Title: Loss Reduction in a Low Voltage Grid with Distributed Generation
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SYNOPSIS:

The aim of this project is reducing losses in a low voltage Danish residential grid with high penetration of distributed generation and presenting a strategy capable of doing it. The project focuses on long-term influence that distributed generation has on the losses. Various devices capable of losses reduction are presented and the possibility of using them analysed. A control strategy for long-term losses reduction is presented.

Pages, total: [41]
Appendix: [-]
Supplements: []

Summary

This project deals with the problem of loss reduction in low voltage (LV) distribution grids under high penetration of distributed generation (DG) originating mostly from renewables. Special focus is put on the case of Denmark.

The first chapter provides a brief introduction to the topic and lists the objectives of the project as well as its limitations.

Further on, the state-of-the-art for loss reduction technologies is presented. A special focus here was put to LV applications and to cases with DG present.

Out of many options possible, Energy Storage Systems (ESS) and On-load Tap Changers (OLTC) are chose as devices to be tested in the simulations. The chosen devices' operation principles are defined. The test grid – multi-feeder and radial – is chosen for the simulation.

Wind and solar power is chosen as an example of DG possible to use both in Denmark and on LV level. The generators are modelled with use of real weather conditions data.

Multiple simulations checking the performance of ESS and OLTC are performed under different conditions (winter, summer and whole year cases) in order to determine the best strategy for loss reduction.

Finally, the results are presented and conclusions made basing on them.

Contents

Chapter 1. Introduction

1.1. Background

One of the main strategical concerns of the developed countries governments is currently the problem of global warming. The most significant purpose of this negative effect is extended use of fossil fuels like coal, oil and natural gas. As a big share of their use contributes to energy production, it is expected that the energy sector should present some solutions leading to more environment-friendly ways for the global economy.

Being a highly developed country, Denmark follows this trend, which is supported by the Danish society. Since that, an ambitious programme of transforming the energy production was presented by the government in 2013. According to this document, all the energy supply of the country will be based on renewable resources by 2050. Moreover, by 2030 coal and oil are supposed to be totally eliminated from the heating supply [1] and replaced mostly by biomass for heat-power plants and electrical heating for individual use. It should also be mentioned, that the plan covers also a shift towards more environment-friendly transport, including encouraging electric cars.

The changes proposed by the government will imply significant change of the Danish energy system. Not only is it a change of energy generation, which will have to be adjusted to new situation. It will also be a change of power system structure that will need to supply new elements like electric cars. It can also be assumed that the load will become more flexible as a result of above mentioned changes.

As the wind is the most easily available source of energy for Denmark, due to county's weather conditions, the strongest focus will be put on wind power. According to the Danish policy, as much as 53% of country's energy supply will come from the wind as soon as in 2020. Wind power share will then grow even more [2].

The data collected by the European Wind Energy Association (EWEA) show that more and more wind power installations are built in the European Union every year. EWEA expects further growth over next years [3] [4]. Some of actual and expected data on wind power installations capacity are presented in the Table 1.

Table 1 Denmark and EU (including Croatia) wind power installations capacity in MW, according to EWEA

	2013 [3]	2014 [4]	2015 [5]	Central 2020 scenario [3]	Central 2030 scenario [4]
Denmark	4,771	4,845	5,064	6,500	8,130
EU	117,288	128,744	141,579	192,453	320,066

For Denmark, predictions for the year 2030 vary from 5.95 GW to 11.32 GW of installed wind power capacity depending on the scenario [4]. The Table 1 shows the central scenario by EWEA being 8.13 GW. Even though the difference between the low and high scenario is significant, all scenarios claim that wind power will become even more significant both for Denmark and the European Union as a whole.

Other energy sources will become more important too. Denmark's huge agriculture sector is able to provide fuel for biogas installations. According to above mentioned national strategies [2], the focus on biogas should be strengthened. Thanks to that, combined heat and power plants (CHP) using coal will be eliminated step-by-step. Another advantage of extended use of biogas in CHP's is, that it will help to mitigate methane emission from livestock manure, which is mentioned as an important problem in The Danish Climate Policy Plan [1].

Even though natural conditions for solar energy production in Denmark are rather weak, the government intends to support this technology. It will be done by subsidies for construction of 100 MW photovoltaic solar modules in large installations until 2020 [6]. Other forms of renewable energy are currently tested, such as geothermal and wave energy.

All of the above mentioned energy sources contribute, and will contribute even more, to the distributed generation (DG). In comparison to conventional energy plants, DG plants can be characterized as smaller and less predictable in terms of the amount of power produced. Also their location is decentralized. [7]

A problem that must be approached is power loss level reduction in grids with high level of DG. As it is pointed out by many authors, optimal sizing [15] and location [15] [16] of DG units contributes significantly to loss reduction and hence should be an important concern of line losses minimization algorithms.

It should be mentioned, that the problem of losses is especially important in low voltage (LV) grids as they are usually more difficult to control due to the lack of information about the state of the grid. This is because of the fact that sensors are rarely installed on LV level []. Thus, it would be beneficial to develop control strategies that can base just on very limited information.

Another problem specific to LV grids is that some of the devices that can be used for loss reduction are not widely used at this voltage level. This fact limits significantly the variety of loss reduction methods if compared to MV grids. This topic will be addressed in the chapter 3.

Finally, as always, the control strategy for distribution grids with high DG penetration has to ensure reliable operation of the system. All the aspects mentioned above show that the problem of control of a distribution grid with highly distributed generation and flexible load is a complex one.

1.2. Problem formulation

It is clear that power losses are a negative effect from the DSO's point of view. This is due to the fact that power losses increase the operation cost. This means that even a small reduction of losses can bring remarkable savings in the long term.

As mentioned in the previous subchapter, the voltage control possibilities in LV grids are different and more limited than in MV grids. At the same time, renewable sources are often connected at the low voltage level, creating problems typical for distributed generation. The most significant of them is unpredictable nature of DG sources (due to the weather conditions) that lead to under- and overvoltage in grids with high DG penetration. Furthermore, distributed generation can produce reverse power flow and is generally more difficult to observe, as it requires more measurements to get a good insight into the state of a grid with multiple sources.

On the other hand, DG brings also opportunities for reducing the losses. This is mainly due to the fact that DG units can support the grid in the places located far from the central generator. Therefore, developing a strategy able to reduce the losses in a distribution grid on the low voltage level is a complicated challenge.

The problem of power losses is especially challenging in the rural or small-intensity residential areas where the distance between power consumers is longer. Reducing losses in such grids is then an especially vital challenge.

Taking into consideration the facts mentioned above, the aim of this project is to suggest a control strategy for long-term loss reduction in an LV grid representing a residential area in Denmark. The chosen area will be characterised by high level of distributed generation. The strategy should utilise only the assets suitable – both technically and economically – for LV applications. Furthermore, the final strategy must take into consideration existing legal limitations: Danish grid codes [] and EN 50160 [] standard. Successful completing of this task can contribute to energy savings, which in turn will limit the necessary generation and help reaching the environmental policy goals [].

1.3. Objectives

The main goal of this work is to develop and assess a control strategy capable of reducing the losses in an LV grid located in Denmark. In order to complete this general objective, some task will be completed.

First of all, the analysis of various devices and strategies that can be used for power loss reduction will be performed. The effect of this analysis will be choosing assets that later will be used for developing of the control strategy. These assets will be chosen basing on their suitability for LV grids, their cost and complexity.

After choosing the devices to be utilised, an LV grid representative for a Danish residential area will be modelled. This will require presenting load characteristics typical for Danish residential power consumers and generation characteristics for small-scale DG sources. Both of the characteristics mentioned above will correspond to typical weather conditions in Denmark, especially to its seasonal variations.

The control strategy will be developed using assets and the grid model obtained previously. As the losses depend on generation and load characteristics and both of them change over the year, the study of loss reduction possibilities must take into consideration all the seasons. Because of that, the simulations will show the results of implementing the suggested strategy over the time period of one year. Consequently, the focus of this project is long-term loss reduction.

1.4. Methodology and limitations

As the problem of losses in LV grid is very complex, some limitations to the project's scope are necessary. These limitations will influence the used methodology.

Among many DG sources that can be used, wind and solar power will be chosen as most suitable. Not only are they common in Danish grids but also represent all the typical features of distributed generation: dependence on weather conditions and possibility to connect them at LV level. The justification of their choice will be presented later in the work. The characteristics for distributed generation will be obtained basing on real weather conditions data (wind speed, temperature and solar irradiation) from Denmark.

The load in the grid will represent households, which means that typical features of household consumption, especially in terms of summer-winter difference due to heating will be present in the characteristics.

The grid will represent an 400 V grid from a residential area in Denmark. In order for this case to be realistic, it will be a multi-feeder grid of radial type.

As the aim of the project is to present a control strategy for long-term losses reduction, the focus will be to simulate the whole year. In order to limit the simulation complexity it is then necessary to set the resolution of measurement in the simulation to one hour. This means that no transient or short-term effects will be discussed.

The simulations will be performed using DIgSILENT Power Factory environment. Due to the long duration of the simulations and grid complexity, only power flow simulations will be performed.

Even though some remarks on the cost of equipment that can be used for loss mitigation will be made, the economic analysis is not the point of interest of this project. Therefore, the technical criteria will be most important when preparing the control strategy.

On the contrary, the standard EN 50160 and Danish grid codes will be considered as constraints limiting the allowed voltage level during simulations. It is assumed that for the strategy to be useful, it should not violate those regulations.

1.5. Content of the report

This report consists of six chapters. The first of them is an introduction presenting a brief background of the project and formulating the problem this work is attempting to solve. Later this chapter lists the objectives and describes the methodology of the project, as well as its limitations.

The second chapter presents the state-of-art with regard to the problem of loss reduction in LV grids with distributed generation. The impact of DG on power grid and its important features are discussed here together with grid codes regulating the operation of grid-connected DG units.

Then, the LV grids are introduced with a special focus on the Danish case. Subsequently, the problem of losses in such grids is shown and the important concepts of voltage control and equipment used for it presented basing on the literature.

The third chapter describes the grid model created as a part of the project and shows model's elements. Also the concept of simulations is presented here with their various test cases and objectives.

The detailed description of the modelling is presented in the fourth chapter. It presents the models of particular components of the system introduced in the chapter three: generation units, loads and voltage regulation equipment. The chosen control strategy is also presented here and the modelling in DIgSILENT explained.

The fifth chapter presents the results obtained by means of the simulations proposed before. Relevant findings from various test cases are pointed out here and discussed.

The last chapter summarises the results and conclusions of the report. Then, the future work is suggested and the whole project concluded.

Chapter 2. Losses in low voltage grid

2.1. Conventional versus active distribution grids

As it was stated in the previous chapter, increasing penetration of DG in distribution grids leads to changes in power flow. In this section, the difference between a conventional and an active grid will be explained.

The conventional conception of a distribution grid assumes, that power is supplied to a feeder from a substation only. Some loads consuming active power are connected at various points along the feeder. This situation is presented in the Figure 1.

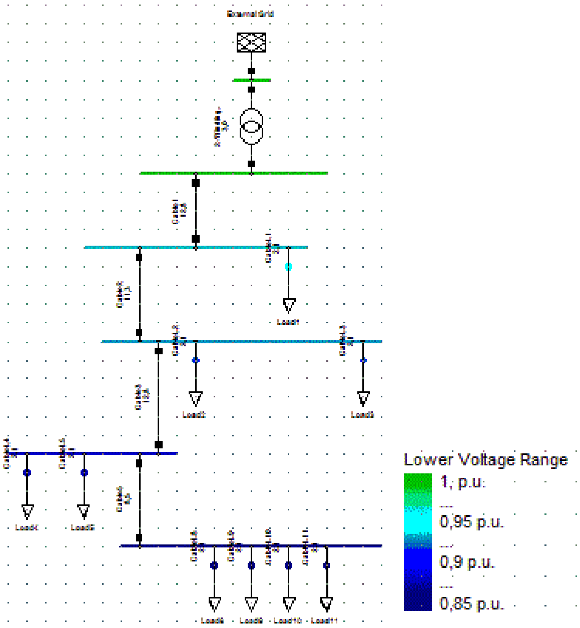

Figure 1. Voltage drop along the feeder in a conventional grid.

As it can be seen, the longer the distance from the substation, the more voltage level falls. In the example shown above, the voltage in the last busbar drops to 0.845 p. u. and the total active power losses of the system reach 2.75 kW (at external grid infeed of 18.41 kW) This effect can be explained by line losses.

Unlike transmission networks, distribution networks can be characterized by line resistance comparable to their reactance [7], which means that line losses corresponding to active power cannot be neglected. Because of that, the voltage drop formula can be written as:

$$V_S - V_L = \frac{RP_L + XQ_L}{V_L} \tag{1}$$

where P_L and Q_L denote active and reactive load power respectively, R and X are line resistance and reactance, V_S is the voltage at the substation while V_L is the voltage at the load.

By introduction of a DG unit connected to the last busbar, the power flow within the system can be changed, thus the grid becomes an active distribution network (ADN). The most distant loads will now be supplied from the DG unit, which in the scenario presented in the Figure 2 will generate 10.17 kW, while the external grid infeed will decrease to 8,41 kW.

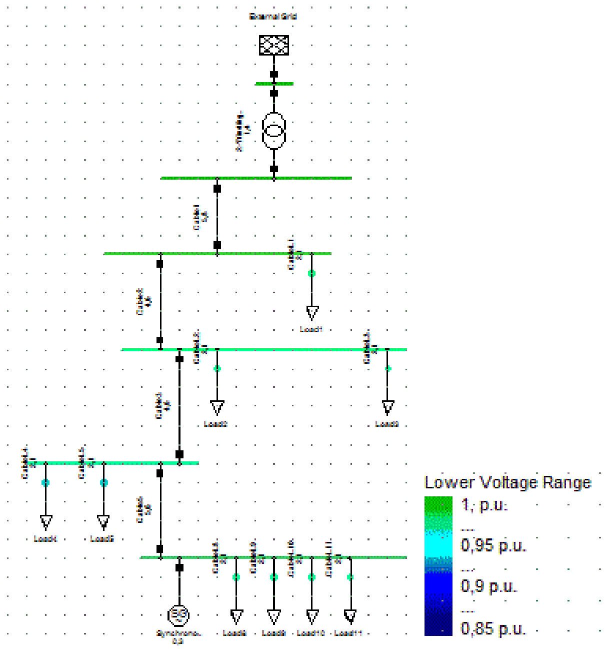

Figure 2. Voltage drop along the feeder compensated by a DG unit.

In consequence, the voltage level will not fall below 0.969 p. u. in any busbar and the total system losses will be reduced to 1.05 kW.

The voltage level in the ADN scenario is improved comparing to the conventional grid. This is reached by introducing a DG unit generating power to supply the last busbar of the feeder. The improvement, though, is not limited just to the most distant area of the grid, as the power flow is reversed in the line connecting the last busbar with the penultimate one. The decrease of power demand in the end part of the feeder releases the stress for the first two busbars.

The effect of reverse power flow may just be observed in ADN's – in the example above it refers just to the last line of the feeder but sometimes this effect can be noticed even all along the feeder. Although it contributes to voltage level improvement in neighbouring busbars, its existence brings also some risks for the system.

The most important of them is, that if the DG level increases too high, the problem of undervoltage can be replaced with the problem of overvoltage, which can propagate in the system by means of a reversed power flow. This is the key reason for introducing control strategies in ADN's.

2.2. Losses in an active distribution grid

Although several sources of losses in a distribution grid can be named, line losses contribute most to the general loss of the system. Therefore, they will be described below.

The line losses are present due to the fact that current flow in a real system is only possible through a line, whose impedance cannot be neglected. The following formulas (2) and (3) show respectively active and reactive power losses in the line when the power is transferred from node A to node B:

$$\Delta P_{A,B} = \frac{P^2 + Q^2}{V_A^2} R \tag{2}$$

$$\Delta Q_{A,B} = \frac{P^2 + Q^2}{V_A^2} X \tag{3}$$

where:

$\Delta P_{A,B}$ – active power loss for power flow from A to B,

$\Delta Q_{A,B}$ – reactive power loss forpower flow from A to B,

P,Q – active and reactive power transferred through a line,

R,X – line resistance and reactance,

V_A – voltage at node A.

Formulas (1), (2) and (3) show the close relation between the line losses and the voltage drop and explain why in the example shown in the previous subchapter the system losses were reduced along with improvement of the voltage profile in the case of DG unit installed.

This effect of DG makes it possible to use one of the most widespread approaches to loss reduction problem that can be found in the literature. [], [] and [] as well as many others suggest optimal location of DG units as a means of mitigating the losses. As DG, especially PV, is often connected at LV level (majority of PV in Denmark [] and as much as 95% of PV in Austria according to []), this technique is especially suitable for LV grids.

The optimal placement of DG installations may be considered together with their optimal sizing. This approach is also widely used in the literature, together with optimal placement [] or alone [], []. Both of the methods can be implemented with help of multiple optimisation algorithms or heuristic methods.

An important feature of optimal placement and optimal sizing is that they can just be used at the stage of planning of grid connection of a DG unit such as wind turbine. It must be remembered that in many cases the problem of loss reduction is considered for the existing grid. In such a case adding or removing another DG installation can be impossible or at least complicated.

First of all, the ownership structure of DG units tends to be much more complicated than the one of central plants. Whoever the owner is, his perspective might not match the perspective of a DSO – while DSO cares mostly about the power quality and is eager to introduce improvements in the grid structure, the owners are interested in their own income. Therefore, adding or removing generators in an existing grid hardly ever can really be taken into consideration. Even if we assume that it would be possible, the optimal location of an installation would rarely be feasible. Especially in residential LV grids, the electrically optimal place can be impossible to utilise because of environmental effects of the DG unit. For instance, a wind turbine cannot be installed to close to houses.

Because of that, another methods need to be considered in order to reduce losses in an existing LV grid. They are described in the next subchapter.

2.3. Overview of loss reduction methods for an LV grid with DG.

2.3.1 General principle

As the main source of losses is power transport through lines, they can be reduced by reducing the amount of power transferred. This can be seen from the formulas (2) and (3). In order to obtain such a result, it should be ensured that the power is consumed near the place where it is supplied from. The higher line resistance and reactance, the more important it becomes to avoid transferring more than neccesary power on long distances through such lines.

Another important conclusion from the formulas (2) and (3) is that voltage level affects the losses. As the example presented in the subchapter 2.1, the voltage drop increases with the distance from the substation or DG unit, which means that highest line losses should be expected there.

A few conclusions can be made from these remarks. Firstly, the devices suitable for loss reduction can work on the principle of consuming or producing active or reactive power. Even though the simple DG units were discarded as an option in the previous subchapter, active power generation (and consumption) can still be partly obtained by utilising energy storage systems (ESS), as in [] and []. However, reactive power compensation bings much more possibilities than trying to affect the active power balance. As for reactive power compensation, multiple devices are used, such as Static Var Compensator (SVC) [] or Distribution Static Synchronous Compensator (DSTATCOM) [].

Secondly, loss reduction can be obtained by improving the voltage profile. This can be done indirectly with reactive power compensation methods mentioned above or directly by increasing the voltage level with a transformer. Two groups of devices must be mentioned here: On-load Tap Changers (OLTC) [], [] and Step Voltage Regulators (SVR) [].

Last but not least, as the unnecessary power transfer should be avoided, many of the devices mentioned below should be placed close to the crucial nodes of the grid, which depending on their kind will be: generators, intensive loads or busbars most likely to experience undervoltage. It must be remembered too, that the topology of the grid, the changing generation patterns and varying load will all affect the power flow within the considered grid. Therefore, a problem of placement of the chosen devices is a vital one.

2.3.2 Energy Storage Systems

Energy Storage Systems are one of the most often referenced devices when it comes to loss reduction applications [], [], []. There are many different technologies of ESS using electrical, mechanical or chemical effects for storing energy. Out of them, the Battery Energy Storage Systems (BESS) should be mentioned.

The Figure 3 below [] presents a comparison of energy storage technologies by their power output's size and discharge time. It can be seen that battery technologies present wide range of available sizing as well as discharge time in a range of minutes.

As many battery technologies exist, their pros and cons also vary. Even though a development is still observed in battery technologies, some of them are already well examined and cheap. This makes them the most widespread devices for use in power systems [].

The main advantages of BESS are: wide range of powers and capacities available, low complexity and cost and relatively short reaction time facilitating their control. They operate basing on active power generation and consumption data from the grid. They can be used both as big units connected at the substation level or as a small ones connected to particular DGs, which makes it possible to adjust the strategy depending on the needs.

On the other hand, even though well-known BESS are quite difficult to model because their parameters depend on temperature and state of charge. Furthermore, they change also over lifetime and show hysteresis effect: different characteristic for charging and recharging. This makes modelling of batteries a challenge, as it is always a trade-off between precision and simplicity.

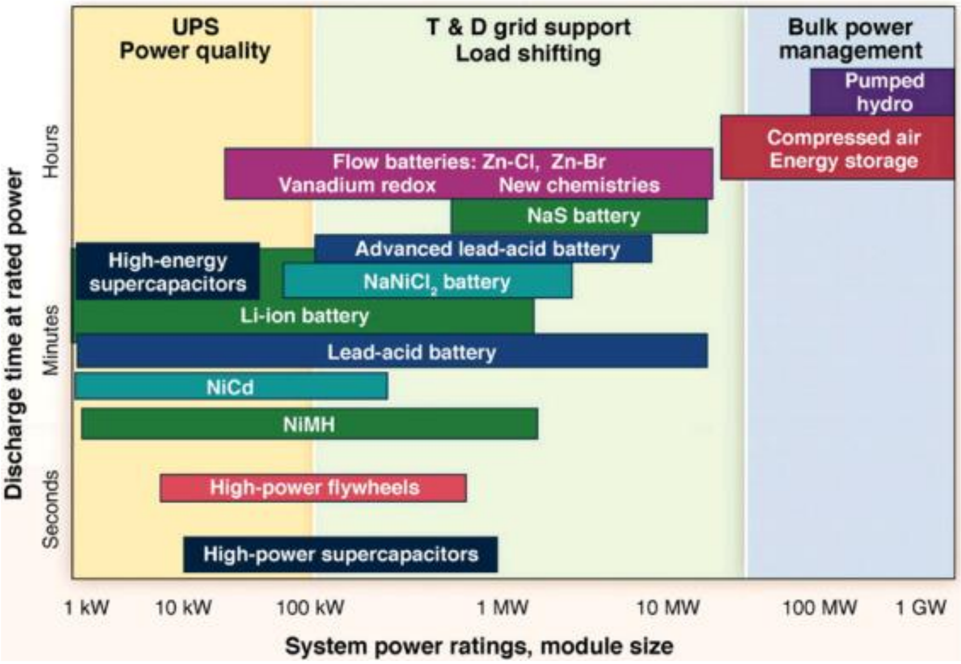

Figure 3. Comparison of various storage technologies in terms of module size and discharge time [49].

To sum up, BESS are very flexible in terms of sizing and number of units needed, they can also deliver continuous output. Many of them are well-known technologies of low complexity, widely used in power system applications, also in LV grids. At the same time other technologies are still under development and modelling of batteries can be challenging.

2.3.3 Reactive Power Compensation devices.

Reactive power compensation can be obtained with different devices, of which shunt capacitors are most widely mentioned in the literature [], [], []. They can be used both at substation level or elsewhere along the feeder and may be merged in capacitor banks to enhance their power. It is further possible to control different capacitors independently, thus providing more smooth (but still discrete) reactive power compensation.

In spite of their simplicity, high sizing flexibility and simple control methods basing on local voltage measurement, shunt capacitors have drawbacks too. Firstly, many of them are needed to support the grid, secondly, the output of a single unit is not scalable. Anyway, shunt capacitors remain one of the more popular devices for LV applications [].

As the capacitors can just deal with undervoltage, they are sometimes combined with inductors (reactors) that provide inductive reactive power, thus decreasing the voltage level. The device combining controllable capacitors and reactors for reactive power support is called the Static Var Compensator (SVC).

Both capacitors and reactors are usually thyristor-controlled, although capacitor banks can also be fixed []. The control of thyristors can be obtained by a PI controller comparing reference voltage to terminal voltage v_T []. As SVC consists of multiple units that can be controlled independently, it is an easily scalable and thus quite a precise instrument.

Figure 4 below presents the relation between SVC's current and voltage change at the connection point. It can be seen that by using an SVC wide range of voltages can be obtained, so it can improve voltage in the point where it is connected as well as in the neighbouring areas of the grid.

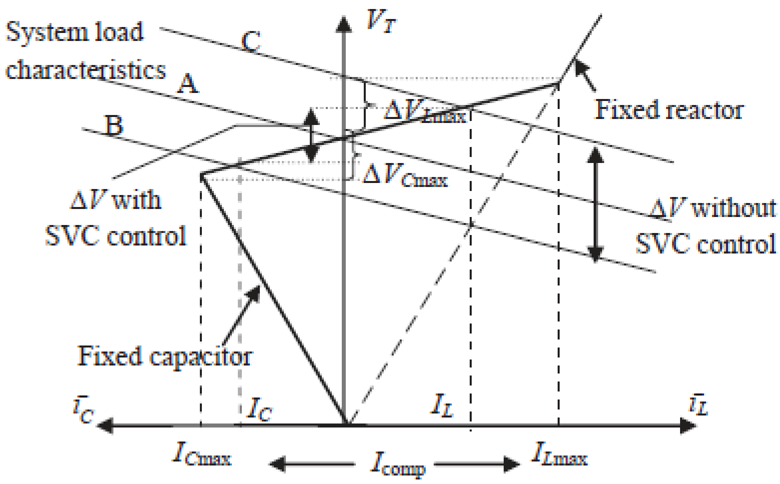

Figure 4. Voltage-current characteristic of SVC [44].

It is worth mentioning that the goal of SVC is not to keep exactly the set voltage level but rather to decrease the voltage drop, as shown in the figure above [42]. This can be done as long as the drop is within the constraints originating from maximum capacitive (I_{Cmax}) current in case of undervoltage (line B) and inductive (I_{Lmax}) current in case of overvoltage (line C) that SVC is able to deliver.

To conlude, SVC is a complex device that can bring very good results thanks to its precision. It is however hardly ever used at LV level because of its limited sizing possibilities.

Another option is a Static Synchronous Compensator, or STATCOM, that provides reactive power by means of an inverter. STATCOM's principle of work is the same as SVC's. It must be mentioned though, that STATCOM's characteristic is more flat, which provides opportunity for better voltage drop reduction. More importantly, STATCOM is capable of supporting the grid even at very low voltage levels, which is not a case of SVC.

A special Distribution (D) STATCOM with very high switching frequency inverter is used for LV applications. In general, DSTATCOM is most suitable for LV grids of the three reactive power compensation devices listed above. On the other hand, it is also the most technically complicated and hence the most expensive one. DSTATCOM is usually controlled with Pulse Width Modulation (PWM) technique and installed at the substation level. It is mostly used when there is a problem of harmonics injection.

DSTATCOM is well suited for LV applications but even more complex than SVC. On the other hand, it is a very precise device able to support the grid not only in case of under- and overvoltage but also in presence of harmonics.

2.3.4 Controllable transformers

As explained in the subchapter 2.1, voltage level drops along the feeder, which may produce undervoltage in the most distant grid parts. The easiest way of dealing with this problem (often utilised when solving various problems []) is by using an On-Load Tap Changer (OLTC) as a part of a transformer.

By regulating transformer ratio, an OLTC can increase (or decrease if needed) the voltage level in the beginning of a feeder. This, with the same voltage drop, will let the voltage level increase also towards the end of the feeder.

OLTC's can normally set tap position at several levels within $\pm 10\%$ of the nominal value. First of all, that means that very big over- or undervoltage cannot be improved by OLTC only. Secondly, since a tap changer is a part of the transformer, all its changes affect all the grid on transformer's secondary side. Moreover, the number of tap positions is often limited to just a few, so every action will affect the grid quite heavily, normally by 1%-2% of nominal voltage.

This means that OLTC suits the need of improving voltage level as a reaction to all-grid issues but must be used very carefully if the aim is to deal with just local problems. Another issue is the fact that MV/LV transformers are rarely equipped with OLTC [], which are predominantly used in HV/MV transformers. This limits OLTC usage in LV grids to situations when it is at all possible. However, in grids with high penetration of DG it is rational to use OLTC in MV/LV transformers as well because, as the Figure 5 shows, its principle of operation serves this kind of grid perfectly [].

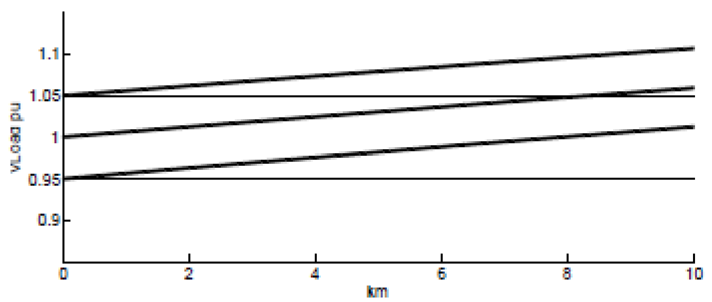

Figure 5. OLTC principle in a grid with high DG penetration [8].

In the situation shown in the Figure 5, very high DG penetration (300%) [] leads to overvoltage that can be compensated by setting the OLTC below 1 p.u. Although this situation is theoretical, overvoltage from DG is a real risk. OLTC can be then especially useful in grids with high share of PV generation because PV installations are normally distributed and thus a whole-grid approach facilitated by OLTC is needed [].

A challenge while operating OLTC is reducing tap-switching number because that device's lifetime depends highly on how often it is switched. What is more, as much as 30% of all substation transformers failures can be contributed to ageing processes of an OLTC[]. The typical number of switching operations for OLTC is 5000 per year [], which yields 13-14 per day. This is why OLTC is often designed with relatively large difference between available tap states.

Step Voltage Regulator's (SVR) principle of use is pretty similar to OLTC's. As the name suggests, an SVR produces a step-shaped voltage change in the place where it is installed. As it can be somewhere along the feeder, not just in its beginning, SVR concept addresses a problem mentioned previously as OLTC's significant drawback – its disability to be used locally. It still affects all the grid behind the place it is installed.

From the loss reduction point of view, the biggest drawback of SVR is that it is an additional transformer and as such, creates additional iron losses in the system. This is not the case of OLTC because it is installed as a part of existing transformer and since that do not introduce new iron losses to the grid. On the other hand, OLC switching will contribute to change of copper losses of the transformer. This way, reducing the tap position will increase the copper losses due to the higher current in transformer's windings. Similarly, increasing the tap position will limit the current und thus the losses in the transformer.

2.4. Comparison of loss reduction devices.

2.4.1 Comparison criteria.

Basing on the findings of the previous subchapter and key features of the problem, important criteria for choosing devices suitable for loss reduction in an LV grid in presence of DG can be presented.

Device complexity – this criterion reflects the technical complexity of a considered device. It is clear that the devices of lower complexity are generally cheaper and therefore more suitable, especially if many of them are needed.

No. of units required – some devices are typically used in groups which must be taken into consideration while calculating the overall cost. On the other hand, more units allow more flexible operation strategy, so this number can always be considered both as an asset or a drawback of a device.

Control complexity – some devices can be difficult to operate without complicated control strategy, while others are more straight-forward, which increases their attractiveness.

Data needed – the criterion shows the input information needed by a device.

Output step size – a device may or may not be able to produce continuous output signal. If the output is discrete, the difference between two closest steps can also be smaller or bigger.

Output sign – this criterion shows if a device can deal with just undervoltage or with both under- and overvoltage, which is important in presence of DG in the grid.

Sizing flexibility – it is desired that a device can be purchased in a size suitable for the system but some devices can be available just in narrow range of sizes.

LV applications – this criterion shows to which extent a device can be used in LV grids and if the technology is well-established for such use.

Comments – additional information vital for the choice of a device.

2.4.2 Comparison results.

The comparison of considered devices is presented in the Table 2.

Table 2. Comparison of loss reduction devices.

Device	ESS	Shunt capacitor	SVC	DSTATCOM	OLTC	SVR
Device complexity	low	very low	high	very high	medium	medium
No. of units required	flexible	large	one to few	usually one	one	one to few
Control complexity	medium	low	high	high	medium	medium
Data needed	active power generation and consumption	local voltage	voltage	voltage	voltage	local voltage
Output step size	continuous	large	small	small	large	large
Output sign	both	undervoltage	both	both	both	both
Sizing flexibility	high	high	low	low	low	medium
LV applications	widespread	known	no	known	known	known
Comments				suitable in presence of harmonics		increases losses

The assessment of important features of the devices taken into consideration leads to choice of ESS and OLTC as the devices which will be used further in this project.

The ESS was chosen due to its flexibility in terms of number of units, output sign and step size and because of its broad usage for mitigating losses in LV grids. It is a better choice than a shunt capacitor because its output is easily scalable and allows overvoltage support. It beats other shunt compensator with its simplicity and cost.

Even though in terms of many criteria SVR looks better than OLTC, the latter produces no additional losses and thus wins the competition. It is also much less complex (also in terms of control) than SVC and DSTATCOM. Last but not least, OLTC needs just investments in one place (substation transformer) where it is installed – plus additional voltage measurement which other devices also need.

Equipping MV/LV transformers in OLTC is not very widespread at the moment. However, the positives of doing so are more and more often pointed out in the literature [], []

In the next chapters a strategy for loss reduction with ESS and OLTC will be developed and assessed. From this point it will be assumed that other possible loss reduction devices are beyond the scope of the project. The system, in which the strategy will be developed and tested, will be presented in the next chapter.

Chapter 3. Impact of distributed generation on a grid

3.1. Test grid model

This chapter presents the grid used in the project and presents the methodology of the tests that will be performed further on. First, the grid topology and parameters will be presented, then the use of devices chosen in the previous chapter defined for the tests. Finally, the test cases will be characterised in terms of load and generation scenarios and the success criteria defined.

The grid model used throughout the project is based on []. It is a radial LV grid from a residential area with loads representing three types of households. Load characteristics of three kinds will be presented in the next subchapter. The grid topology can be found in the Figure 6 and the Figure 7.

The grid consists of an MV/LV transformer and four feeders, out of which the feeder no. 3 consists just of a single load. Transformer parameters can be found in the Table 3.

Table 3. Transformer specifications.

Parameter	Value
Rated power	0.4 MVA
Rated voltage	10/0.4 kV
Vector group	Dyn5
Short circuit voltage Uk	4.45%
Copper losses	4.7 kW
Iron losses	410 W

Feeder no. 2 is slightly more complex, connecting 22 households via 9 busbars grouped in 6 levels. Most of the households connected to this feeder represent the medium pattern of the load characteristics. This is also where the wind turbines are connected, in the far end of the feeder, to busbar no. 15. The wind turbines will be described in the next subchapter.

Feeder no.1 has 15 loads-households connected to it through 6 busbars organised in 4 levels. It is shorter than the feeder no. 4 but their characteristics are similar. The last feeder, no. 4, is the longest one (10 busbars in 6 levels) supplying biggest number of households: 30.

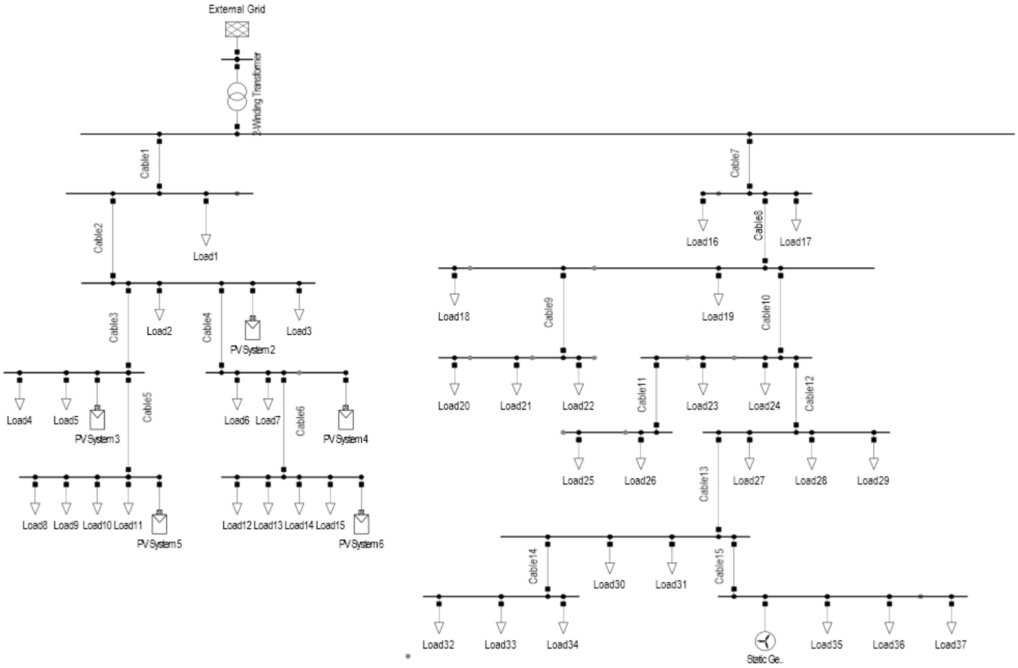

Figure 6. Feeders no. 1 (left) and no. 2 (right).

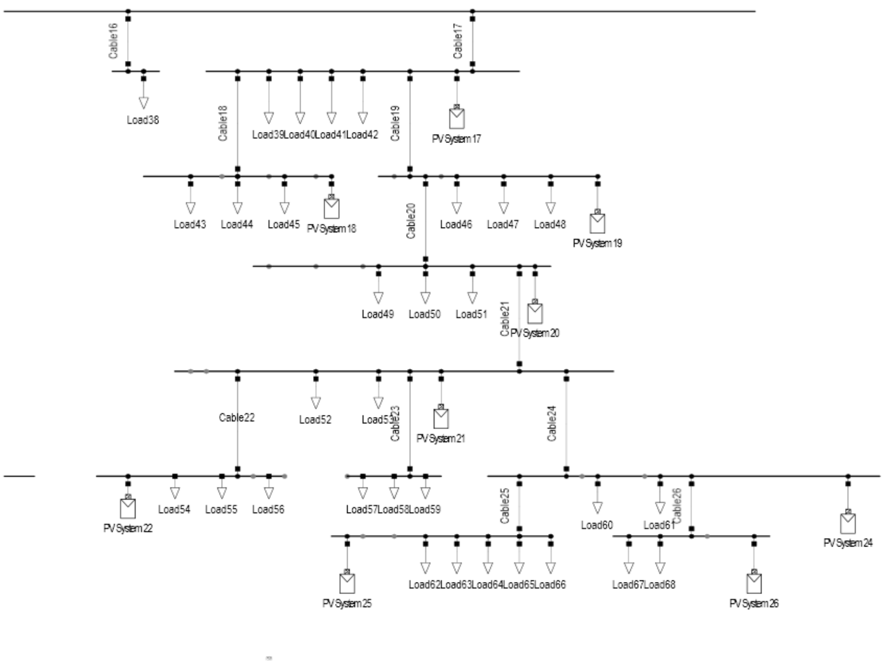

Figure 7. Feeders no. 3 (top left) and no. 4 (right).

These feeders represent areas with higher share of family houses, many of them equipped with their own small PV installations. It is assumed that solar panels are installed on the roofs of big houses, which means the households described by high-load characteristics.

The busbars are connected using cables. Following [], three types of cables were modelled. Table 4 presents the parameters of the three types and Table 5 shows which cable belongs to which type. Cable parameters come from[].

Table 4. Cable parameters[].

Parameter	Unit	Cable type 1	Cable type 2	Cable type 3
Rated voltage	kV	0.4	0.4	0.4
Rated current	kA	0.27	0.21	0.14
Resistance R’ (20°C)	Ω/km	0.21	0.32	0.64
Reactance X’	Ω/km	0.072	0.075	0.079
Resistance R0’	Ω/km	0.83	1.28	2.57
Reactance X0’	Ω/km	0.29	0.3	0.31

Table 5. Cable types.

Cable no.	Type	Cable no.	Type
1	2	14	1
2	2	15	3
3	3	16	1
4	3	17	1
5	3	18	3
6	3	19	1
7	1	20	1
8	1	21	2
9	3	22	3
10	1	23	3
11	3	24	2
12	1	25	3
13	1	26	3

The characteristics of generation and load will be described in the chapter 4. In the next subchapter, the planned simulations will be listed.

3.2. Simulation cases

3.2.1 Use of devices

The first simulation case is supposed to show the initial situation with no loss reduction applied. Then, as OLTC was chosen as a device for loss reduction, a strategy including just the use of OLTC will be simulated in order to find the impact of OLTC on the system – the impact that can be contributed to this particular device. The placement of OLTC itself does not need to be decided as it only can be placed in the substation transformer. What can be decided though, is the placement of sensors that will provide voltage measurements for the OLTC. A case of one sensor located in the end of one of the feeders will be compared with a case of three sensors gathering data from three different feeders.

In case of ESS, its placement can be changed in order to check its performance at different points of the grid. The scenarios taken into consideration will be: one central ESS located near the wind turbine, three ESS units for each long feeder and multiple ESS units controlled by local voltage.

In both cases: OLTC and ESS, the best options will be chosen and then integrated into a combined OLTC+ESS scenario, which will be simulated in order to check if the combination of devices brings better results than use of single ones.

To summarise, a list of use of devices cases is presented below:

- No device – the basic case,
- OLTC, 1 sensor,
- OLTC, 3 sensors,
- 1 ESS,
- Combination - OLTC+ESS.

3.2.2 Test cases

When loss reduction is aimed, the result strategy should work independent of the seasonal variations of the weather. This means that the strategy must be tested in generation and load conditions representing various scenarios that can be met during normal system operation. To make sure that the strategy fulfils its goals, its desirable to test it over timespan of a whole year.

However, in order to observe some more detailed results for particular devices, it can be useful to perform simulations of a shorter period being a special case. In terms of generation and load, the special cases will be summer – with high PV generation and low load – and winter – with low PV generation and high load. These cases should be examined before performing the final, whole-year simulation of the system.

Combining these assumptions with the simulation plan for particular devices, we obtain the list of test cases to perform. For better orientation, they are presented in form of a Table 6.

Table 6. Use of devices vs. grid operation scenarios in simulations.

	No device	OLTC, 1 sensor	OLTC, sensors	ESS	Combination
Summer	X	X	X	X	X
Winter	X	X	X	X	X
Year	X				X

3.2.3 Evaluation criteria

The aim of the project is to obtain the loss reduction. There are also constraints that need to be fulfilled according to [], [], []. Therefore, a list of evaluation criteria can be presented as follows:

- A total loss reduction in the system, measured as the sum of line losses, at least 3% of the initial value.
- Voltage at all busbars within $\pm 10\%$ of its rated value (400 V).
- No need to disconnect the DG units from the grid.
- Maximum number of tap position switching – 4 times a day.

Meeting such criteria will mean that the project objectives were met.

Chapter 4. Modelling studies

4.1. Load characteristics

As it was already mentioned, the loads represent three types of households. Following[], they can be described as presented in the Table 7:

Table 7. Load profiles description[].

Load profile:	Low	Medium	High
Annual energy consumption [kWh]:	1155	3028	8387
Dwelling size [m^2]:	65	65	108
Inhabitant(s):	Single male	Mother + 2 children	Mother + 5 children
Year	2005	2005	2003

Among the households, 18 represents low load profile, 24 belong to medium load category and 26 are high load dwellings. Detailed list of household is displayed in the Table 8:

Table 8. Households types (L - low, M - medium, H - high load profile).

Load no.	Type:	Load no.	Type:	Load no.	Type:	Load no.	Type:
1	M	18	M	35	H	52	M
2	H	19	M	36	L	53	H
3	H	20	M	37	H	54	H
4	L	21	L	38	M	55	H
5	H	22	L	39	H	56	M
6	M	23	M	40	H	57	L
7	H	24	M	41	L	58	L
8	L	25	L	42	L	59	L
9	L	26	L	43	H	60	H
10	M	27	M	44	M	61	H
11	H	28	L	45	H	62	H
13	M	29	L	46	H	63	M
13	H	30	M	47	H	64	M
14	L	31	L	48	M	65	H
15	L	32	M	49	M	66	H
16	M	33	M	50	H	67	H
17	M	34	M	51	H	68	H

The load characteristics contain load data for a whole year with 1 hour resolution. It is assumed that during each of one-hour periods the power consumption remains constant. All the loads are also assumed to work at constant power factor of 0.97.

The idea behind choosing whole year as the simulation time has two purposes. Firstly, it was assumed that the simulations will cover whole year. Secondly, during a whole year, it is possible to capture the seasonal variations that are important when considering distributed generation.

Because of that, the month of February was chosen to represent winter and the month of June to represent summer. June is considered a better choice than for example July because it is not a holiday month, which could affect the load values.

4.2. Generation characteristics

4.2.1 Wind generation characteristics

Two wind turbines are installed in the end of the feeder no. 2 in order to support the voltage in that feeder. The wind turbines are small ones, their rated power 20 kW each. Wind turbine specifications come from [] and can be seen in the Table 9. Their power output is limited by pitch control, as explained in the previous chapter.

Table 9. Wind turbine characteristic speed values [62].

Characteristic speed	Value [m/s]
Cut-in speed	3
Rated speed	11
Cut-out speed	30
Survival speed	50

Basing on the producer’s specification presented in the Figure 8, the power curve was defined. The curve together with wind speed data for Gistrup near Aalborg were used to obtain wind generation characteristics with energyPRO 4.4 software. EnergyPRO is an environment developed by EMD International A/S for energy systems analysis with particular focus on economic analysis[]. One of advantages of energyPRO is its weather data database that was used for wind speed statistics.

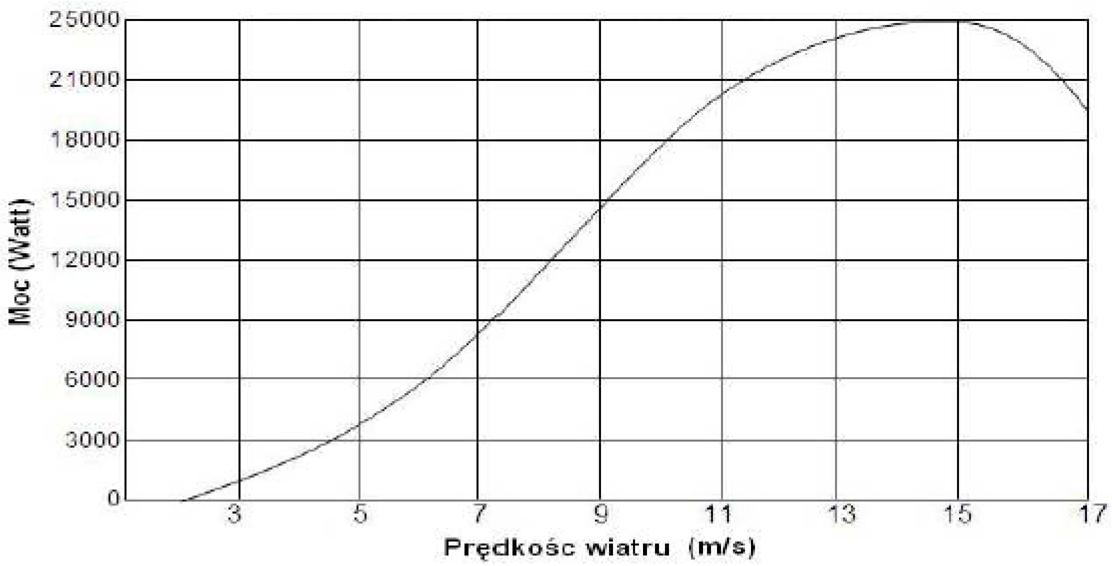

Figure 8. Power curve of a 20 kW wind turbine[].

This way, wind generation data were obtained. Then, two sets of them were extracted to match the season of load characteristics. Because the data provided by energyPRO have resolution of 1 hour, the power output of wind turbine was interpolated (using simple line interpolation). As in case of the load characteristics, the data for winter and summer scenario were extracted from the whole year data, representing respectively February and June.

Wind turbine characteristics can be seen in the Figure 9:

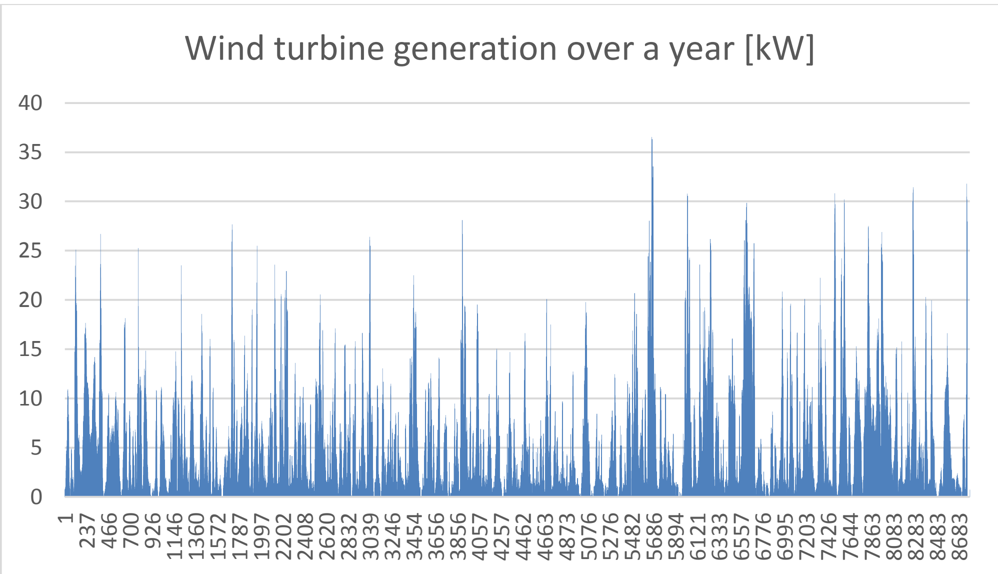

Figure 9. Wind turbine generation every hour.

4.2.2 PV generation characteristics

It was mentioned before that the households representing high load profile are grouped in feeders no. 1 and 4. It is further estimated that each of the high-load houses has the same PV unit installed. It is 4 kW device consisting on 10x400 W panels mounted on the roof, so fixed at 35° angle and facing directly south. Other parameters of PVs simulated are presented below in the Table 10:

Table 10. Some of PV parameters.

Parameter	**Value**
Nominal operating cell temperature	45°C
Temperature coefficient c_T	-0,4 %/°C

In a similar way as in case of wind generation, the characteristics were obtained with energyPRO software taking irradiance and temperature data for Gistrup.

4.3. Devices placing and operation.

4.3.1 OLTC

The OLTC was assumed to be able to deliver up to 10% transformer ratio change, both up and down. The step size was and 2%, which yields 5 positions up and the same number down from the neutral position.

As the test grid contains just one transformer, OLTC has to be located there. As mentioned in the previous chapter, the difference between the two OLTC use cases is the number of sensors used. In the first case (OLTC 1 sensor), just the voltage at busbar 25 is taken into consideration. In the second case (OLTC 3 sensors), also voltages at busbars 6 and 15 are considered.

The OLTC is controlled by a simple principle []. The control is applied before the control variable (which in this case is the voltage of busbar no. 25) hits the constraint. The value of 0.95 p.u. was chosen as a trigger of tap changing (up) and 1.05 for the down change.

In case of three sensors available (OLTC 3 sensors), the situation when the tap position is changed is defined in a slightly more complex way. The change up is triggered by Bus 25 voltage below 0.95 p.u. only if additional conditions are met:

1. Voltage at busbar 6 below 1.02,
2. Voltage at busbar 15 below 1.00.

The difference between thresholds for the two busbars is because busbar 15 is located in the feeder 2 with wind turbines connected to it, while busbar 6 is located in the shorter feeder 1. Thus, voltage at busbar 15 can grow more suddenly.

Similar sets of conditions can be formed for undervoltage in feeders 1 and 2:

1. Voltage at busbar 6 below 0.95,
2. Voltage at busbar 15 below 1.00
3. Voltage at busbar 25 below 1.02

Or:

1. Voltage at busbar 15 below 0.95,
2. Voltage at busbar 6 below 1.02
3. Voltage at busbar 25 below 1.02

In case of switching the tap one position down, a similar set of cases is defined:

1. Voltage at busbar 6 over 1.05,
2. Voltage at busbar 15 over 1.00,
3. Voltage at busbar 25 over 1.00

Or:

1. Voltage at busbar 6 over 1.00,
2. Voltage at busbar 15 over 1.05,
3. Voltage at busbar 25 over 1.00

Or:

1. Voltage at busbar 6 over 1.00,
2. Voltage at busbar 15 over 1.00,
3. Voltage at busbar 25 over 1.05.

It can be noticed that in case of switching down, no difference is made between busbar 15 and the remaining ones. This is because the wind turbine connected to busbar 15 can suddenly increase generation, while its sudden decrease is unlikely because of the fact that higher wind speeds are observed less often than lower ones.

The Table 11 summarizes the conditions of switching tap positions. It must be underlined that switching the position up always is due to the same condition, as well as switching down is always triggered in the same way. For example, there is no difference between switching from tap position 0 to 1 and switching from 3 to 4.

Table 11. Sets of conditions for switching the tap position.

<table>
<tr><td rowspan="3">UP</td><td>V6<0.95</td><td rowspan="3">OR</td><td>V6<1.00</td><td rowspan="3">OR</td><td>V6<0.95</td><td rowspan="3">AND</td><td rowspan="3">tap position <5</td></tr>
<tr><td>V15<1.02</td><td>V15<0.95</td><td>V15<1.02</td></tr>
<tr><td>V25<1.00</td><td>V25<1.00</td><td>V25<0.95</td></tr>
<tr><td rowspan="3">DOWN</td><td>V6>1.05</td><td rowspan="3">OR</td><td>V6>1.00</td><td rowspan="3">OR</td><td>V6>1.00</td><td rowspan="3">AND</td><td rowspan="3">tap position >-5</td></tr>
<tr><td>V15>1.00</td><td>V15>1.05</td><td>V15>1.00</td></tr>
<tr><td>V25>1.00</td><td>V25>1.00</td><td>V25>1.05</td></tr>
</table>

4.3.2 ESS

The ESS can be used in various sizes, therefore three cases of its use can be tested. Because of the grid structure, however, it can be supposed that the best place for installing an ESS will be at Busbar 15, where the wind turbine is also connected.

This choice can be justified by the fact that the wind turbine is the largest generator in the analysed grid, therefore the ESS should be placed close to it.

The ESS uses constant voltage control strategy to reduce under- or overvoltage and thus mitigate the losses. The ESS used in the project has rated power of 40 kVA.

Chapter 5. Simulations results

5.1. No control case

As it can be seen from the Figure 10, in the basic case with no loos mitigation devices the grid suffers both high under- and overvoltage over a year. This is because of the high penetration of DG and also because of long feeders in this grid. The Figure 10 shows Bus25, where the under- and overvoltage are most significant, as it lies in the end of feeder 4, the longest one.

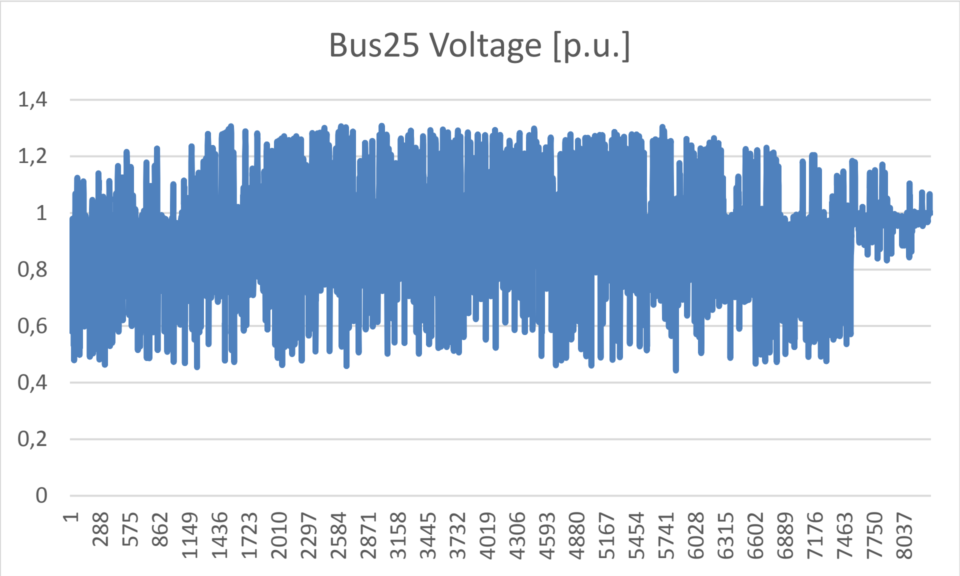

Figure 10. Bus 25 voltage p. u. every hour of a year.

5.2. One-month long simulations

In order to decrease the complexity of computations, particular simulation cases were executed over a time of one month. Those simulations brought interesting results.

It was shown that both OLTC and ESS are able to limit the losses in the grid, however in case of ESS the opposite effect was observed too for summer conditions.

I was also observed that increasing the number of sensors do not improve the work of OLTC significantly, therefore it is not recommended because of its cost.

More details on one-month long simulations are presented further in this chapter.

5.3. OLTC1+ESS case

As the OLTC3 case did not bring results much better than OLTC1 in winter and did bring worse results in summer, OLTC1 was decided a better option for combination with ESS.

Unfortunately, the results of whole year simulation are disappointing. Over- and undervoltage were not eliminated, just slightly limited, as can be seen in the Figure 11. Bus25 voltage every hour of the simulation.

It can be seen from the Figure 12, that the ESS supported the grid when the wind conditions needed it. The Figure 13 shows that OLTC was often required to operate at its maximum or minimum setting. This can be a problem with regard to this device's lifetime, as too frequent switching is dangerous for a tap changer.

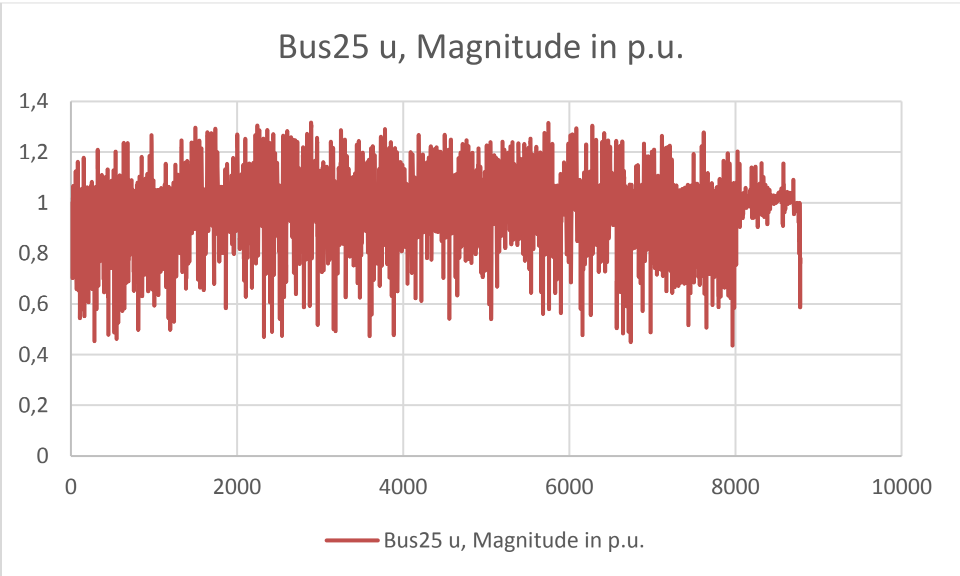

Figure 11. Bus25 voltage every hour of the simulation.

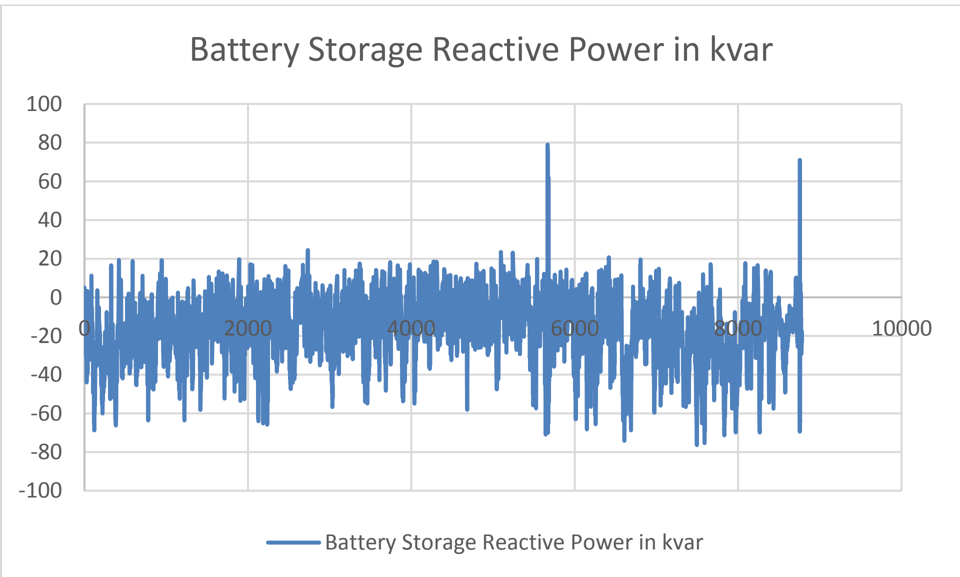

Figure 12. Reactive power supplied by ESS every hour of the simulation.

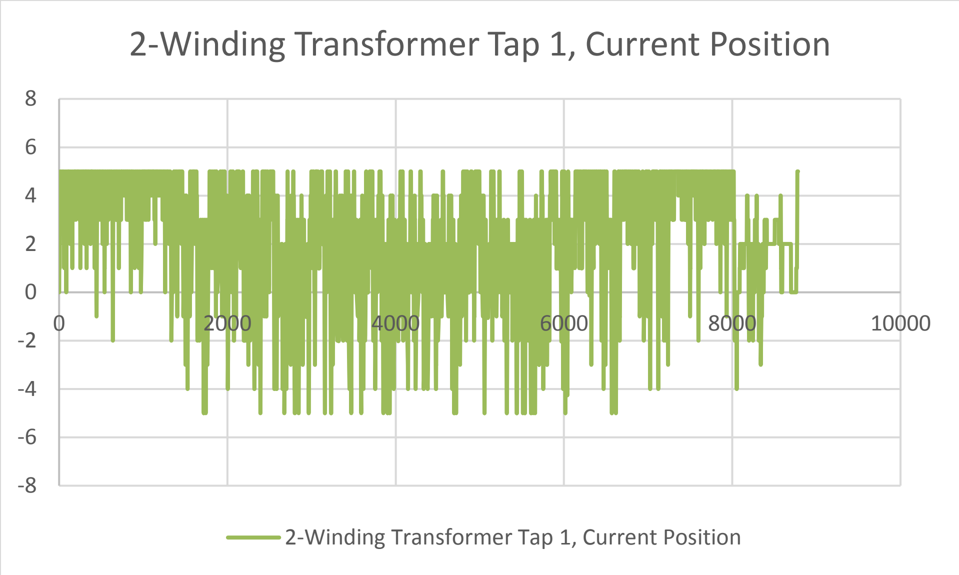

Figure 13. Tap position switching over the period of one year.

5.4. Results summary

The Table 12 presents the total system loss reduction results in kW for all the use of devices and test cases. It can be noticed that three cases: OLTC1, OLTC3 and ESS brought loss reduction in winter scenario. OLTC cases brought loss reduction in summer scenario as well, but ESS failed to decrease losses level in June. Unfortunately, both in summer and winter and also in the whole year the losses increased after using the combined strategy of OLTC1+ESS.

Table 12. Total system losses in kW in various use and test cases.

Device	None	OLTC1	OLTC3	ESS	OLTC1+ESS
Feb	2602,239	2588,656	2589,473	2150,782	6086,819
June	2825,224	2789,236	2897,024	3077,317	3010,753
year	34453,65				60400,694

The results show that OLTC is theoretically well suitable for loss reduction purposes. It is also clear that ESS can contribute very well to the problem solution – the winter result for ESS is better than both OLTC scenarios. On the other hand, the results show that in some situations the ESS increases losses instead of decreasing them. This phenomenon can be explained in a following way.

The ESS was installed next to the wind turbine, which means it supported the grid best, when the turbine worked efficiently – during high wind periods. When the turbine generated little power, though, the ESS replaced it as a generator. That meant introducing current up the feeder – a current that would not flow, had the ESS not been connected. That current obviously contributed to losses, therefore increasing them comparing with the situation of no control.

It must be mentioned though, that in this way, the ESS increased the generation in the grid, and that such a generation could not have been obtained without ESS. Therefore, in spite of increasing the losses, ESS still supported the grid. This situation shows that ESS can be a really useful device for support of Distributed Generation.

It might seem strange that the combination of two useful control strategies is totally ineffective, especially in the winter case. This may be partly contributed to the phenomenon described above but partly it originates from lack of coordination between the strategies. It is a big problem, as the coordination would require additional links between the sensors and therefore would be more difficult to introduce.

This argument can be brought up as a support for simple control strategies using just a single device, like a single ESS. The results showed that in general the benefits of using more devices are limited and sometimes do not appear at all. It seems also to be a better choice from the economic point of view.

Chapter 6. Conclusions

The study performed in this projects shows that various devices can be used for loss mitigation when distributed generation is present. Out of many possible options, two were chosen: ESS and OLTC.

ESS was proven to be a good choice for loss reduction, provided it is installed in a proper point of the grid. ESS is most useful when close to a generators. In some cases it can also be installed at the end of a long feeder, but the option concerning generators is generally better.

On the other hand, ESS can also increase the losses when it introduces additional current when an adjacent generator cannot generate too much power. This increase, however, also supports the grid, as in this case the losses come along with increased generation in the grid if compared to no ESS scenarios.

OLTC seems to be even a better choice for loss reduction. One must however remember that the use of OLTC in MV/LV transformers and their controllability are options rather considered that available nowadays in Denmark. This is another argument for use of ESS, especially of battery type, as this technology develops really fast and becomes more present also at low voltage level.

Even though both OLTC and ESS can be useful for loss reduction, their combination needs proper coordination to be fully effective. As this project focused on local control solutions, this is a topic for further study.

Another big point that has to be addressed in the future is avoiding over- and undervoltage with help of control devices. In this project it was only succeeded to reduce the over- and undervoltage but the improvement is not satisfactory yet.

Also the number of OLTC switchings was higher than expected. That is another argument against using the OLTC for loss reduction. It might be, however, that a coordinated strategy for use both OLTC and other devices could limit the stress put on OLTC and make it more useful.

To sum up, the project has shown positive results in loss reduction, however the constraints introduced in its beginning are still violated. That was mostly due to the fact that the grid chosen for simulations suffered from huge under- and overvoltage from the beginning. Anyway, the most crucial goal of the project was met.

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