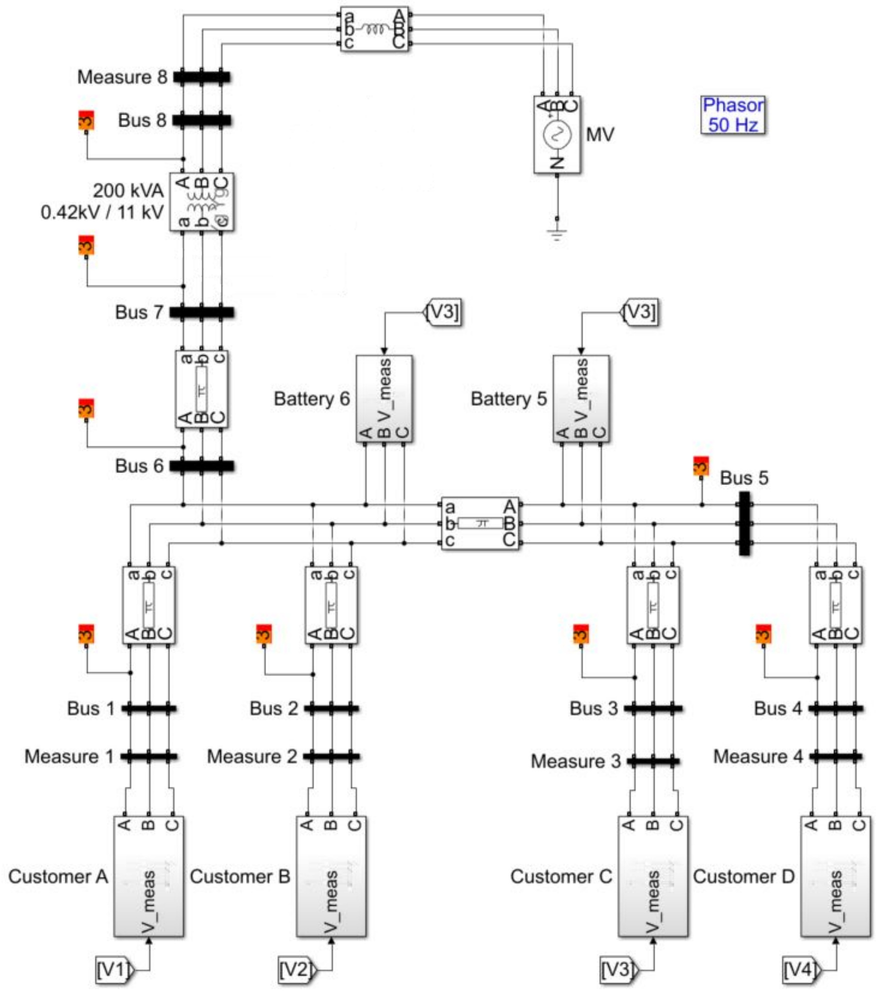

Figure 7: The case study network implemented in Simulink.

An overview of the Simulink model is shown in Figure 7. The system consists of a signal domain and a three-phase symmetric power domain. The electrical part of the system is a 50 Hz, three-phase system consisting of the overlying MV grid represented as a Thévenin equivalent, a 0.42 kV/11 kV 200 kVA transformer, lines, buses, simple three-phase loads, battery inverters and PV inverters. These components are created with the Simscape library in Simulink and can be identified as lines with square-shaped connections in Figure 7. The signal part of the system consists of mathematical signals between blocks and can be identified as lines with arrows in Figure 7. The orange buses are load flow buses necessary to obtain initial values for the simulation. The block that states "Phasor 50 Hz" is a mandatory powergui block, defining the type of simulation to be conducted.

The lines are represented by π-sections which is a common way of modeling the impact of resistance, inductance and capacitance of power lines.

The Thévenin equivalent of the MV grid consists of a voltage source and a series inductance. The series impedance is calculated using equation 16, where the short-circuit current I_{SC} is a known measurement.

$$L_{grid} = \frac{Z_{grid}}{2\pi f} = \frac{V_{LN,grid}}{I_{SC} 2\pi f} \tag{16}$$

The four customer subsystems are identical and one of them is shown in Figure 8. The electrical system connects to a load, a storage unit and a PV installation. The load block draws active power corresponding to the load profile. The PV installation produces active power defined by the solar irradiation and installed PV capacity. The BESS block can either draw or produce active power by charging or discharging respectively. A PI controller placed with the BESS defines the power flow from the battery. The output information from the BESS is the power it absorbs and its state of charge (SOC).

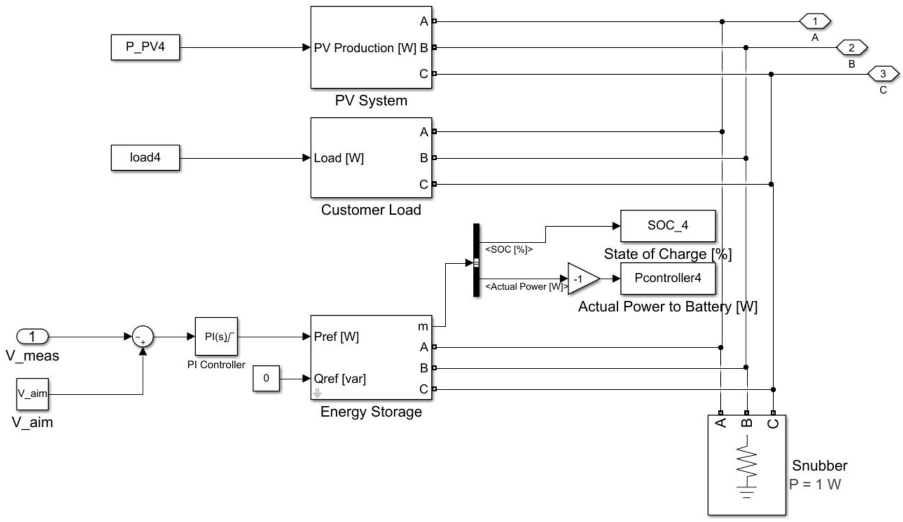

Figure 8: The contents of one of four customer blocks. The block includes load, production and energy storage in the node. The snubber is necessary in order for the currents to be modeled correctly.

Battery blocks are also placed in the two buses representing cable cabinets (bus 5 and 6) that connect two customers each. In a case where there is only one BESS installed in the system, all other BESS are set to 0 kWh storage capacity, which is equivalent to having no BESS in those locations. Similarly, one or more PV installations can be set to 0 kW installed capacity to represent a household with no PV production.

The BESS block can be seen in detail in Figure 9. In the Power Limits block, the absolute value of the power into the BESS is limited to the rated power of the BESS. In the Charge Limits block, the charging is interrupted if the state of charge is exceeding the upper charging limit, and similarly with the lower charging limit. The output of this block is the active and reactive power to (negative) or from (positive) the battery. The reactive power is set to zero throughout all simulations. The signals enter the Stored Energy Calculation where the power is integrated over time to obtain the stored energy of the

BESS. This is then related to the energy storage capability of the BESS, and the output signal is the state of charge of the BESS. The upper bus extracts the measured quantities, SOC and active power. The simple battery inverter converts the active and reactive power signals to physical signals in the Simscape domain.

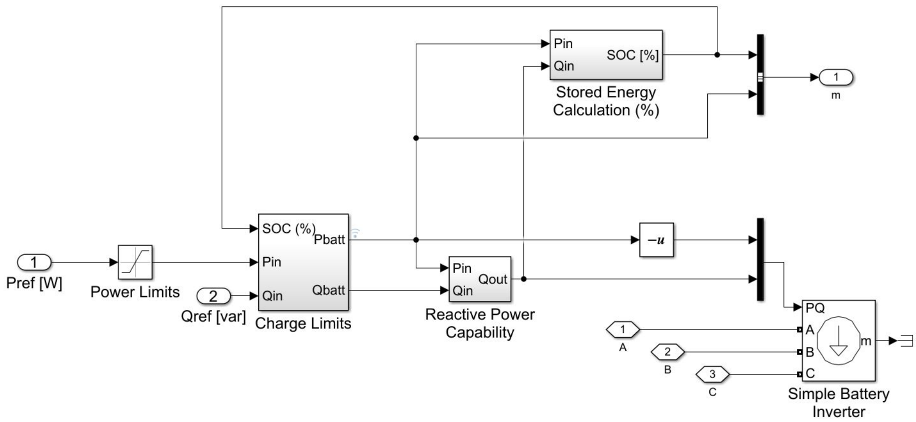

Figure 9: BESS block in the model. These blocks are both placed at each customer as well as in nodes 5, 6 and 7 respectively.

The PV block can be seen in detail in Figure 10. The voltage source converter (VSC) block converts the power signal to voltage phase signals which in turn are connected to a controlled voltage source (CVS) where the voltage signal is converted into a physical signal in the Simscape domain.

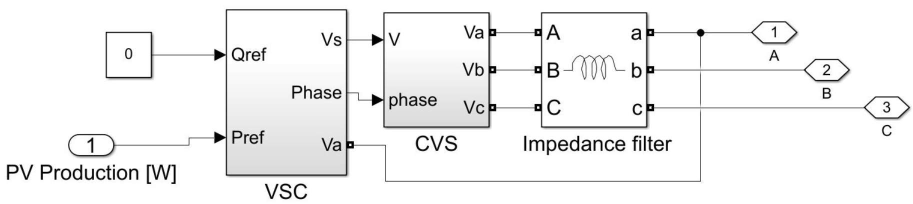

Figure 10: Photovoltaic system block converting the production signal to a physical signal in Simscape.

The load block can be seen in detail in Figure 11. It consists of a simple three-phase load and a dynamic load control. The dynamic load control converts the input power defined in the customer load profile to P and Q values, given the power factor. The simple three-phase load converts the PQ signal to a physical signal in the Simscape domain.

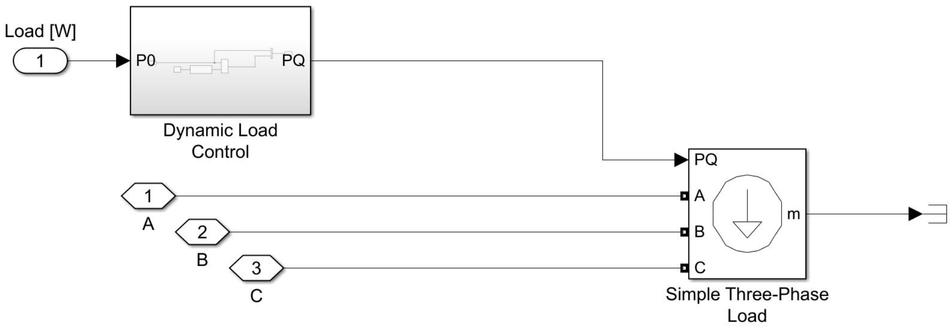

Figure 11: Load block converting the load signal to a physical signal in Simscape.

3.2.2 Voltage Control

The control system was implemented as an ideal PI controller aiming to minimize the difference between setpoint voltage and measured voltage, i.e. to minimize the error term e of equation 15, by controlling the power input to the BESS. The power output from the controller was limited by the BESS power capacity.

3.2.3 Solver

The built in solver "ode23t" (Trapezoidal rule) in Simulink was chosen for solving the system. It was chosen as a compromise between accuracy and speed.

3.2.4 Assumptions

For the model to be fully defined, the following assumptions were made:

- The overall system efficiency of the BESS was 100 %.
- The upper charge limit of the BESS was 100 % and the lower charge limit was 0 %.
- The maximum charging and discharging power of the BESS were equal.

3.3 Voltage Sensitivity Matrix

The voltage sensitivity matrix of the case study network was calculated using equation 13, and is presented in 17. The unit is $\frac{\text{V}}{\text{kW}}$. The voltage sensitivity matrix is a theoretical representation of how much the voltage (in the unit V) in node "row number" changes per kW change in drawn active power in the node "column number".

$$\mathbf{S} = \begin{bmatrix} -0.339 & -0.145 & -0.145 & -0.145 & -0.145 - 0.145 \\ -0.145 & -0.215 & -0.145 & -0.145 & -0.145 - 0.145 \\ -0.145 & -0.145 & -0.841 & -0.318 & -0.318 - 0.145 \\ -0.145 & -0.145 & -0.318 & -0.443 & -0.318 - 0.145 \\ -0.145 & -0.145 & -0.318 & -0.318 & -0.318 - 0.145 \\ -0.145 & -0.145 & -0.145 & -0.145 & -0.145 - 0.145 \end{bmatrix} \tag{17}$$

3.4 Simulation

A load flow analysis was performed in Simulink in order to find appropriate initial values. The resulting voltages were applied as the initial values for all simulations. All simulations were made with a sample time of 0.25 hours. Although the input data consisted of hourly values, the shorter sample time enabled a faster response from the PI controller. The choice was based knowing that future electricity meters will be able to measure at shorter sample times [51].

3.4.1 Worst Case Scenario

In order to find a the worst day, i.e. the day with the largest BESS needed, an initial base case with 30 kW installed solar power at each of the four customers was established. This installation size was chosen because it provoked overvoltage at one customer but not the others. The voltage sensitivity matrix presented in 17 showed that customer C was most sensitive to overvoltage due to active power injection. An oversized BESS was thereafter placed at customer C. A simulation was then performed over the entire dataset and the power input to the BESS as well as the stored energy in the BESS were measured at each time step. The necessary power and energy storage capacities were determined by finding the maximum power to the BESS and maximum stored energy during the simulation time. The maximum power and energy storage volume were identified to occur on 2020-06-07 and 2018-06-05 respectively. The maximum power of 2018-06-05 was only exceeded on nine occasions during the simulation over the entire dataset. Therefore, 2018-06-05 was chosen as a worst case scenario and used for further simulations instead of running the simulation across the entire dataset every simulation. This was done to save time during simulations. The consumption and production of customer C this day are presented in Figure 12.

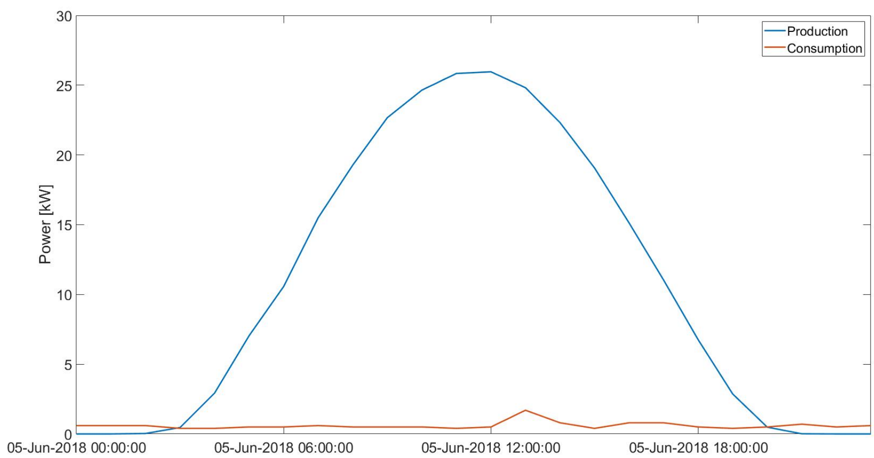

Figure 12: Production and consumption profile of customer C on the day where the highest power input is requested of the BESS.

3.4.2 Simulation Cases

Each simulation was performed in two steps. Initially, the BESS power and energy capacities were deliberately oversized and one simulation was performed to identify the maximum charging power needed from the BESS in order to never saturate the PI controller output. At this point, the BESS was allowed to discharge at a higher power than the charging power. In order to minimize the power capacity of the battery, in the second step, the charging and discharging power of the BESS were limited to the maximum charging power from step one and the simulation was repeated. From the second step, the minimum energy storage capacity needed in order to never hit the minimum and maximum SOC could be determined. A summary of all simulation cases is presented in table 3.

Determine K_p and K_i: Simulation case A was performed first in order to determine the gain (K_p and K_i) values for the other simulations. K_p was varied between 20 000 to 60 000 in steps of 20 000 and K_i was varied between 500 and 1500 in steps of 500. One simulation was performed for each possible combination of these parameters and the voltage was plotted.

Determine control performance: The control performance was determined by comparing the results of simulation case C with 30 kWp at each customer and a battery in node 3, to the same case with no battery in the system.

Impact of PV capacity on BESS: Simulation case B and G were performed in order to determine the impact of installed PV power on the BESS dimensions in node 3. In case B, only customer C had PV installations and a BESS. The installed PV power was varied between 45 and 100 kWp in steps of 5 and the resulting power and energy dimensions were plotted. In case G, all four customers had PV installations, and only customer C had a BESS. All PV installations were simultaneously varied between 20 and 40 kWp installed power in steps of 5 kW.

Impact of battery placement on capacity of BESS: Simulation case C served as one of the cases used to determine the BESS dimensions needed depending on where in the network the BESS was placed. In simulation case D, the BESS was moved to node 5 and the PV power was varied in the same way as for case C. Simulation case E was performed accordingly, but with the BESS in node 6. For simulation case F, one BESS was placed in node 3 and one in node 4. The resulting BESS dimensions were recorded for both of the BESS for the same intervals of installed PV power as in cases C, D and E.

Impact of line parameters on capacity of BESS: Simulation case H was performed in the same way as case G, with altered line parameters to represent overhead lines instead of underground cables. The inductance was assumed to be 0.25 mH/km and capacitance 0.01 Ω/km for all lines. The resistance for a common overhead line with dimensions 4x95 mm^2 was looked up to be 0.32 Ω/km. The resistance was assumed to be inversely proportional to the cross-section area of the line which resulted in the parameters presented in table 2.

Time period needed for voltage control: Simulation cases I and J were performed in order to determine during what time periods on both a yearly and a daily basis that a BESS in node 3 was used for voltage control. For case I, the installed PV was 30 kWp at each of the four customers. In case J, the same total power of 120 kWp was concentrated to only customer C.

Table 2: Altered line data for the network, designed to represent a change from underground cables to equivalent overhead lines.

From bus	**To bus**	**Line dimensions [mm^2]**	**L [mH/km]**	**C [μF/km]**	**R [Ω/km]**	**Length [m]**
7	6	4x150	0.25	0.01	0.20	295
6	1	4x10	0.25	0.01	3.04	17
6	1	4x50	0.25	0.01	0.61	79
6	5	4x95	0.25	0.01	0.32	227
6	2	4x50	0.25	0.01	0.61	46
5	3	4x10	0.25	0.01	3.04	97
5	3	4x10	0.25	0.01	3.04	23
5	4	4x50	0.25	0.01	0.61	82

Table 3: Summary of all simulation cases performed.

Case	Simulation period	PV production	BESS placement	Control parameters	Line properties	Research purpose
A	2018-06-05	A: 30 kWp B: 30 kWp C: 30 kWp D: 30 kWp	Node 3	K_p = 20000-60000 K_i = 500-1500	Original	Control performance
B	2018-06-05	A: 0 kWp B: 0 kWp C: 45-100 kWp D: 0 kWp	Node 3	$K_p = 40000$ $K_i = 1000$	Original	PV penetration
C	2018-06-05	A: 30-60 kWp B: 30-60 kWp C: 30-60 kWp D: 30-60 kWp	Node 3	$K_p = 40000$ $K_i = 1000$	Original	PV penetration, BESS placement, control performance
D	2018-06-05	A: 30-60 kWp B: 30-60 kWp C: 30-60 kWp D: 30-60 kWp	Node 5	$K_p = 40000$ $K_i = 1000$	Original	BESS placement
E	2018-06-05	A: 30-60 kWp B: 30-60 kWp C: 30-60 kWp D: 30-60 kWp	Node 6	$K_p = 40000$ $K_i = 1000$	Original	BESS placement
F	2018-06-05	A: 30-60 kWp B: 30-60 kWp C: 30-60 kWp D: 30-60 kWp	Node 3 and 4	$K_p = 40000$ $K_i = 1000$	Original	BESS placement
G	2018-06-05	A: 20-40 kWp B: 20-40 kWp C: 20-40 kWp D: 20-40 kWp	Node 3	$K_p = 40000$ $K_i = 1000$	Original	Line parameters
H	2018-06-05	A: 20-40 kWp B: 20-40 kWp C: 20-40 kWp D: 20-40 kWp	Node 3	$K_p = 40000$ $K_i = 1000$	Overhead lines	Line parameters
I	2017-01-01-2020-10-31	A: 30 kWp B: 30 kWp C: 30 kWp D: 30 kWp	Node 3	$K_p = 40000$ $K_i = 1000$	Original	Availability for additional services
J	2017-01-01-2020-10-31	A: 0 kWp B: 0 kWp C: 120 kWp D: 0 kWp	Node 3	$K_p = 40000$ $K_i = 1000$	Original	Availability for additional services

4 Results

In this section, the results of the calculations and simulations described in the previous section are presented.

4.1 Case A and C: Control Performance

The results of simulation case A for a step in PV production that causes overvoltage that the PI controller must handle are shown in Figure 13. The parameters for further simulations were chosen to be $K_i = 1000$ and $K_p = 40000$ (green line in figure 13), as a compromise between response time and overshoot. The voltage control performance of simulation case C can be seen in Figure 14. The case with a controlled BESS at customer C is compared to an identical case without any BESS placed in the system.

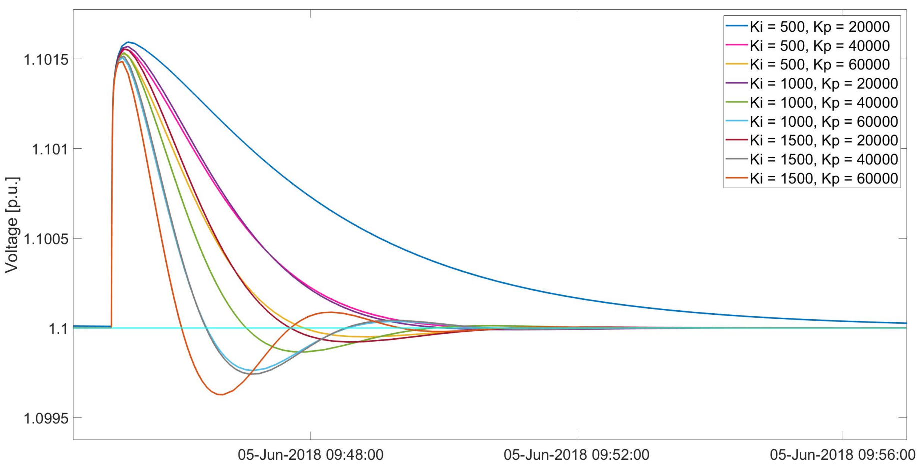

Figure 13: The voltage at customer C when the PI controller detects an overvoltage and restores it to the setpoint of 1.1 p.u. The different colored lines correspond to different combinations of proportional and integral gain. The green one with K_i=1000 and K_p=40000 was chosen for further simulations. The time axis starts at 05-Jun-18 09:44:30.

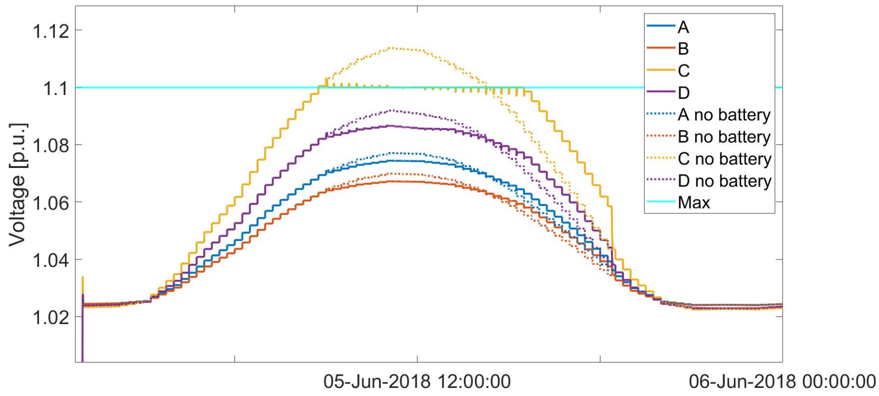

Figure 14: Voltage at customer A, B, C and D when a controlled BESS is placed at customer C (solid lines, simulation case C with 30 kWp at each customer) compared to the case where no BESS is placed in the system (dotted lines). Note that the PI controller is symmetric, i.e. both downregulates overvoltage and upregulates undervoltage. Upregulation of undervoltage in practice corresponds to a discharge of the battery and is done to make sure the BESS has charging capacity left for future overvoltage. The time axis starts at 05-Jun-2018 00:00:00.

4.2 Case B and G: PV Penetration

The resulting power and energy dimensions for a BESS placed at customer C with different sizes of installed PV at each customer (simulation case G) can be seen in Figure 15. The corresponding results for installed PV only at customer C (simulation case B) are presented in Figure 16.

4.3 Case C, D, E and F: BESS Placement

The results of simulation case C, D and E can be seen in Figure 17. The results of simulation F, where BESS were placed in both node 3 and 4 are presented in Figure 18.

4.4 Case G and H: Overhead Lines vs Cables

The results of simulation case G (cables) and H (overhead lines) can be seen in Figure 19 and 20. Figure 19 shows the necessary power dimensions needed for a BESS placed in node 3 with the original underground cables compared to overhead lines, and Figure 20 shows the necessary energy dimensions for the same scenarios.

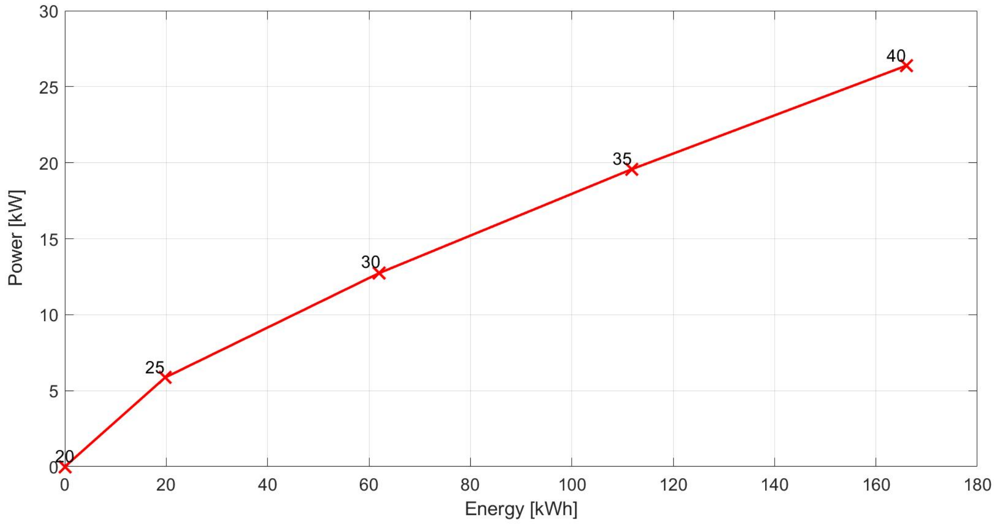

Figure 15: BESS energy and power dimensions needed to control voltage for simulation case G (PV at all customers, BESS only at customer C). The numbers next to the data points show the installed PV power at each customer in kW.

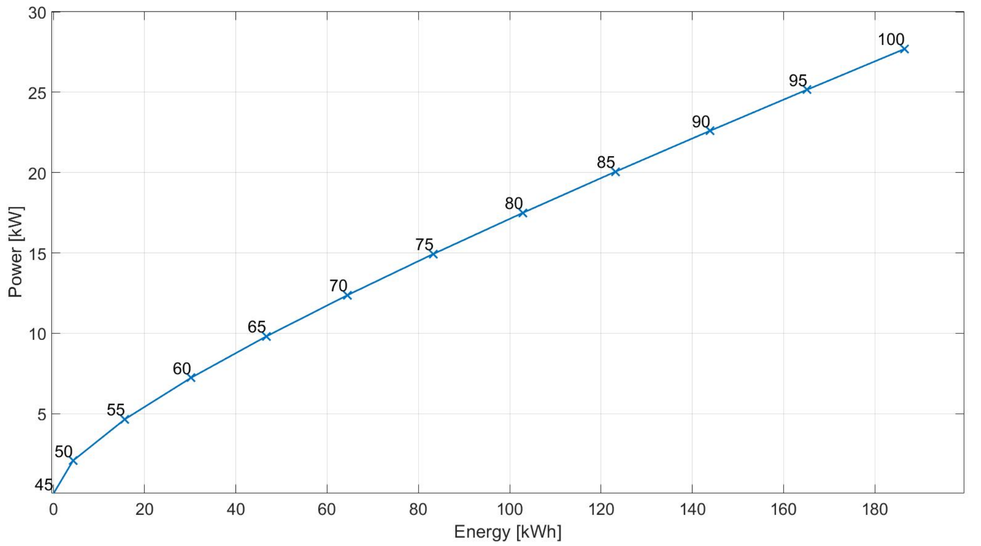

Figure 16: BESS energy and power dimensions needed to control voltage for simulation case B. The numbers next to the data points show the installed PV power at customer C in kW.

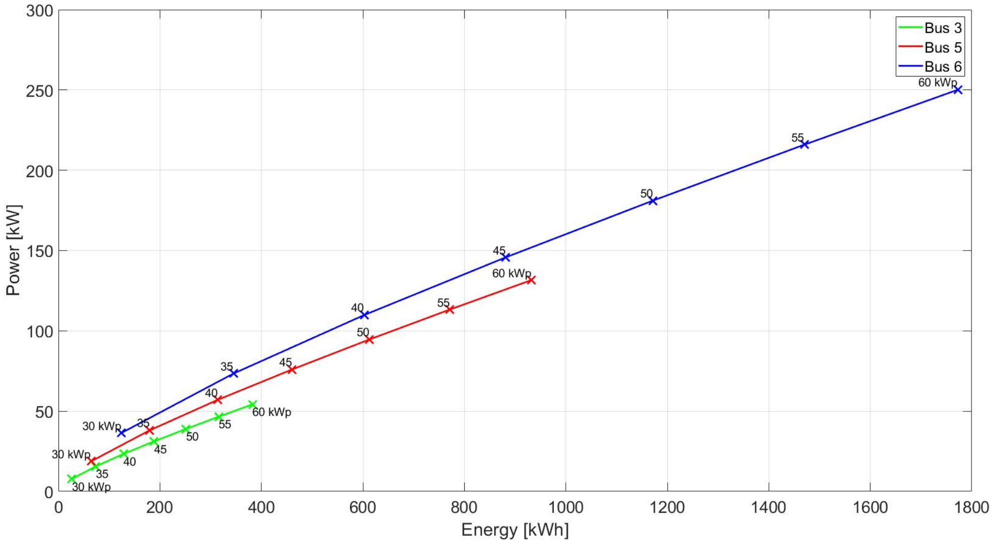

Figure 17: The required power and energy dimensions of a BESS when it is placed in node 3, 5 and 6 respectively (case C, D and E). The numbers next to the data points show the installed PV capacity at each customer in kW.

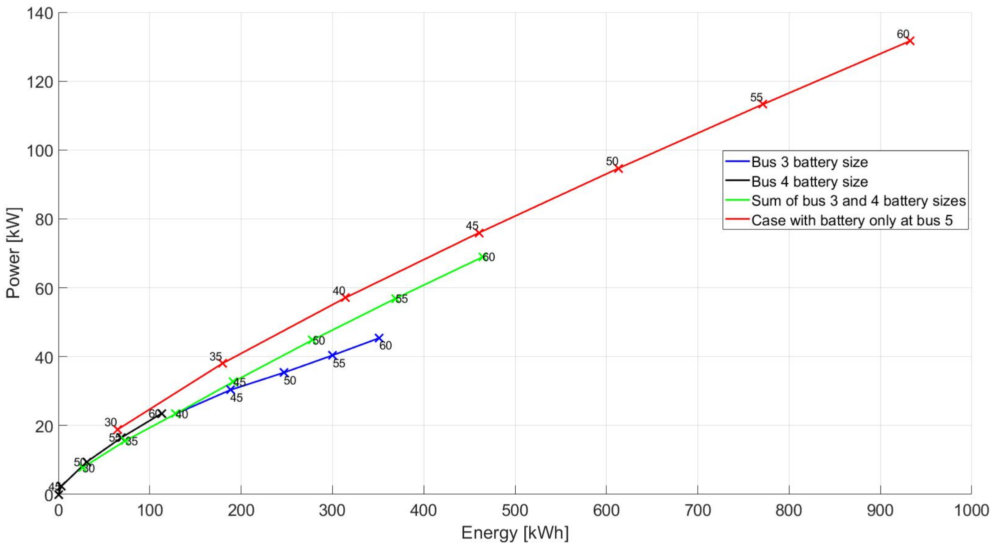

Figure 18: The required power and energy dimensions of two BESS placed in node 3 and 4 are shown in blue and black (case F). The sum of these is shown in green and is compared to the required dimension of a single BESS placed in node 5 in red (case D). The numbers next to the data points show the installed PV capacity at each customer. Note that the scale is different from figure 17.

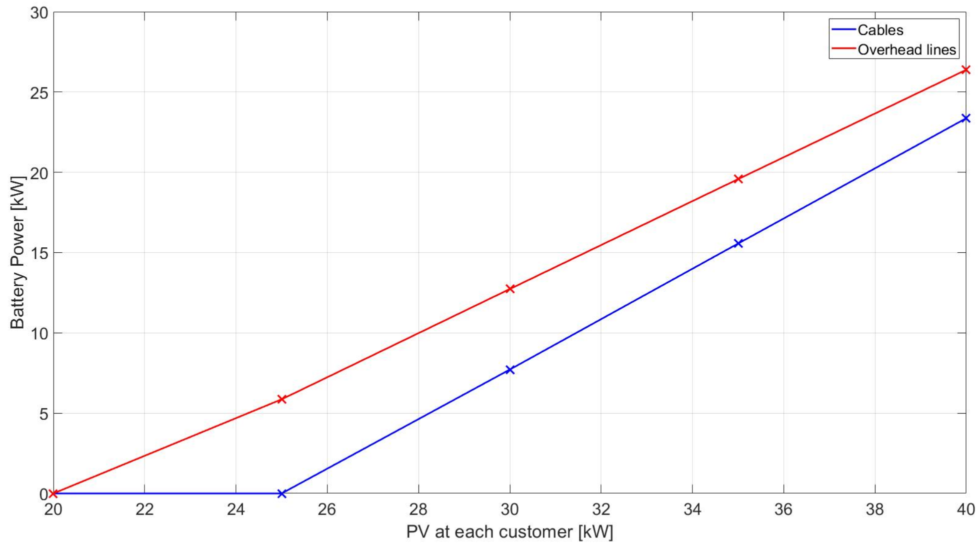

Figure 19: Power capacity of BESS required for the original cable network compared to the same network with overhead lines instead.

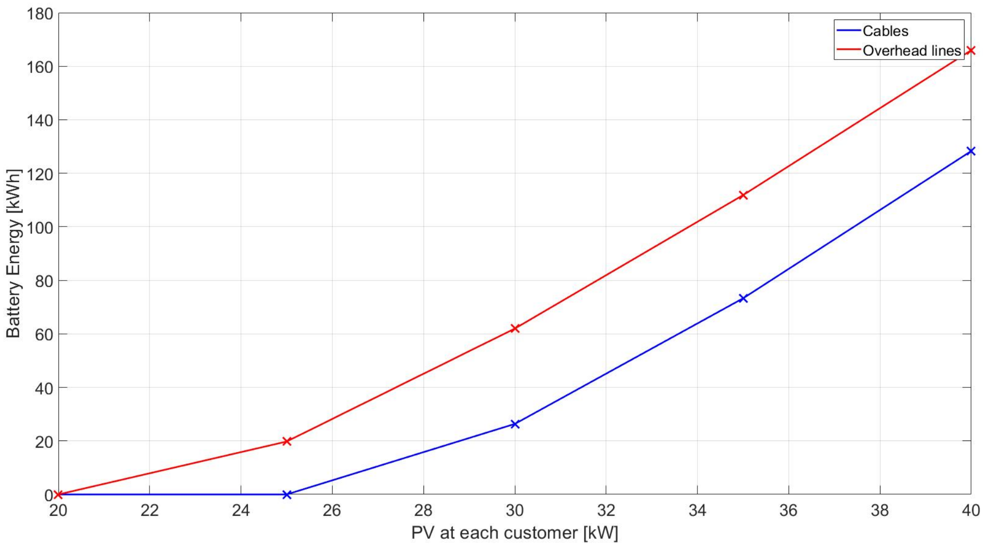

Figure 20: Energy storage capacity of BESS required for the original cable network compared to the same network with overhead lines instead.

4.5 Case I and J: Availability for Additional Services

Hourly averages of power and stored energy for simulation case I (30 kWp at each customer, battery at customer C) are presented in Figure 21. The resulting power to the BESS and state of charge of the BESS for simulation case I are shown in Figure 22 and 23. The first and last day of the year when the BESS is needed are presented in table 4. The hours per day that the battery is needed are presented in table 5. The corresponding results for simulation case J, where all 120 kW of installed PV is concentrated at customer C, are presented in Figure 24, 25 and tables 6 and 7. Figure 26 shows a zoomed in section of 25 in which the BESS does not reach 0 % state of charge during night time. This never occurs for simulation case I.

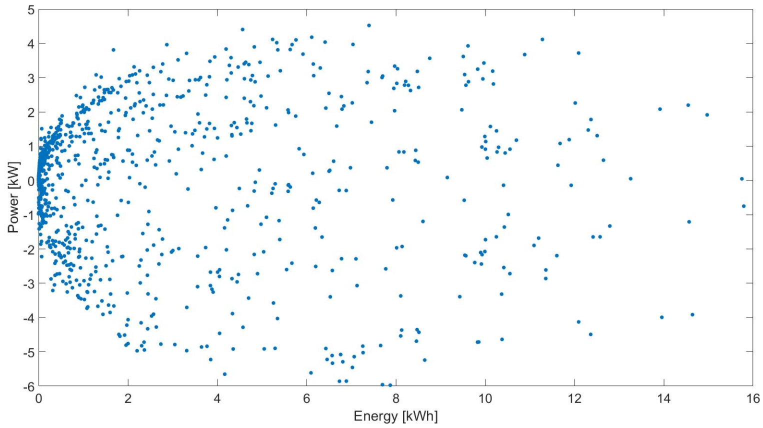

Figure 21: Hourly averages of power and stored energy with 30 kWp installed PV at each customer and an oversized BESS installed at customer C (simulation case I).

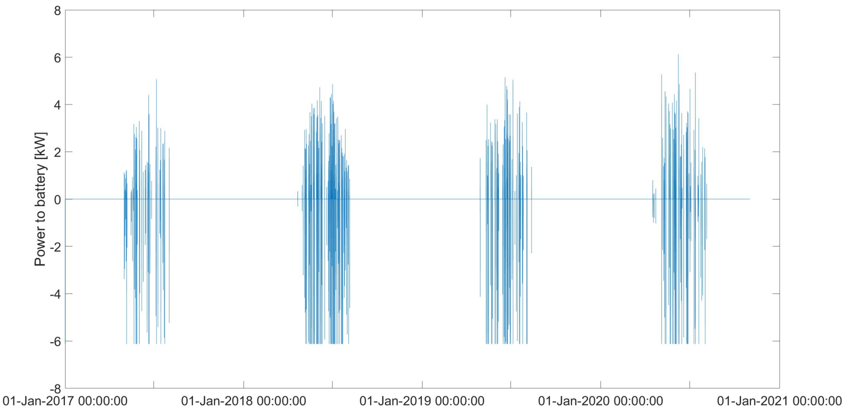

Figure 22: Power to BESS for a simulation across the entire dataset, 2017-01-01 - 2020-10-31, with 30 kWp installed PV at each customer and an oversized BESS installed at customer C (simulation case I).

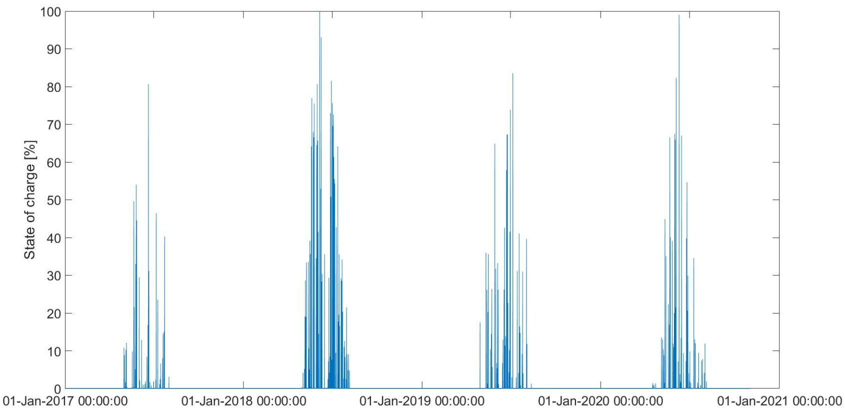

Figure 23: State of charge of BESS for a simulation across the entire dataset, 2017-01-01 - 2020-10-31, with 30 kWp installed PV at each customer and an oversized BESS installed at customer C (simulation case I).

Table 4: Key figures of simulation case I. *Input data for 2020: 1 January-31 October. Results assume no need of BESS in November and December 2020.

Year	2017	2018	2019	2020*
First day needed	1 May	21 April	29 April	16 April
Last day needed	1 August	5 August	12 August	4 August
Length of period needed	92 days	106 days	105 days	110 days
Percentage of year	25.2 %	29.0 %	28.8 %	30.1 %
Number of days needed	38	69	46	52
Percentage of period	41.3 %	65.1 %	43.8 %	47.3 %

Table 5: Results of simulation case I. The time period when the BESS is used is defined as the time from when the state of charge exceeds 0 % until it is back at 0 % again. *Input data for 2020: 1 January-31 October. Results assume no need of BESS in November and December 2020.

Year	2017	2018	2019	2020*
Average time used per day (when used) [h]	3.66	5.36	4.37	3.85
Percentage of day	15.2 %	22.3 %	18.2 %	16.0 %
Maximum time used per day [h]	8	9	9	9
Percentage of day	33.3 %	37.5 %	37.5 %	37.5 %

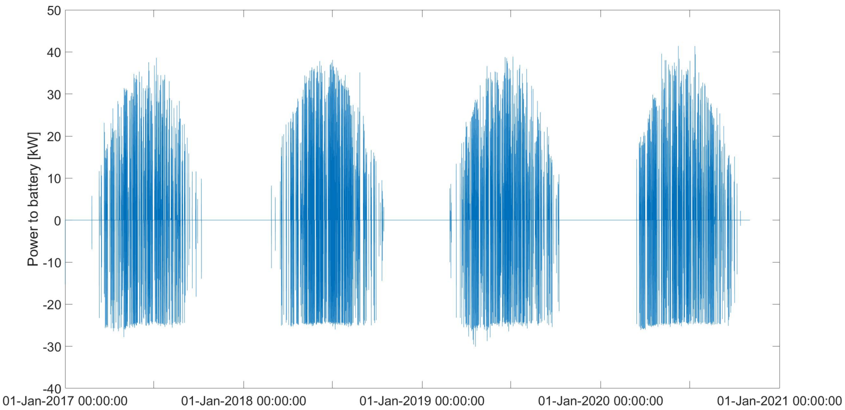

Figure 24: Power to BESS for a simulation across the entire dataset, 2017-01-01 - 2020-10-31, with 120 kWp PV and an oversized BESS installed at customer C (simulation case J).

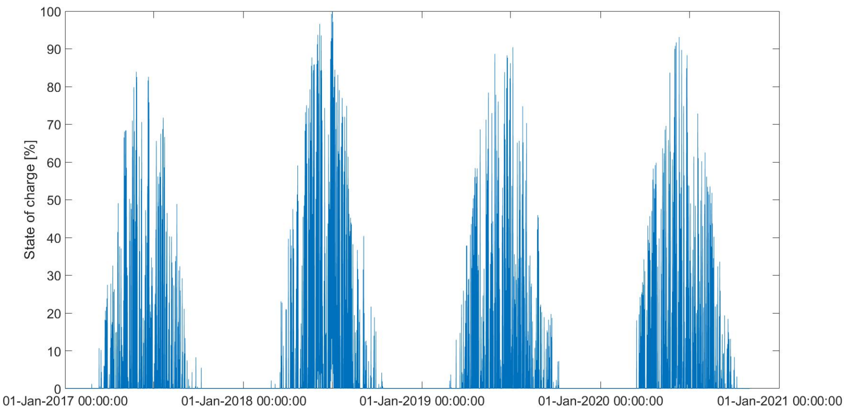

Figure 25: State of charge of BESS for a simulation across the entire dataset, 2017-01-01 - 2020-10-31, with 120 kWp PV and an oversized BESS installed at customer C (simulation case J).

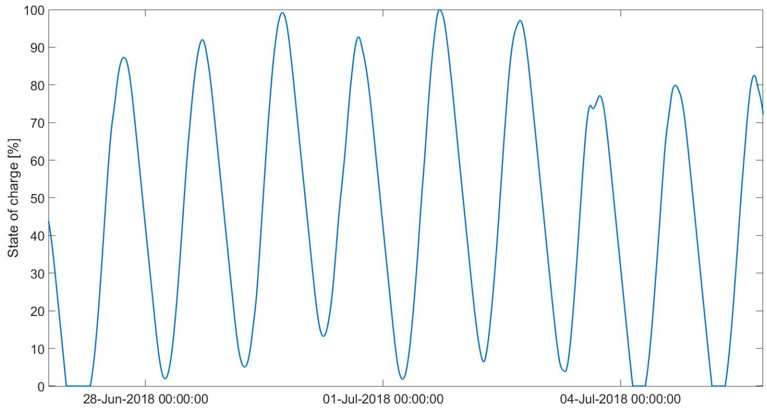

Figure 26: Zoomed in section of Figure 25, during a time period where the state of charge does not fall to 0 % during night time. The simulation is performed with 120 kWp PV and an oversized BESS installed at customer C (simulation case J).

Table 6: Key figures of simulation case J. *Input data for 2020: 1 January-31 October. Results assume no need of BESS in November and December 2020.

Year	**2017**	**2018**	**2019**	**2020***
First day needed	25 February	26 February	26 February	15 March
Last day needed	6 October	14 October	7 October	10 October
Length of period needed	224 days	231 days	224 days	209 days
Percentage of year	61.4 %	63.3 %	61.4 %	57.2 %
Number of days needed	152	162	176	167
Percentage of period	67.9 %	70.1 %	78.6 %	79.9 %

Table 7: Results of simulation case J. The time period when the BESS is used is defined as the time from when the state of charge exceeds 0 % until it is back at 0 % again. *Input data for 2020: 1 January-31 October. Results assume no need of BESS in November and December 2020.

Year	**2017**	**2018**	**2019**	**2020***
Average time used per day (when used) [h]	11.4	13.6	11.6	12.4
Percentage of day	47.6 %	56.6 %	48.2 %	51.5 %
Maximum time used per day [h]	22	24	23	24
Percentage of day	91.7 %	100 %	95.8 %	100 %

5 Discussion

This section provides a discussion of the results of this thesis. Specific conclusions from the case study are presented, as well as some more general conclusions that can be made from the results.

5.1 Voltage Sensitivity

From the main diagonal of the voltage sensitivity matrix, it can be noted that node 3 gets the largest change in voltage from a change in active power in the node. It is followed by node 4, 1 and then 2. This is consistent with the resulting voltages when adding solar power, shown in Figure 14. The voltage sensitivity matrix serves as a good indication of how simulations will turn out and is therefore a natural take-off point when conducting this type of network studies. In this study of a LV network, the active power is the main power component that will affect voltage. It should however be noted that the reactive power should be taken into account in networks with large reactive power flows or in higher voltage networks.

5.2 Control Performance

From the results of simulation case A, it can be seen that different values of proportional gain affect how fast the voltage stabilizes and different values of integral gain affect how large the overshoot is. This is expected behavior of a PI controller. In this thesis, the focus was not aimed at finding optimal gain parameters for a specific situation, but rather to find a reasonable compromise between speed and overshoot for use in further simulations.

Another important setting of the PI controller is the setpoint. In these simulations, the setpoint was chosen to be 1.1 p.u. for all simulations. This is the general maximum voltage allowed according to the grid codes introduced in section 2.1. Figure 13 and 14 both show that this value is exceeded during the time it takes for the controller to detect the overvoltage and restore voltage to the setpoint value. According to grid codes, this is allowed to happen for short periods of time. However, in this theoretical study, the grid codes have not been strictly followed. In a practical application, the setpoint and gain parameters should be chosen so that no grid codes are violated during a worst case-scenario in that specific grid. The reason for choosing the setpoint as high as possible is to keep the dimensions of the BESS small. From Figure 14 it can be noticed that the PI controller both downregulates overvoltages and upregulates voltages below 1.1 p.u. In practice, an upregulation of voltage corresponds to a discharge of the BESS, so the reason for upregulation of voltages below 1.1 p.u. is to make sure that energy storage capacity is always available for downregulation at a later time.

5.3 Sizing and Placement

As one could expect, the BESS dimensions needed in order to regulate the voltage are larger for larger PV installations in the grid. The magnitudes depend on where the PV installations are placed as well as where the BESS are placed. It should be noted that PV installations or BESS placed at one customer affect voltage levels at other customers as well. The extent of this is reflected by the non-zero off-diagonal elements of the voltage sensitivity matrix. Nevertheless, a customer without any PV installations is most likely not willing to install a BESS because their neighbor is installing a large PV system, at least not if they can gain no economic benefit from it. The PV owner however could have interest in investing in a BESS if this means that they can install their PV faster than if the DSO had to perform grid reinforcements before the connection could be made. Furthermore, they could gain economic benefit from other income streams if the battery is used for other purposes when voltage control is not needed.

The results of the BESS placement simulations that are presented in Figure 17 show that placing a BESS in the same node where overvoltage occurs requires the smallest BESS dimensions. These results are consistent with what can be expected from looking at the voltage sensitivity matrix, where the elements of the main diagonal are larger than the off diagonal elements for the nodes where overvoltage occurs.

In Figure 18, the power and energy dimensions of a BESS placed in a cable cabinet (node 5) are compared to the dimensions of two BESS placed at each node connected to that same cable cabinet (node 3 and 4). When gradually increasing the installed PV power at each customer, the overvoltage occurs first at node 3. When the installed capacity reaches 45 kWp at each customer, node 4 starts to experience overvoltage as well. The BESS dimensions needed at node 4 will remain smaller than those of node 3 throughout the entire increase in installed power. The sum of energy storage capacity in node 3 and 4 and power capacity of the same nodes is compared to placing a BESS in node 5 only. Results show that the total power and energy needed are smaller when two BESS are placed in node 3 and 4 respectively. The option of placing a BESS in node 5 instead should however not be neglected completely. Some benefits of placing the BESS there instead is that two smaller BESS could be more expensive than one large BESS. Furthermore, the BESS would not be placed behind the meter of a customer, which simplifies a third-part ownership of the BESS. A drawback of placing the BESS in a cable cabinet is that the voltage measurements of the most sensitive nodes have to be communicated to the node where the BESS is placed, or estimated from measurements in the cable cabinet and known line parameters.

Figure 19 and 20 compared the need of power and energy capacity of a BESS placed in node 3 of the actual network to a similar network where the cables are replaced by overhead lines. As one could expect from changing to more resistive lines, the overvoltage occurred at smaller installed PV capacity and consequently the BESS had to be larger in both power and energy. From these figures it can also be noticed that the BESS power needed increased linearly for increasing PV power, while the energy appears to follow a parabola.

5.4 Usage Time

The results of simulations across the entire dataset of almost 4 years show that the BESS is not needed for voltage control during the entire year or during night time, at least not in the case with 30 kW installed PV power at each customer. These results are important for determining whether the BESS is economically viable. The flexibility of the battery should be used for as many services as possible in order to maximize the magnitude of income streams.

In the case with 30 kW installed PV at each customer, the BESS is needed for voltage control during a period of 25-30 % of the days of the year, in the summer. During this period, they are needed when high enough production occurs to cause overvoltage, between 41-65 % of the days. During the days when the BESS is used, they are needed on average between 15-22 % of the day. When deciding during which days and hours the BESS should be reserved for voltage control it is important to include margins allowing unexpected weather or load events. Solar power production is predictable in the sense that the sunrise and sunset time are known for each day of the year. To be on the safe side, the BESS should therefore be dimensioned to be able to handle multiple clear days in a row, i.e., the BESS should always be back at 0 % state of charge by the time it is needed for voltage control the next day. This is not the case in simulation case I, which can be seen in Figure 26. The more consecutive days that the BESS is pushed to its limit like this, the larger the storage capacity of the BESS has to be. Since the number of consecutive clear days can not be easily predicted, this phenomena can become an issue if not carefully considered in dimensioning the BESS. In extreme situations where this type of wind-up is likely to occur, it might be of interest to look into other solutions for handling overvoltage, such as network reinforcement or even PV curtailment, either in combination with BESS or standalone.

In the simulations of this thesis, the load profiles of the customers are included, meaning that the net power from a customer equals the produced solar power minus the load. If the BESS is dimensioned assuming a certain load, an unexpected decrease in load could lead to the BESS being fully charged too soon and overvoltage occurring. To summarize, in order to always be 100 % sure that the BESS will be able to handle overvoltages, it should be dimensioned for a clear sky and zero load. The only way around that at this point would be PV power curtailment or advanced flexible load control, both involving new challenges regarding regulations and technology.

To summarize, the usage time per day and per year depend on the installed PV capacity in the system as well as where it is placed. For this particular network, with 30 kWp PV installed at each customer, one could presuppose that the battery is used for voltage control at least between April 16th through August 12th during nine hours per day.

5.5 Other Services

Moving further to the possibilities of using the BESS for other services when it is not needed for voltage control, frequency control is one of the most promising fields of application. The FCR-N market prices are often highest during night time which is when the BESS is available, and the hourly bidding intervals, soon to be 15-minute intervals, suit well with the daily fluctuations in voltage control needs. An important thing to consider for the BESS to be able to contribute on the FCR-N market is that the sold power capacity has to be available as both charging and discharging, i.e. to maximize the bid, the BESS has to be at a 50 % state of charge at the beginning of the period. For a single BESS, this means that the BESS needs an hour to restore its state of charge to 50 % between each hour it is available for frequency control, limiting the opportunities of a large income stream. Aggregating parties could provide a way around this if they have many flexible resources that cooperate. When participating on the frequency control market, one should be careful not to contribute with too much power so that overvoltages are caused by discharging the BESS too fast.

Other than frequency control, a BESS could provide the possibility of peak shaving of load. With the present fuse size-based grid cost changing to a peak power-based grid cost in the future, customers will have larger economic incentive to reduce their load- and production peaks. The production peaks will naturally be smaller if the voltage control scheme proposed in this thesis is in operation. Furthermore, since large load peaks usually occur in the winter when the BESS is not needed for voltage control, the BESS is perfectly suited for shaving of peak loads as well.

To summarize the availability for additional services of the BESS, the winter and night time are often relieved from overvoltage issues. During these times the BESS could be used for other services such as frequency control or peak shaving. It could also be noted from Figure 22, 23 and 21 that the BESS is not usually used to its capacity limits, and that the full power and energy storage capacities are reached during a concentrated time period in the middle of the summer season. A worst case scenario (no load and only clear days) simulation should lead to a quantification of this period, and part of the BESS capacity could be used for additional services also during this time.

5.6 Future Work

This thesis focuses on a specific part of Kraftringens' grid and the results are mainly representative for that grid. A natural next step would be to repeat the analysis for other grids. It would also be interesting to create a tool for calculating the necessary BESS sizes for any grid, given the same type of network data that is used in this thesis.

In order to refine the model further, losses in the BESS, lines and other components could be taken into account. The fact that batteries degrade over time is also something to consider, as well as what control measures that can be taken in order to maximize the lifetime of the BESS or the benefits that the BESS can provide during its lifetime. It would also be interesting to see if the dimensions of the battery would need to be any different if a fast recharge was allowed, i.e. if the battery would be able to discharge at a higher rate than it charges. This might be a solution to the issue identified in figure 26, with the battery not having time to discharge fast enough to be fully available for the next day.

If deemed necessary, the gain parameters of the PI controller could be optimized and the setpoint voltage could be adjusted in order to never violate the upper voltage limit.

The economic benefits of using BESS for voltage control instead of traditional network reinforcement could be quantified. Both for specific cases, as well as generalized in order to assess the feasibility of the solution for different scenarios of future electricity prices, tax levels etc. This could also include the value of other services that the BESS can provide when not used for voltage control.

Lastly, it would be interesting to determine the environmental impact of the solution. While installing large amounts of PV power is usually considered environmentally friendly, it comes with an environmental cost of both production of the PV units as well as network lines and components, or in this case a battery energy storage system. Is it always a smart choice for the environment to install more PV power together with large BESS? How do BESS and network reinforcement compare on an environmental basis? These are questions that should be answered before choosing to use a solution like BESS for voltage control.

5.7 Conclusions

This thesis aimed to answer to what extent BESS can be used as a solution for overvoltage in LV grids with high PV penetration, suitable energy storage capacity, power capacity and placement of the BESS as well as what additional services the BESS could provide in order to make it economically viable.

The PI controller turned out to perform well in order to keep the voltage within accepted limits, however the gain and setpoint could be further tuned in order to make sure that no voltage limits are violated. In the case where only the customer most sensitive to overvoltage had installed PV and a BESS, a PV installation of 60 kWp required a BESS size of 7.2 kW / 30 kWh. When all four customers had 30 kWp installed capacity, a BESS placed in the same point required dimensions of 13 kW / 62 kWh.

When each customer had equal installed PV power, both total energy and power dimensions of the BESS were minimized by placing it in the node or nodes where overvoltage occurred. In the case with 30 kW installed PV at each customer, a BESS placed in node 3 was needed for voltage control 41-65 % of the days between mid-April and mid-August and unused the rest of the year. The days when the BESS was needed, it was used for an average of 4.3 hours and a maximum of 9 hours. Concentrating all PV power to node 3 resulted in the BESS being needed 68-80 % of the days between late February and mid-October and unused the rest of the year. When the BESS was used, it was used during an average of 12 hours and a maximum of 24 hours per day, meaning that the BESS was not always back to a 0 % state of charge during night time.

Since the PV power installed in order to provoke overvoltage had to be large in comparison to common PV installations today, this particular network is not likely to need any BESS in order to keep voltage within acceptable limits in the near future. However, the results of this thesis showed that networks with overhead lines are more sensitive to overvoltages and therefore need larger BESS to control voltage. In situations where large amounts of PV power is installed in weak parts of a grid, BESS could be a viable option to network reinforcement, in particular if the BESS capacity is being used for additional purposes during winter and night time.

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