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Loss Variation Calculations in Distribution Grids

Master of Science Thesis in the Master Degree Program,
Electric Power Engineering

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Göteborg, Sweden, 2006

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Abstract

Initially the intention was to investigate what loss levels to expect in different grid areas and to compare the levels to those obtained by the Grid Settlement Group at E.ON Elnät. The data from the grid settlement vary a lot between different grid areas and within a certain network during the year. There has been doubt about the accuracy in determining these variations.

Network calculations and simulations of a grid area at voltage levels of 10 kV and below were performed, using computer programmes. The available software turned out to be useful only to obtain yearly energy losses and only for one of the studied networks. Lack of quality data and limitations in software made accurate monthly energy loss calculations impossible. Consequently key factors, crucial for further studies, have been identified.

The major conclusion from this thesis is that E.ON Elnät does not have proper tools for precise determination of monthly energy loss levels in distribution networks. Improvement of available software, or on site measurements is recommended in order to improve the accuracy in loss determination.

Keywords: Losses, Power system, Grid, Settlement, Distribution

Acknowledgements

This thesis is the final part of my education at the Master Programme of Electric Power Engineering at Chalmers University of Technology. During the process I have really discovered how challenging it can be to work with real problems and real data.

The project presented in this report has been carried out at E.ON Elnät in Malmö. I would like to thank Alf Larsen and Nils Funke, my supervisors at E.ON Elnät, for great support. I would also like to thank Christian Andersson, Andy Karlsson and all other nice people at E.ON Elnät who have helped me and also made me feel welcome. I also appreciate the financial support from E.ON Elnät very much. Finally I want to thank my examiner at Chalmers, Robert Carlsson.

The work with the thesis has given me an experience, which is a valuable complement to the theoretical and practical education at Chalmers and inspiration for the working life ahead. I am looking forward to my first employment as a master of electric power engineering with greater confidence now than I did before starting to work with this thesis.

Lisa Ljungberg
Malmö 31 August 2006

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1 Introduction

1.1 Background

Calculations of losses in power systems have been attempted since long. Earlier efforts concentrated on energy loss estimation on a yearly basis and power loss estimations for maximum load situations. The estimated losses were important data when calculating the energy losses and planning grids. After the global deregulation of electricity markets, the situation has completely changed. Knowledge of the magnitude of losses with high accuracy is crucial for fair competition in deregulated markets. Today the energy market is divided into several segments; grid owners, energy suppliers and independent system operator. All of them, as well as the consumers expect the grid owners to report and handle losses with highest accuracy. Correct allotment of losses is necessary for correct allotment of loss costs. The grid owners are today expected to report correct losses monthly. However, even today most consumers have yearly read meters, which means that the monthly consumptions are based on models.

To be able to calculate losses with high accuracy, high quality data on power input and output is required. There are several ongoing projects dedicated to improve the data quality. One example is the replacement of old energy meters. Recently the grid owners in Sweden started to change all energy meters. This work will be completed in 2009, when all consumer meters will be monthly and automatically read.

1.2 Problem Statement

E.ON Elnät desires to improve its knowledge on the level of reasonable losses to obtain better reference values to the results of grid settlement. Since losses vary, knowledge on how losses vary within a certain network during different times of the year, different load conditions etc would be valuable. If the normal loss variations were known, errors in the metering, reporting and grid settlement would be much easier to detect.

1.3 Objectives

-To study data for a couple of real grid areas.
-To study a couple of grid areas using network calculation software.
-To study one grid area in detail.

1.4 Limitations

Both transmission and distribution levels are of interest within the subject of loss studies. In this thesis only distribution losses are considered. The losses are studied from the low voltage bus bar of the substations down to consumer level.

It is not possible to study all E.ON Elnät’s grid areas within a thesis work. Five grid areas are studied; one of them is studied in detail.

1.5 Procedure Statement

Today monthly losses are calculated by the Grid Settlement Group at E.ON Elnät as the difference between energy fed into a grid area and the energy for which the consumers are invoiced. Most consumers have annually read meters and the monthly consumptions are based on models. In this thesis the results of the grid settlement are studied for five grid areas in order to see what loss levels are reported today. The results for two grid areas are compared in detail, and discussed in relation to number of customers and total cable length.

To make accurate loss estimations, hourly measurements at locations where energy is fed into the system and at locations where energy is consumed would be necessary. These kinds of measurements are not available today; other methods have to be used in order to determine reasonable loss levels.

Power flow in power systems is quite complicated to study. Software simulations might be useful alternatives when actual frequent measurements are not available. At E.ON Elnät there are two network calculation and simulation tools available, Facilplus and PSS\E. Facilplus has access to data on individual customer consumption as well as data on equipment like cables and transformers. There were however problems related to data quality; nevertheless it was possible to run complete simulations for one of the studied grid areas. In PSS\E no data on real grid areas is available. Instead the user first draws a network; then edits data for all components and finally a simulation can be run. Both drawing and data editing are time consuming tasks. In this report a simulation of a 10 kV grid is performed and then the influence of cable length is studied.

1.6 Structure of the Thesis

Chapter 2: General Theories. Classification of losses and different methods for loss determination. General equations related to power and energy.

Chapter 3: Loss Magnitudes Obtained by Grid Settlement. Presentation of the loss magnitudes calculated by the Grid Settlement Group. Comparison of losses in different grid areas.

Chapter 4: Facilplus Simulations. Simulation of networks from 10 kV down to 0.4 kV in the computer program Facilplus Spatial.

Chapter 5: PSS/E Simulations. Simulations and sensitivity analysis of a grid. The computer programmes Facilplus and PSS\E were used.

Chapter 6: Conclusion and Recommendations. Conclusions, comparison of results from different parts of the report. Suggestions for future loss studies.

1.7 Abbreviations

1.7.1 Software

PSS\E: Power System Simulator for Engineering
SAP: Solution Application Program

1.7.2 Grid Areas

OBY: Osby
UVI: Uppvidinge
MMO: Malmö
OLD: Öland
HHM: Hässleholm

2 General Theories

2.1 Characterisation of Losses

To make it easier to investigate losses it is helpful to divide different types of losses into different categories. It is common to use two categories, technical losses and non-technical losses. Technical losses are losses that occur in electrical equipment, especially cables, overhead lines and power transformers. The other category, the non-technical losses, consists of losses not related to the physical power system but rather to loss sources like electricity thefts and errors in billing and meter reading. To find errors in networks and also to be able to reduce losses it is important for grid owners to know how much of the losses that are technical and how much that are non-technical.

2.2 Technical Losses

There are different ways to classify technical losses. One possible classification is to use the categories load losses and no-load losses. This classification method is particularly useful when studying the dependence of losses on power flow. Current flowing through cables and other pieces of electrical equipment causes load losses. No-load losses are losses that are independent of the actual load situation. Sources of no-load losses are the iron cores of transformers and corona discharges. There are also resistive losses in the primary winding of transformers contributing to the no-load losses. These resistive losses are so small that they can be neglected (Cronqvist Ed., 2006). Another source of no-load losses is energy meters. These losses are mainly iron losses in the voltage coils (Oliveira et al., undated).

Another way to categorise technical losses is to divide the losses into resistive losses, leakage losses and corona losses depending on the origin of the losses. The resistive losses, or copper losses, are losses due to the finite conductivity of the conductors in cables, lines, transformers and other pieces of equipment. Conductors can be modelled as impedances. Higher impedance corresponds to lower conductivity, which in a conductor results in higher losses. The leakage losses are losses due to the finite resistance of the insulation materials. For example no cable insulation is ideal; they always have a certain conductivity resulting in a small current flow through the insulator. Also dust and pollution on string insulators supporting overhead lines cause leakage currents and thereby leakage losses. At really high voltage levels corona losses also occur. Corona losses are caused by partial discharges in the air surrounding overhead lines.

2.3 Non-Technical Losses

Non-technical losses, sometimes called “commercial losses”, are very important because they often contribute to a large extent to the power that the utility is not paid for. Non-technical losses are often related to metering errors, inaccurate meters, improperly read meters and estimated consumption due to lack of meters. Unauthorised connections as well as administrative errors are other possible sources of non-technical losses. From the examples above it is clear that most non-technical losses are associated with low voltage distribution networks. At medium voltage distribution level, non-technical losses are primarily caused by inaccurate meters and tampering with measurement transformers (Dortolina and Nadira 2005).

At transmission voltage level non-technical losses are often related to metering errors at nodes where electricity is bought or sold on the wholesale market. On transmission level, non-technical losses are rare and can be neglected (Dortolina and Nadira 2005).

2.4 Loss Determination Methods

Correct calculations of losses are important for several reasons. In the deregulated markets trust between different operators; grid owners, energy suppliers, those responsible for energy balance, consumers and independent system operator, is essential. Everyone wants to get paid for the services they provide and no one wants to pay the bill for someone else. Accurate loss allotment maintains trust in the integrity of the grid owners.

Loss determination seems first quite simple; losses are the energy input to the grid minus the energy delivered to consumers. However, in practise it is not that easy. If high accuracy is wanted a lot of high quality data is necessary. Often sufficient data for a detailed analysis is not available. This problem can partly be overcome by the use of models and computer simulations. Sensitivity analysis can be used to study the influence of different parameters.

Like methods in many other branches of industry loss determination methods can be divided into top down (system perspective) and bottom up (component perspective) approaches. Characteristic for top down methods are quick estimates that are not very exact. Bottom up methods are more detailed and thereby more exact solutions are obtained. These more detailed methods require more data and are also more time consuming than the top down methods. There are also different kinds of methods that could be classified as hybrids of top down and bottom up methods. These methods yield more accurate solutions than the top down methods and are less time consuming than the bottom up methods.

Dortolina and Nadira (2005) have suggested a top down/bottom up approach, which can be applied when detailed data is available only for some parts of the grid. Their method can be carried out as follows:

> Step 1. The bottom up method is used to perform accurate calculations for regions with sufficient data available.
>
> Step 2. The top down approach is used for the remaining parts of the grid. The regions are divided into different groups, similar regions in the same group. Then by applying the results from the bottom up analysis losses in the other regions can be estimated.

Ferreyra and Paoletich (2001) have developed a model for calculation of losses and the ratio of technical and non-technical losses. To calculate the total losses, data on input energy to the network and data on the amount of energy sold to consumers are used. To be able to find the amount of non-technical losses, the power flow through the system is followed and the technical losses corresponding to each level is determined.

2.5 Loss Reduction – Technical Losses

From an environmental and sustainable development perspective, the short and long-term detection and reduction of technical losses at first seems important. Additional energy needs to be produced and transferred to cover technical losses. During peak load non-renewable energy resources like gas and oil are often used and the energy prices at these occasions are high. Energy consumption increases continuously and if losses are successfully reduced, the length of life of the present networks are extended, since the loss reduction facilitates a certain consumption increase. By reducing losses, money can be saved and the impact on environment can be reduced.

The recently introduced trade with emission rights also makes it more economical to reduce losses during peak load. Reduction of losses in power systems reduces both the cost of energy production and energy transportation. Improved knowledge on energy losses is a major objective for all operators involved.

However it is often expensive and difficult to reduce technical losses. Replacement of old equipment is one way to reduce technical losses. Electrical power components are very expensive and built to last for a long time, often 30 years or more. They are too expensive to be replaced, if not necessary for other reasons e.g. damage. However when installing new transformers, cables and other pieces of equipment; losses should be taken into consideration. Due to the long lifetime of power system components, a more expensive piece of equipment can be less costly when losses are taken into consideration than the unit that at first seemed to be the cheapest.

The following measures may be taken to reduce technical losses:

- A flat voltage profile reduces the losses. If the network is not simply radial but more grid structured circulating currents will appear if the voltage profile is not kept at a common level throughout the network. The circulating currents cause losses. To avoid this, the voltage is allowed to vary only a few percent from nominal value.
- Reactive power compensation, i.e. keeping power factor close to 1, is a common way to minimize losses. By keeping the power factor close to unity, reactive power flow is reduced and thereby current flow and active power losses are reduced. At large inductive loads, for example large induction motors, capacitors are installed close to the load. In the case of long underground capacitive cables, shunt reactors can be needed to reduce the reactive power flow. By keeping the power factor close to one, not only currents through the lines are reduced but also the voltage drop over the line is reduced, resulting in a more flat voltage profile.
- Increasing the normal voltage level of the network reduces the losses; because at higher voltage a lower current is needed to transfer the same amount of power, see equation 2. Reduced current results in less resistive losses and also reduced inductive losses.
- Phase balancing is another way to reduce losses. Phase balancing means that all three phases carry the same amount of power. This is an issue especially for heavily loaded lines (Davidson et al. 2002).

2.6 Loss Reduction Non-Technical Losses

Non-technical losses often decrease rapidly after privatisation (Dortolina and Nadira 2005). Private companies are interested in increasing their profit and one way to accomplish this is to reduce losses. It is usually easier and less costly to reduce non-technical losses than technical losses and many private companies invest in improved meters and customer billing systems.

Some measures that can be taken to reduce non-technical losses are the following:

- Improving metering equipment.
- Improving reading of meters.
- Improving billing systems.

2.7 General Equations

2.7.1 Power and Energy

In this chapter the relation between power and energy is presented. If nothing else is indicated, the concepts power and energy are always used in the sense active power and active energy. The concept losses are used in the sense technical losses, in this chapter, were nothing else is indicated.

The three-phase power can be written

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos \rho \qquad (1)$$

The power factor is close to one in power grids, and can sometimes be assumed to equal unity. Equation 1 can then be simplified and rewritten

$$P = \sqrt{3} \cdot U \cdot I \qquad (2)$$

Using Ohm's law equation 2 can be rewritten

$$P = 3 \cdot R \cdot I^2 \qquad (3)$$

Energy W is defined as the time integral of power P.

$$W = \int_0^T P dt \qquad (4)$$

In other words the area below the power curve, see Figure 1.

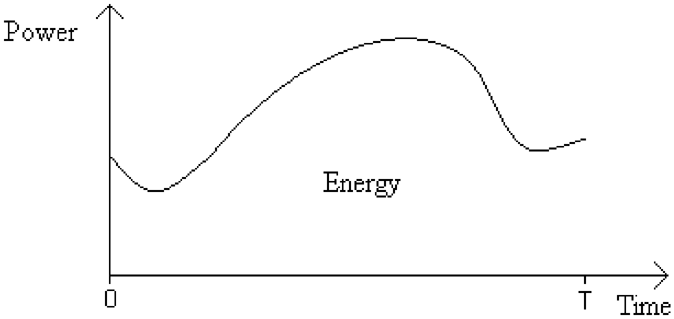

Figure 1 Relation between energy and power

The energy can also be calculated as the average power multiplied by the duration of the studied period

$$W = P_{average} \cdot T \qquad (5)$$

Often the maximum power P_{max} is known, but not the average power. In these cases load duration time τ can be used instead of the actual duration of the studied period. The following equation can be used

$$W = P_{\max} \cdot \tau \tag{6}$$

Similar equations are valid for loss calculations, the energy loss can be written

$$W_{loss} = \int_0^T P_{loss} dt \tag{7}$$

It is also possible to use the maximum power loss and loss duration time to obtain the energy loss

$$W_{loss} = P_{loss,\max} \cdot \tau_{loss} \tag{8}$$

2.7.2 Resistive Losses

In this section the theories of losses due to resistance in conductors, R_c, are studied. For one phase the momentary total active power loss P_{loss} can be written

$$P_{loss} = R_c \cdot I^2 \tag{9}$$

When studying the total power consumption in a three-phase system all three phases have to be taken into consideration, i.e. equation 9 should be multiplied by 3.

$$P_{loss} = 3 \cdot R_c \cdot I^2 \tag{10}$$

The reactive losses depend on both the inductance and the capacitance of the line. The inductance consumes reactive power and the capacitance produces reactive power. In this thesis only active losses are considered. For comparison to equation 10 however, the formula for reactive power loss due to inductance can be interesting.

$$Q_{loss} = 3 \cdot X_c \cdot I^2 \tag{11}$$

From equation 10 it is clear that the power losses depend on the load current in square. In this report the focus is on energy losses, which are not dependent on the load current in square, but rather on the changes in power and thereby changes in load current in square. During two different months the total amount of energy fed into one system can be the same, while during one month the power flow may have been almost constant and during the other the power flow may have fluctuated a lot. This kind of differences in power flow may cause different losses in one grid during different parts of the year.

Since the load current changes continuously the loss power also changes all the time. To come around the integral calculations the loss duration time and high load current can be used to calculate the active energy losses. The active energy loss can be written

$$W_{loss} = 3 \cdot R_c \cdot I_{\max}^2 \cdot \tau_{loss} \tag{12}$$

The relation between current and power is

$$I = \frac{S}{\sqrt{3} \cdot U} = \frac{\sqrt{P^2 + Q^2}}{\sqrt{3} \cdot U} \tag{13}$$

Where S represents apparent power, P active power and Q reactive power.

Equation 13 can be inserted into equation 10, resulting in the following active loss power equation

$$P_{loss} = R_c \cdot \left(\frac{P}{U} \right)^2 + R_c \cdot \left(\frac{Q}{U} \right)^2 \tag{14}$$

3 Loss Magnitudes Obtained by Grid Settlement

3.1 Introduction

In this part of the master thesis values from the Grid Settlement Group are presented in order to obtain an overview of the subject, and to see what loss levels are used today. The approach in this section is a system approach and can be considered as a top down method.

The data used in this section is measured input energy to every substation and values of energy consumption obtained by grid settlement. Most consumers have yearly read meters and their monthly consumptions are estimated by the use of models. These models are common and used by all grid owners. Svensk Elmarknadshandbok (2006) is designed to ensure common routines for operators on the Swedish electricity market. There is a certain amount of uncertainty regarding the accuracy of the models. However it is interesting to study loss magnitudes obtained by the loss determination method used by grid owners in Sweden.

With support from Nils Funke five suitable grid areas were chosen: OBY, UVI, MMO, OLD, HHM. First an overview of all grid areas was studied and then different grid areas were studied separately. The OBY grid area was investigated in detail, to make comparisons to results obtained in later chapters possible. To find measurement data on energy fed into different substations, the computer program M2 was used. In M2 data on energy input to all substations is stored.

Every grid area is fed through several substations, which are not connected to each other during normal operation. A grid area is a geographical area; it is not an electrical connected grid. Data on input energy is available for every substation, while the loss calculations performed by the Grid Settlement Group are performed for every grid area, containing one or more substations. The losses are defined as the input energy minus the energy for which the consumers are invoiced. The losses consist of both technical and non-technical losses, but the ratio is not known. When the loss is given as a percentage, it is calculated as the energy loss divided by the total amount of energy fed into that particular grid.

There are several sources of errors. Energy consumed by control equipment, radiators and water pumps in substations is not measured on site, but the energy is estimated for each grid area. If the accuracy of these estimations is high, substation equipment should not result in errors in loss calculations performed by the Grid Settlement Group.

Street lighting is another possible source of errors. Energy used for lighting is measured in the MMO grid area. In the other studied grid areas improved fictitious metering was introduced in 2005. Before year 2005 the charging of municipals was based on an earlier version of fictitious metering. The rated power of the light bulbs was multiplied by the burning time and the number of light bulbs. The accuracy of the fictitious metering is crucial for the accuracy of the energy used for lighting and thereby the energy losses.

Metering contributes to errors in several ways. First, the accuracy of the meter itself is not perfect. Another source of errors in the metering process is related to meter reading. The reading and reporting of meter data are done manually, in at least two steps. Each step provides risks for data errors. The first step is the reading of meters. This is often done by the customers themselves and they sometimes fail to read the meters correctly. There is also a potential risk of fraud. The second step when the report card data is fed into a database contains error risks. The data is often written by hand and correct interpreting and editing of reported digits is crucial in order to obtain a high degree of accuracy.

In this section data from year 2004 and the first part of 2005 is used. The first twelve months in the figures corresponds to 2004 and month 13-16 corresponds to January, February, March and April 2005.

3.2 Results

3.2.1 Losses - Overview

To compare losses in different grid areas, the losses as a percentage for all grid areas were plotted in one figure. At a first glance Figure 2 seems messy; however one can come to a few conclusions. The curves seem to be smoother from month 13. This is a result of the quality work performed by the Grid Settlement Group at E.ON Elnät. Examples of this quality work are improved algorithms in SAP and improved general routines. In this chapter the more recently obtained data is more reliable than the older data. The extreme values in Figure 2, for example the high peak in the MMO grid area, correspond to grid settlement errors. The negative values also correspond to errors in the grid settlement. Due to the methods used to obtain loss values, there may be more error points. In Figure 2 the losses of OLD is zero the last four months. The reported loss data was not zero, but since the Grid Settlement Group has changed routines concerning the data of OLD, the results for these months are not comparable to the data previous months and have therefore been omitted.

From Figure 2 one can see that different network areas do have different losses, for example the percentage losses in the MMO grid area are always below the percentage losses in the OBY grid area (except for the data error points). The relatively low losses in the MMO grid area could be a result of the grid topography. The MMO grid supplies a dense populated area; there are many consumers in relation to cable length. Short cables result in low losses.

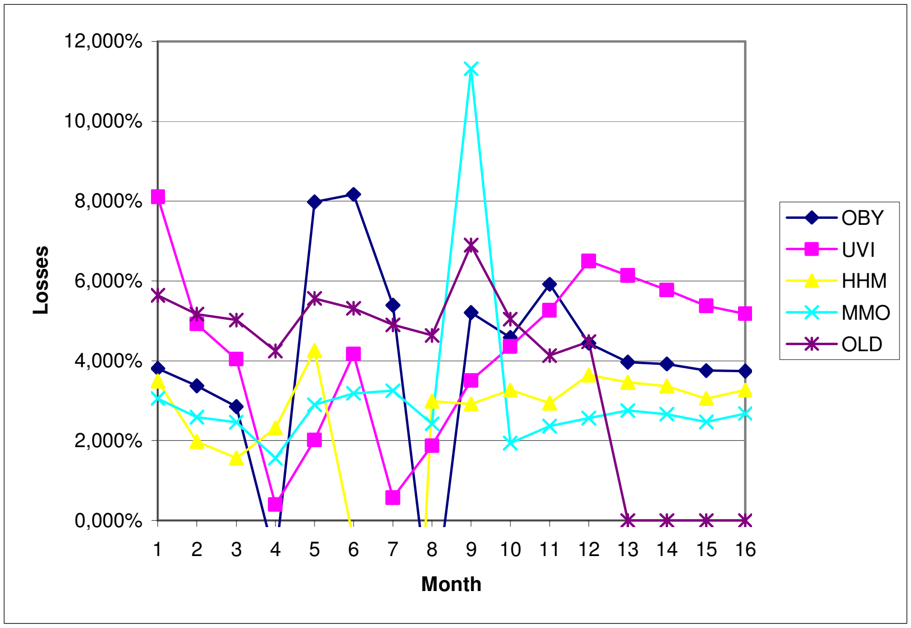

Figure 2 Losses different months 2004-2005 for five areas

3.2.2 Losses – Details OBY

In Table 1 the energy input and the energy losses in the OBY grid area are presented. The zero values correspond to negative losses, i.e. obvious errors in the grid settlement. The losses in Table 1 are plotted in Figure 3 and Figure 4.

Table 1 Energy input and energy losses in OBY

Month	**Input Energy [MWh]**	**Losses [MWh]**	**Losses [%]**
2004 – Jan	7954	303	3.8
2004 – Feb	6951	235	3.4
2004 – Mar	6952	198	2.9
2004 – Apr	5308	0	0
2004 – May	4589	366	8.0
2004 – Jun	4192	342	8.2
2004 – jul	3586	193	5.4
2004 – Aug	4130	0	0
2004 – Sep	4686	244	5.2
2004 – Oct	5649	259	4.6
2004 – Nov	6744	399	5.9
2004 – Dec	7128	317	4.4
Sum	67870	2856	4.2

In Figure 3 the magnitudes of losses in the OBY grid area are plotted as a function of energy fed into the system. The absolute magnitudes of the losses seem to be independent of input energy; the losses seem to be random. This could be a result of grid connection changes during the year; another possible explanation might be low quality data. In other words low similarity between reality and the common models used by grid owners to spread annual energy consumptions over the months. This seems to be quite likely when studying Figure 2, where the losses in the OBY grid area vary quite a lot during 2004.

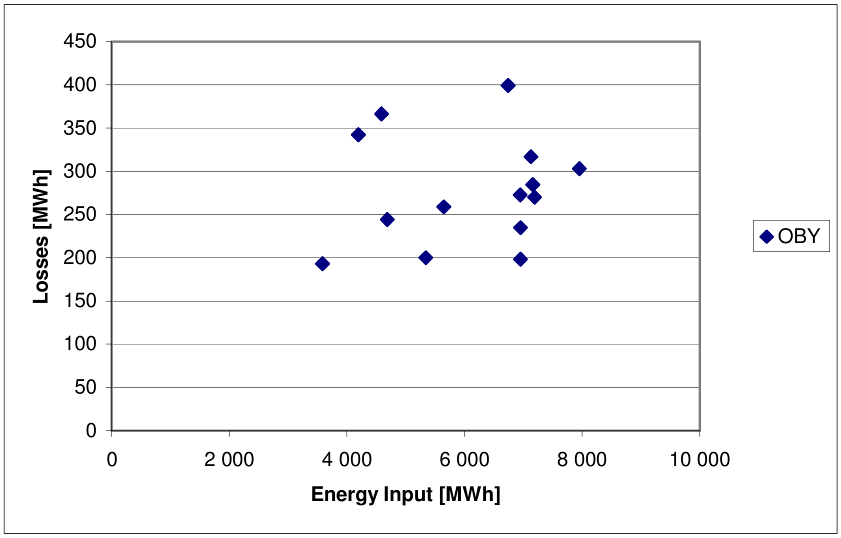

Figure 3 Losses in MWh as a function of the energy fed into the system different months

In Figure 4 the percentage loss values are plotted and there seems to be a negative slope. The negative slope could be explained by high no-load losses. No-load losses constitute a larger amount of the total energy losses at low energy input than at high energy input. This results in high percentage losses for low energy input. Even though there is a negative slope, the variations along a fictitious line are remarkably large.

Another possible interpretation of Figure 4 may be random losses between 3% and 6% and two months with loss levels of 8% might correspond to metering or settlement errors. No physical explanation to random losses has been found during the research for this thesis.

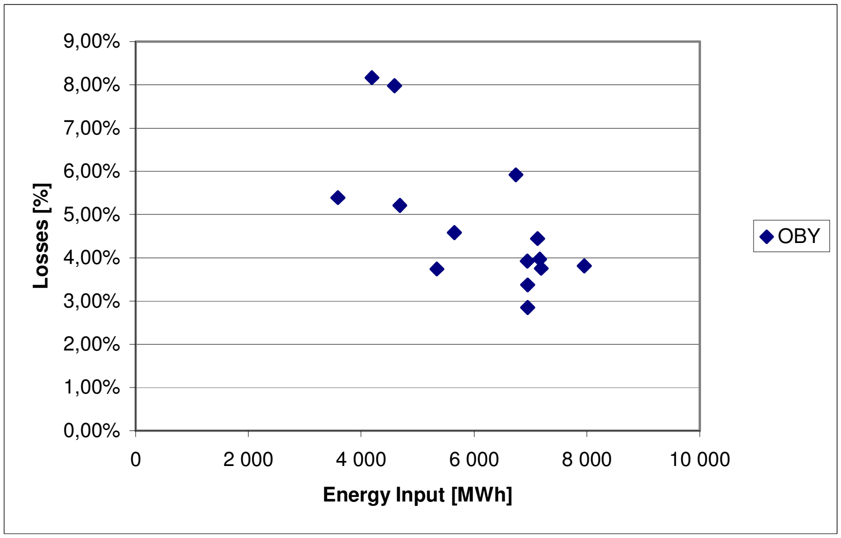

Figure 4 Losses in % as a function of the energy fed into the system different months

3.2.3 Losses – Details UVI

For the UVI grid area there seems to be a relation between input energy and absolute energy losses, see Figure 5. Power losses in conductors, as absolute values, increase linearly with input power since both power losses and input power is proportional to the load current in square; see equation 3 and equation 9. This means that there should be a linear relation between input power and power losses. The relation in Figure 5 seems to be almost linear. In this chapter energy losses are considered, not power losses. To calculate energy losses changes in power losses has to be considered, but they are not known. The explanation might however be used as an indication of relations between losses and energy input, or as an indication of the difficulties involved when discussing energy losses. The UVI grid area supplies a sparsely populated area so a fair assumption is that losses due to power distribution through long cables constitute a large part of the total losses.

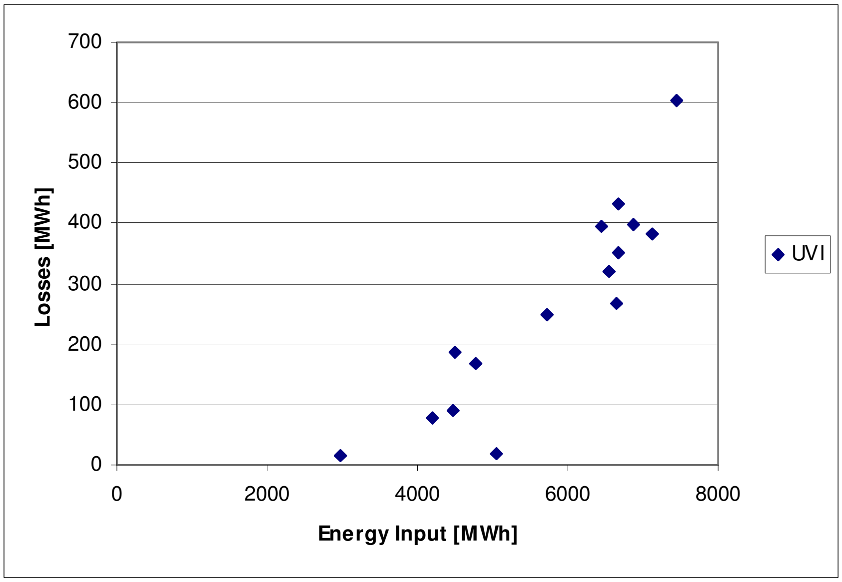

Figure 5 Losses in MWh as a function of the energy fed into the system different months

In Figure 6 the percentage losses in the UVI grid area are plotted as a function of energy input. The percentage losses increase almost linear with energy input, Figure 5 and Figure 6 looks similar. The increase in Figure 5 is however not linear, if it was linear the trend in Figure 6 ought to be a constant loss level, corresponding to the slope of a fictitious curve fitted in Figure 5. The increasing trend in Figure 5 is of a degree between first order and second order.

There is possibly an administrative explanation. The models used for breakdown of annual energy consumption by month might not mirror the real energy consumption. The models used for breakdown of yearly energy consumption by month are certainly not exact. A crucial difficulty is to evaluate the accuracy of the models, and thereby the accuracy of obtained loss values.

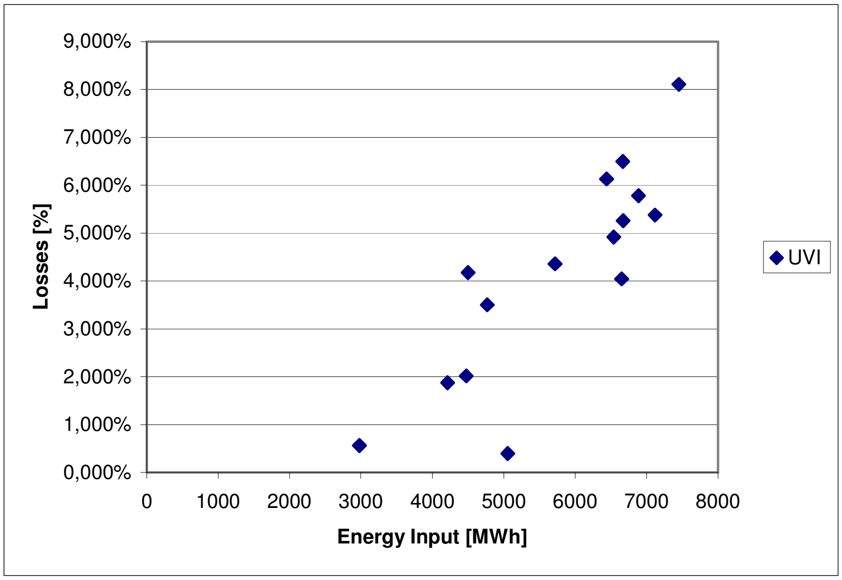

Figure 6 Losses in % as a function of the energy fed into the system different months

3.2.4 Losses – Details MMO

In Figure 7 and 8 the losses, absolute values and percentage values, in the MMO grid area are plotted as a function of energy fed into the system. The extremely high value of 11% originates from a grid settlement error.

In Figure 7 the losses seem to be almost constant, with a small increase for high levels of energy input. The almost constant level of loss magnitude is a little strange, there ought to be a certain increase in losses for increase in energy input. Almost constant loss magnitudes could be explained by extremely high no-load losses in relation to load losses. This is however not a probable explanation to the almost constant loss magnitude in Figure 7.

The dots in Figure 7 might also be interpreted as linearly increasing if five data values would correspond to errors and therefore could be neglected. It is difficult to accurately tell if a data value is accurate or not. Equation 3 and 9 validates the interpretation of the dots as linearly increasing; both power losses and input power in conductors are proportional to the load current in square. This results in a linear increase of power losses with input power. If this relation is valid for energy losses or not, is dependent on the variations during the month. These variations are not known.

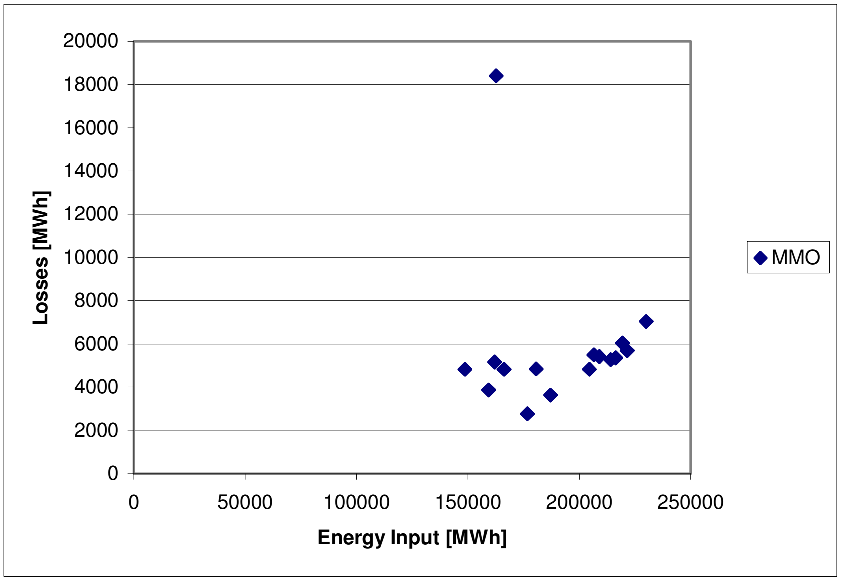

Figure 7 Losses in MWh as a function of the energy fed into the system different months

The percentage losses in Figure 8 seem to be quite constant, independent of the energy fed into the area. One explanation could be that losses in conductors, as absolute values, increase linearly with input power since both power losses and input power is proportional to the load current in square; see equation 3 and equation 9. This means that there should be a linear relation between input power and absolute power losses; resulting in constant percentage power loss values. As discussed in previous sections of this chapter, it cannot be taken for granted that this explanation based on power is valid also for energy.

Another explanation to Figure 7 might be that the model, used by grid owners in Sweden, spread the annual energy consumption smoothly over the months in relation to the monthly measured energy input. This might result in constant percentage losses.

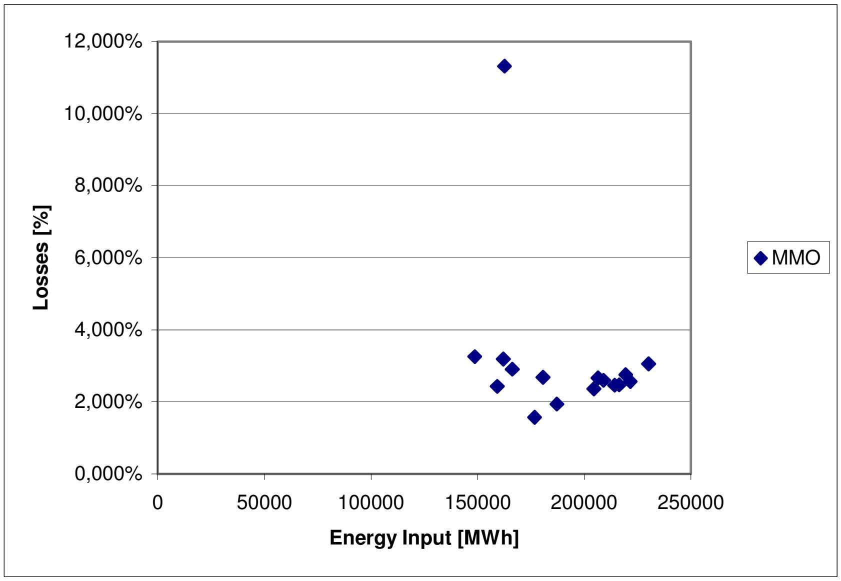

Figure 8 Losses in % as a function of the energy fed into the system different months

3.2.5 Losses – Details OLD

In Figure 9 the losses in the OLD grid area are plotted. The absolute magnitudes of the energy losses seem to increase with increasing input energy. Power losses increase linearly with input power since both power losses and input power is proportional to the load current in square; see equation 3 and equation 9. This means that there should be a linear relation between input power and power losses. However there are errors introduced when this kind of explanations based on power are used; see previous sections in this chapter.

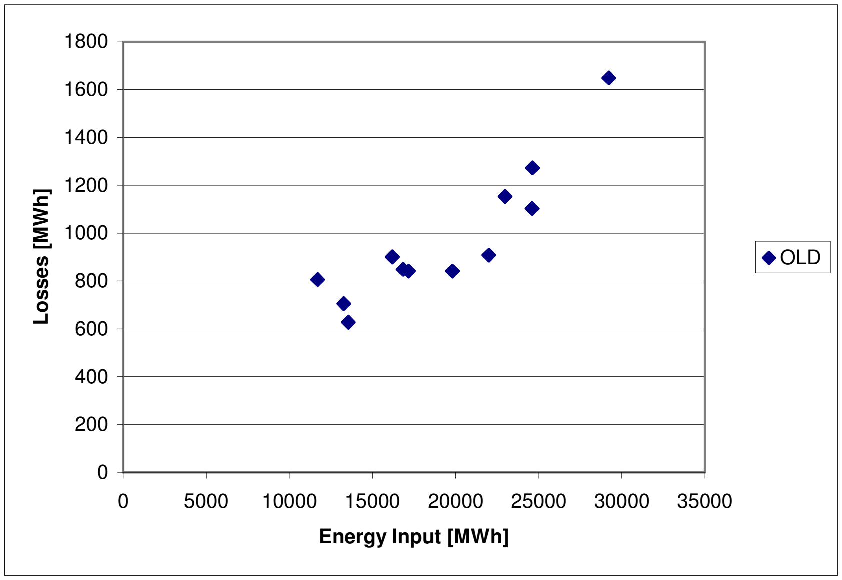

Figure 9 Losses in MWh as a function of the energy fed into the system different months

The losses as percentage values seem to be quite random; see Figure 10. If it is assumed that the dot at a loss level of 7% corresponds to a measurement or grid settlement error, the general trend in Figure 10 might be interpreted as a horizontal line. In other words, the percentage losses are constant. This is what theoretically might be assumed if the relation between power and power losses also may be applied to energy and energy losses, as discussed before.

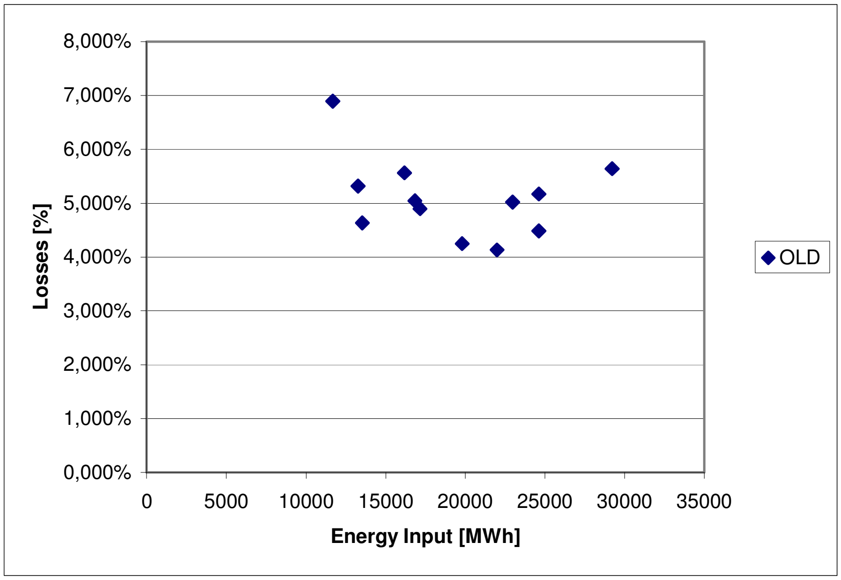

Figure 10 Losses in % as a function of the energy fed into the system different months

In the OLD grid area there is a large number of windmills. Windmills in power systems often reduce losses, but the relation is quite complicated. The influence of windmills is not an issue of this project.

3.2.6 Comparison: OBY and UVI

Of course input energy differs between network areas, but out of the chosen areas there are actually two with similar energy input magnitude. The energy fed into the OBY grid area is similar to the energy fed into the UVI grid area; see Figure 11. The variations during the year are also similar. Actually in most networks the variations during a year have this shape.

During month 12 and 13 there is a clear difference in the amount of energy fed into the two areas, see Figure 11. More energy is fed into the OBY grid area. However when studying the losses these months, see Figure 12, it can be noticed that the losses in the UVI grid area are higher than the losses in the OBY grid area.

In Figure 12 there are two months for which the losses in the OBY grid area are negative, i.e. there are obvious errors in the grid settlement. These data points have been omitted.

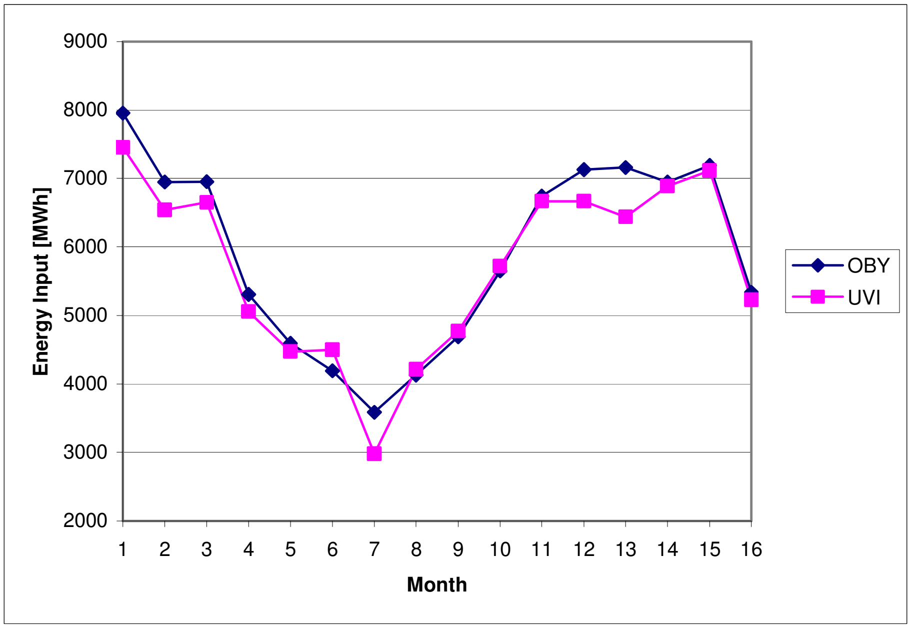

Figure 11 Energy fed into the grid area different months

The loss values from year 2005 are smoother and easier to compare than the loss values from year 2004. From month 12 to month 16 the losses in UVI is slightly higher than the losses in OBY, however the amount of energy fed into the grid every month is lower for UVI than for OBY, according to Figure 11. This means that in this period the losses in relation to the input energy, in UVI are higher than the losses in OBY, which also can be seen in Figure 2.

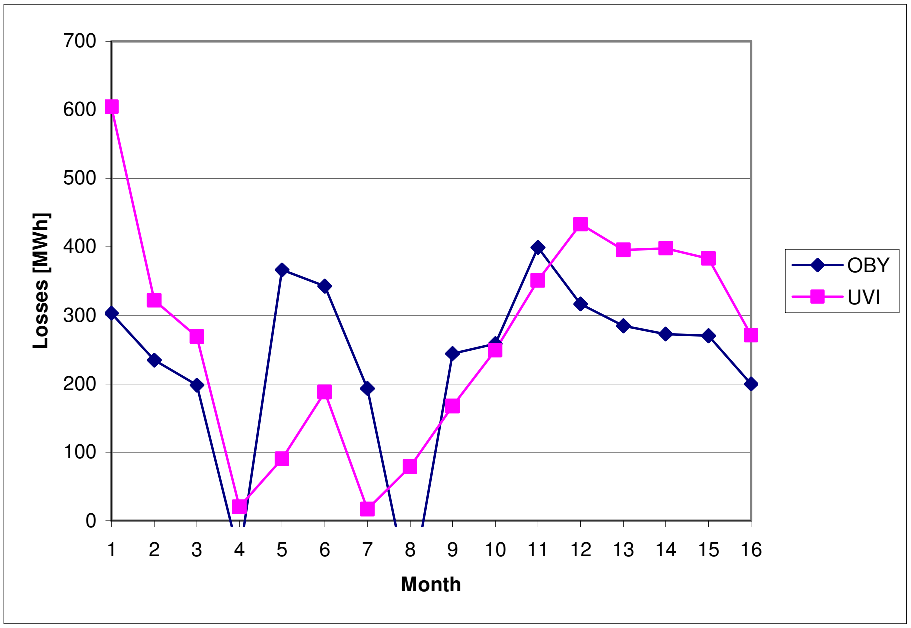

Figure 12 Losses in OBY and UVI

In Table 2 grid data for the OBY grid area and the UVI grid area is presented, the data is generated from the Facilplus software (for more information on Facilplus, see chapter 4). Since UVI consists of three substations, the presented data is the sum of the data from the three substations. It is clear that the total cable length in UVI is more than twice the length of the cables in the OBY grid area, both at 10 kV and 0.4 kV level. Despite the long line length in UVI, OBY is the grid area with more consumers. The energy fed into the two grid areas are of similar magnitude, but the number of consumers differs remarkably. The UVI grid area is a typical rural area, while the OBY grid area is denser populated. The longer lines in the UVI grid area could explain the higher losses in UVI during month 12 to 16 in Figure 12.

Table 2 Data for OBY and UVI

Grid Area	**Number of Consumers**	**Total Length of Cables & Lines 20 kV [km]**	**Total Length of Cables & Lines 10 kV [km]**	**Total Length of Cables & Lines 0.4 kV [km]**
OBY	4100	0	78	252
UVI	2400	99	381	580

In section 3.2.2 and section 3.2.3 the losses in OBY and UVI were studied separately. By comparing Figure 4 to Figure 6 an interesting difference can be noticed; while the percentage losses in OBY decrease with increasing energy input, the percentage losses in UVI increase with increasing energy input. The discussions in the sections related to these figures do not fully explain the differences. They might be explained in terms of inaccuracy in measurement or grid settlement. If there are errors in the data used in the sections describing OBY and UVI separately, there are also errors in the data used in this chapter. The same data source was used for the entire Chapter 3.

3.3 Conclusions

From the findings of this chapter it is clear that there are substantial variations in losses calculated by grid settlement, among networks and within a certain network during the year. The variations in the loss percentages are difficult to explain. Comparing the losses and the amount of energy fed into different network areas did not sufficiently explain the loss variations.

The longer line length in the UVI grid area could explain the higher losses in that grid area compared to the losses in the OBY grid area. In OBY there are about 70% more consumers compared to the UVI grid area, however this does not seem to affect the loss levels at all. In order to achieve further knowledge on the impact of consumer numbers on losses, the breakdown of consumers by consumer category probably has to be properly investigated.

In this chapter, only values from the grid settlement have been studied. It is not an established fact that technical losses do vary very much. It is possible that variations depend on the models used to spread the consumers' energy consumption over the year, resulting in loss levels that are not accurate enough. More knowledge on the accuracy of the models would be valuable.

One explanation to the large differences between grid areas could be variations in non-technical losses. Non-technical losses might constitute a large amount of the total energy losses. Efforts to reduce non-technical losses will possibly result both in reduced total losses and increased similarity between loss curves from different grid areas.

The loss data from the grid settlement relates to estimated values, which are less useful when trying to investigate relations in detail. The optimal data would be data obtained by frequent accurate metering.

4 Facilplus Network Calculations

4.1 Introduction

To perform network calculations Facilplus Spatial was used. Facilplus Spatial is a web based power network information system. The database contains maps and information on all components in the network as well as their relative locations. The data is updated every day. The software is primarily used for cable and equipment documentation purposes. It is also possible to perform calculations from substation level down to the consumers.

In this chapter simulations of the OBY grid area are presented. The intention was to present data for all five studied grid areas. Due to data errors in the database used by the software it was not possible to perform successful simulations of all substations in all grid areas. To be able to compare simulation results to the grid settlement results it is important to have simulations for all substations in a grid area. OBY and OLD were the only grid areas with a complete set of successful simulations. The network calculation is a quite time consuming task in Facilplus. Errors are not detected until the complete calculation is performed. One simulation was performed for every substation, and then a decision was made on which grid areas to study further. The decision was based on number and severity of data faults in different grid areas. OBY and OLD were the only grid areas with only small problems. In other grid areas some substations showed strange problems like larger energy losses than input energy and double customer input data, other had problems with diverging solutions. Another common fault is lack of transformer data; however data for standard transformers was used in the simulations. Since lack of transformer data is a concern for only one or two percent of the total number of distribution transformers in a grid, the loss levels is not affected very much by the choice of standard transformer data.

The OLD grid area contains a large number of windmills, by Facilplus just considered negative loads. To get accurate results a much more careful model of wind farms is required. The value of losses in OLD can therefore not be studied with high accuracy in Facilplus and results from the simulations of the OLD grid area are not included in this report.

4.2 Theory

Facilplus collects data from the business system SAP. For smaller consumers like households, the yearly energy consumptions are collected. For larger consumers like industries, both yearly energy consumption and maximum power is available. For all customers SAP stores heating code and type of customer.

In Facilplus there is a possibility to choose between power priority and energy priority. This refers to power customers. The choice power priority means that the maximum power consumption is used in the calculations. Energy priority corresponds to the total energy consumption previous year.

The yearly energy consumption of each consumer is multiplied by a common eligible load level. The load level is chosen as a percentage value of the total energy consumption previous year, i.e. a load level of 100% corresponds to the energy consumption previous year.

Data on yearly energy consumption, heating code and type of customer is combined to determine which calculation category in Facilplus to use for each customer. When considering several loads, all loads should be added. Loads change over time, often independently of each other, reaching maximum power at different occasions. Because of that the maximum total power consumption is less than the sum of the maximum power consumption of all consumers. Instead of just adding all consumptions there are other methods, in Sweden the Velander formula is commonly used. Facilplus Spatial uses this method in combination with data on calculation category to calculate the maximum total load power of several consumers. Each calculation category has its own values of k_1 and k_2 in the Velander formula. The Velander formula is written

$$P_{\max} = k_1 \cdot W + k_2 \cdot \sqrt{W} \tag{15}$$

P_{max} is the estimated maximum total load power and W the sum of the yearly energy consumption of all loads. The constants k_1 and k_2 has been obtained by experience (Blomqvist Ed., 2003). In the software there is an opportunity to use different Velander tables corresponding to different parts of the year. The choice does influence losses by changes in the power consumption pattern, i.e. changes in the constants k_1 and k_2.

The total load power for all small consumers calculated using the Velander formula is added to the loads of the larger consumers.

It is possible to choose number of operating hours for loads and losses. The operating hours are used to calculate the yearly energy consumption for power customers when only power is known.

The annual energy losses, caused by energy transportation to all types of consumers, are obtained for each cable section and each transformer by usage of the Yngve Larsson's equation. Yngve Larsson's equation is useful since it facilitates calculation of energy losses based on annual energy consumption, which is almost always known. The disadvantage of Yngve Larsson's equation is that it is only an approximate model. Once energy losses have been calculated for every section, the losses are added to obtain the total load losses in the network. According to Eldistribution (Berghe et al., undated), Yngve Larssons equation can be written

$$W_{loss} = k \cdot \frac{R}{U^2 \cdot \cos^2 \varphi} \cdot \frac{W^2}{T} \tag{16}$$

W_{loss}: Annual energy losses [kWh]
k: Larsson's constant
R: Resistance [Ω]
U: Voltage [V]
cosρ: Power factor
W: Annual energy consumption [kWh]
T: Number of hours/year

$T = 8760$
$1.2 < k < 1.5$

A high value of Larsson's constant, results in high annual losses. Similarly a low value of Larsson's constant results in low annual energy losses. Different values can be used to calculate losses in different types of networks. However there is no general rule for the choice of Larsson's constant. The power factor cosφ is assumed independent on load level (Berghe et al., undated).

The no-load losses are added to the load losses obtained by Yngve Larsson's equation to get the total annual energy losses. Transformers are the major source of no-load losses.

For loss calculations Facilplus automatically uses graphical length of lines and cables. In the database both graphical length and measured length are available. The measured cable length refers to documented values from the cable laying team. The graphical cable length refers to the length of cables on the maps in Facilplus. Errors may have occurred when the cables were measured and the length reported, on the other hand cable length between earth and the top of a tower is not considered in the graphical presentation.

Monthly energy losses are not available in Facilplus. Data on monthly energy consumption is not available for most consumers and there is no formula for breakdown of annual energy consumptions by month, stored in Facilplus.

The database is updated every day and the result of similar network calculations may consequently differ from one day to another. When studying energy consumption and energy losses on a yearly basis the daily updates cannot influence the results very much.

4.3 Simulations

The simulations were performed from substation level down to consumers. When there are several substations in a grid area the losses from all substation's networks have to be summed in order to calculate the total losses of the grid area.

The measurement equipment used to obtain values for the grid settlement is located on the low voltage side of the substation transformers. To make comparisons between this and the previous chapter possible the simulations were performed from the low voltage bus bar of the substation transformer down to the consumers, i.e. the same pieces of equipment are studied in this and in the previous chapter.

In Facilplus, data on several transformers is missing. In most grid areas one or two distribution transformers out of about one hundred lacks data on rated power, winding connection and impedance. To perform a simulation complete transformer data is required. Standard values were used when no data was available. Since 500 kVA transformers are the most common size, this size of standard transformer, and common data related to 500 kVA transformers were used. In cases where the transformer lacking data was in parallel with another transformer the data of the known transformer was used.

Since the focus is on annual energy losses and annual energy input, 100% load level seems to be the most suitable choice. In this report 100% is used as default, and a series of network calculations with different load levels were performed, to investigate the influence of this parameter on the losses.

In this report energy priority was chosen out of the two choices power priority or energy priority. This choice was made since the scope of this thesis is confined to energy losses.

The default Velander table is the December – March table. The default table has been used in this thesis when nothing else is indicated.

The loss constant Larsson's constant is 1.4 by default, which also has been used in the simulations where nothing else is indicated.

4.4 Results

Due to data errors in the database used by Facilplus, OBY was the only grid area in this project for which it was possible to perform successful simulations. In the other grid areas there were severe errors in the simulations of at least one substation in each grid area. A complete series of simulations is necessary to obtain data comparable to the data obtained by grid settlement.

The results of the simulations at different load levels are presented in Table 3. To each load level in Table 3 there is a corresponding amount of energy fed into the OBY network. 100% load level corresponds to data from previous year, while the other percentages correspond to fictitious years in relation to previous year. The losses as percentage values are calculated as the quotient of total energy losses and total energy input.

Table 3 Results from grid calculations in Facilplus

Load Level [%]	Tot. Energy Fed Into the System During One Year [MWh]	Tot. Energy Losses During One Year [MWh]	Energy Losses During One Year [%]
35	21621	724	3.3
50	30888	876	2.8
60	37065	1011	2.7
75	46331	1267	2.7
85	52509	1475	2.8
100	61775	1848	3.0
120	74130	2464	3.3

In Figure 13 the result from a series of Facilplus calculations are shown. The different magnitudes of input energy correspond to different load levels; see Table 3. As one can expect there is an increase in losses with input energy. Power losses increase linearly with input power since both power losses and input power is proportional to the load current in square; see equation 3 and equation 9. This means that there should be a linear relation between input power and power losses. Energy losses are more complicated since not only the total amount of energy fed into the network is of interest, but also the load power variations.

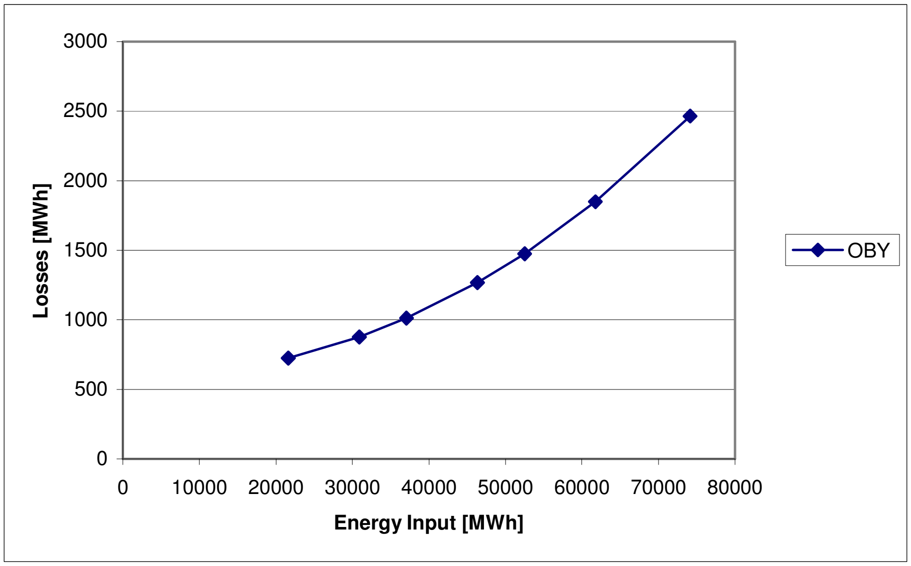

Figure 13 Energy losses as a function of input energy

When studying the losses as a percentage, there is a minimum at a load level of about 60%, with higher loss percentages below and above, see Figure 14.

The increase of losses for low load levels can be explained in terms of no-load losses. No-load losses are constant and not dependent on load level. For low load levels, no-load losses constitute a larger amount of the total losses than for higher load levels. This might result in increasing losses for decreasing load levels.

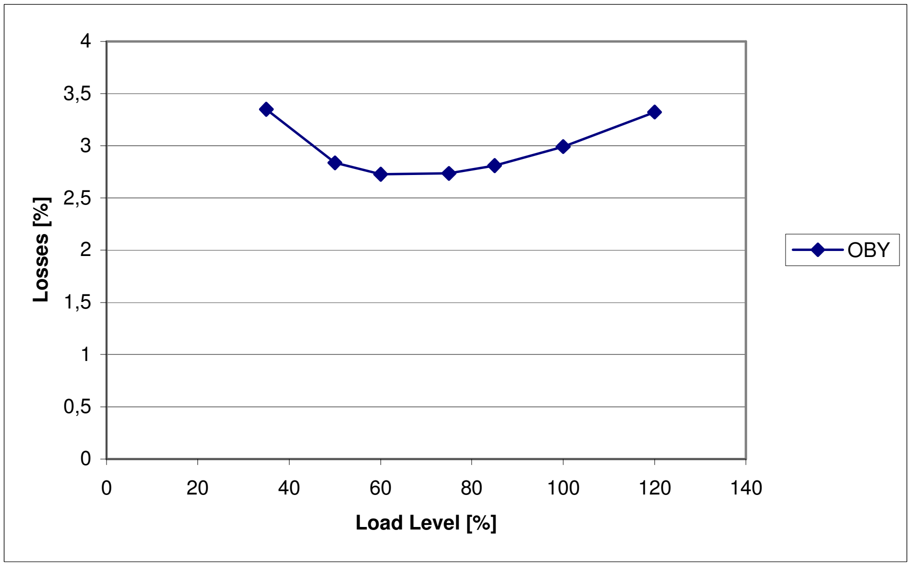

Figure 14 Losses as a function of load level

In Table 4 the relation of losses to the Velander table is shown. The presented losses are annual losses, despite the indications on the Velander tables. The loss percentages were higher when the Velander tables for December to April were used than when the Velander tables for May to November were used. However the variations are not significant.

Table 4 Losses corresponding to different Velander tables

Velander Table	**Annual Losses [%]**
December – March	2.99
April	2.99
May – September	2.69
October – November	2.86

In Table 5 the relations of losses to the values of the loss constant Larsson's constant are presented. According to the notes below equation 16 Larsson's constant may be set to values between 1.2 and 1.5. The simulations were run for values in that interval. The results of the simulations show that the highest loss value is just above 3%; and the lowest is 2.7%.

Table 5 Losses corresponding to different values of Larsson's constant

Larsson's Constant	**Annual Losses [%]**
1.2	2.70
1.3	2.85
1.4	2.99
1.5	3.14

The total length of measured cables in OBY appeared to be 4% longer than the graphical cable length. The fact that Facilplus automatically uses graphical cable length may have resulted in underestimated losses.

4.5 Conclusions

The magnitude of the yearly energy losses calculated by Facilplus depends on the choice of Velander table and the choice of value of Larsson's constant. Velander tables and Larsson's constant have been designed by experience and cannot be mathematically derived. However the influence of these parameters is limited. The technical losses in the OBY grid area vary from 2.7% to 3.1%, when different values of Larsson's constant and Velander tables corresponding to different parts of the year are used. These loss variations can be seen as rough indications on magnitudes of reasonable technical loss variations in the real grid area.

The load level chosen in Facilplus also affects the losses in the OBY grid area. The magnitudes of losses vary between 2.5% and 3.5%. These values could also be used as an indication on the technical loss values to expect from the OBY grid area.

Errors may be introduced in the approximate formulas used by Facilplus. However, if one accepts approximate levels of losses, the simulations can be useful for networks with relatively small data base errors. For OBY it is evident that the technical losses will amount to about 3%.

It is not easy to determine the accuracy in graphical cable length and measured cable length. In the OBY grid area the total measured length is about 4% longer than the total graphical length. If the measured length is more accurate, the compulsory usage of graphical length instead of measured length may have resulted in underestimated technical losses. The difference in length is 4% and transformer losses constitutes a large part of the losses, these facts indicate that the error introduced by the usage of graphical length is less than 4% if the measured length is assumed to be correct.

Since there are so many errors in the database, Facilplus is not a reliable tool to calculate energy losses in a majority of the grid areas. In order to make Facilplus more useful, the data in the database has to be quality checked. Low quality input data can never result in high quality results.

It is not easy to use a computer tool in a scientific manner, when it is hard to get information on the significance of different choices. To be able to use the software effectively and accurately, software documentation needs to be acquired.

The Grid Settlement Group is expected to report correct energy losses monthly. In order to make Facilplus useful for validation of grid settlement results, an option to calculate monthly energy losses must be added.

5 PSS/E Simulations

5.1 Introduction

In this chapter a simulation performed in PSS/E is presented. PSS\E is a computer program for studies of power transmission systems. The benefits of PSS\E are in the area of simulations of meshed networks. This is especially useful for transmission grids. Since this thesis is focused on distribution grids, where meshed networks seldom are used, the major benefits of PSS\E were not used.

First a model is drawn, data is edited and then a simulation can be run and different reports can be created. In the reports data on for example input power and power losses is presented. Values of input energy and energy losses are not available. Non-technical losses and no-load losses are not considered. In this chapter single components are studied and connected together. For that reason the approach of this chapter is a kind of bottom up approach.

In this section only one grid area, the OBY, is studied. The OBY grid area was chosen since it is the only grid area among the ones studied in this project that consists of only one substation.

The losses in the 0.4 kV grid and the no-load losses of the transformers are not considered. This means that no detailed comparison can be performed. Instead the PSS\E simulations are used for studies of influence of different parameters, i.e. sensitivity analysis.

Once a model is drawn, data can be changed relatively easy and a new simulation can be run. This approach has been used to perform sensitivity analyses. The sensitivity analyses can in turn be used to obtain more general conclusions. In this report the influence of 10 kV cable length and load level were studied.

5.2 Simulations

The program includes both steady state analysis and transient analysis. In this project the steady state analysis option was used. PSS\E uses the per unit system, all data to be edited has to be in per unit. The apparent power base was the first value to be chosen, it was chosen to 10 MVA.

The model drawn in PSS\E consists of the grid below the OBY substation; the 10 kV grid, distribution transformers and loads, for scheme see Appendix A. The model does not include the 0.4 kV grids; instead only one load is connected to each distribution transformer representing all loads. Facilplus was used to calculate the load values at each distribution substation.

Once the complete model is drawn and all data is edited a power flow simulation can be run. The fact that the losses are not known before all variables are known is the main difficulty in the process of solving the power flow equations (Daalder, 2005). Five different solution methods are available in the PSS\E software. Three are based on the Newton-Raphson algorithm and two are based on the Gauss-Seidel algorithm. Convergence cannot be guaranteed, but since several methods are available, the number of unsolvable problems in this software is reduced. For the simulations in this report the full Newton-Raphson algorithm has been used.

The data for the transformers are given in Facilplus. The transformer data available in Facilplus is related to the base of the transformer. PSS\E requires transformer data related to the system base. The formulas used are presented in Appendix B.

PSS\E uses the pi model, depicted in Figure 15, for cables and lines. The resistance and inductance of the line are modelled as a series resistor and a series inductor. The capacitance between line and ground is modelled as one capacitor to ground at each end of the line. In Facilplus the cable length and cable type are given for each cable. The cable data for different types of cables used is from a data sheet from Onninen (undated). The cable data is not given in the units that PSS\E requires. The derivation of required quantities can be found in Appendix B.

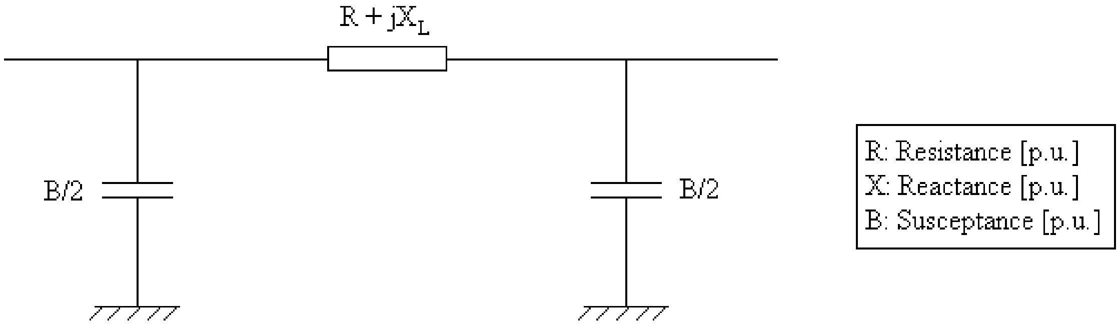

Figure 15 Pi model of transmission line

In Facilplus both graphical cable length and measured cable length are available. In the PSS\E simulations measured length were used to avoid underestimated cable losses, the total length of measured cables in OBY appeared to be 4% longer than the total graphical cable length.

To decide what load levels to use in Facilplus, different results were compared. According to grid settlement, the magnitude of energy fed into the OBY grid during 2004 was 67870 MWh; see Table 1. Comparing this value to the values obtained by the Facilplus calculations, see Table 3, it is clear that 100% load results in the value closest to 67870 MWh.
From the Operation Group of E.ON Elnät the following values of active and reactive input power a high load day were received.
Maximum values for OBY: P = 16.7 MW
Q = 3.9 MVAr

Multiplying the magnitude of the active power P by the number of operating hours results in the yearly energy consumption in the OBY grid area. Facilplus uses 4000 hours as default.

16.7*4000=66800 MWh

This result also indicates that 100% distribution substation loads from Facilplus should be used when performing simulations in PSS\E.

5.3 Results

In PSS\E there is an option to change the load level of all loads. In Figure 16 the losses at different load levels are presented. The losses include losses in 10 kV lines and cables and in distribution substation transformers. From Figure 16 it is clear that the losses increase with increasing power fed into the system. The increase is linear. This is a reasonable result because both the power fed into a grid and the losses in a grid is proportional to the current in square; see equation 3 and equation 9. This means that there should be a linear relation between input power and power losses.

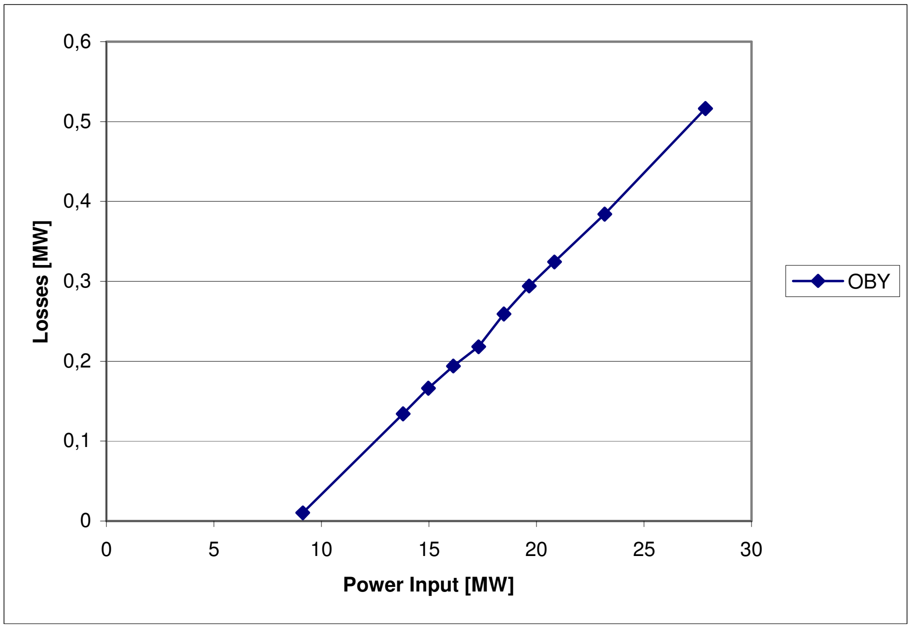

Figure 16 Losses in 10 kV cables and distribution substation transformers

In Figure 17 the losses as a percentage value of the power fed into the system are plotted. The general trend is an increase in losses as a percentage value with increasing power.

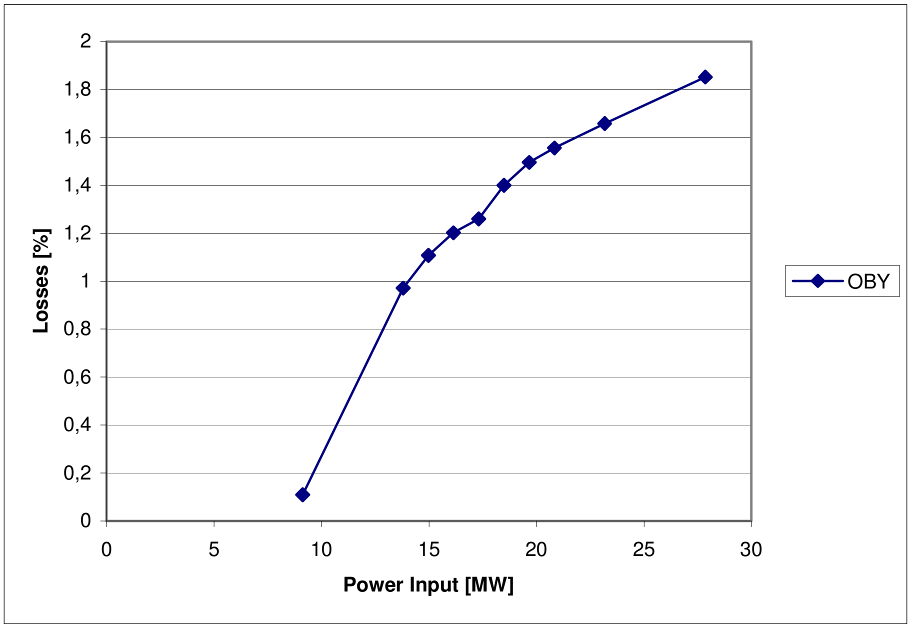

Figure 17 Losses in 10 kV cables and distribution substation transformers

In Figure 18 losses in grids with different cable length are compared. The first simulation was performed for the OBY grid. The second simulation was also performed for the OBY grid, but with cable length twice the measured length. As one could expect the losses are always highest for the long cable model.

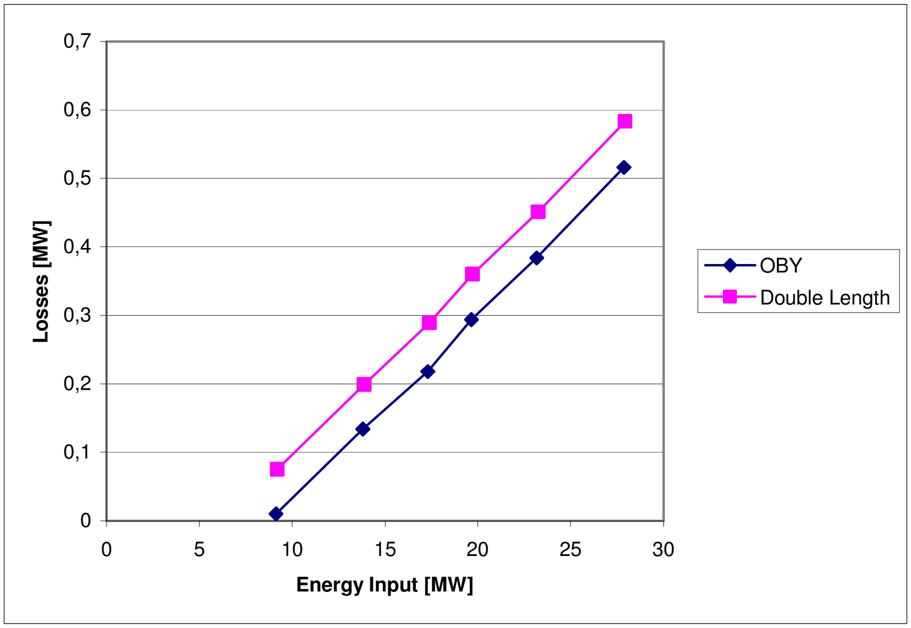

Figure 18 Losses, different cable length

In this chapter the power losses have been studied. If one wants to calculate the energy losses the changes in power consumption have to be taken into consideration. This is not an easy task. To show these difficulties the maximum daily input current to the OBY grid area year 2005, at the low voltage side of the substation, are plotted in Figure 19. Data for the plot was collected from Eldorado. Eldorado is the software used by the Operation Group at E.ON Elnät.

Power is proportional to current in square; see equation 3. The dots in Figure 19 correspond to daily maximum currents. In Figure 19 the dots form two parallel curves. The dots in the upper curve correspond to weekdays, when people work and large quantities of energy are used. The dots in the lower curve correspond to weekends. In Figure 19 it is also possible to see the variation during a year, high energy consumption and therefore high currents during winter while the energy and currents are lower during summertime. There is a large variation in daily maximum current; much more energy is consumed during day than during night. To be able to study the energy losses with high accuracy not only the daily maximum currents have to be known but also the hourly maximum currents.

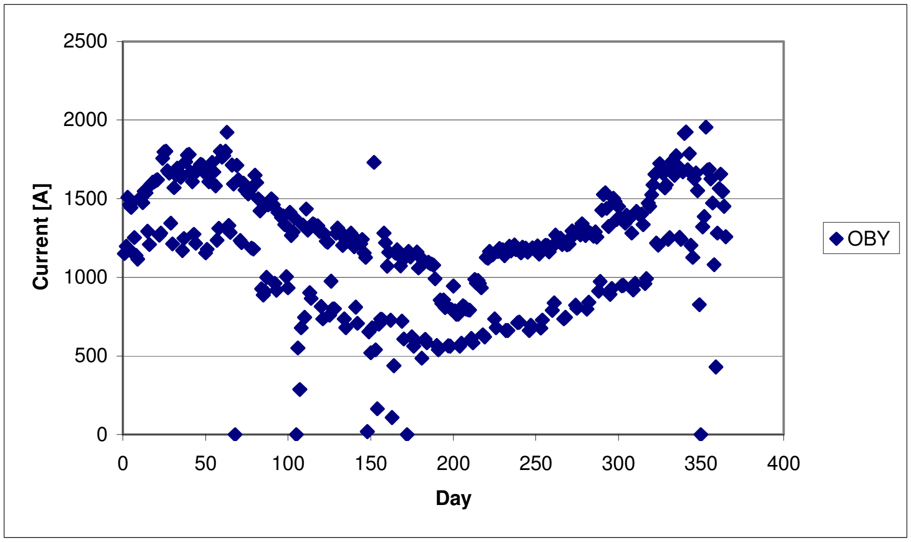

Figure 19 Input current OBY year 2005

5.4 Conclusions

Load values for all distribution substations used in the PSS\E simulations in this chapter were obtained by network calculations in Facilplus. Errors in Facilplus calculations obviously result in errors in the PSS\E simulations. Cable data and transformer data for the simulations was also collected from Facilplus. Cable and transformer data is not obtained by software calculations but by collecting actual data from the database. This results in fewer possible sources of errors compared to the distribution substation load data.

It is very time consuming to draw grids and edit data in PSS\E; it is not realistic to use PSS\E simulations for an entire grid area. PSS\E is rather a tool suitable for simulations of less extensive grids.

The simulations in PSS\E indicate that the total length of conductors has a major impact on the loss levels. Cable length is probably one of the most crucial parameters when studying losses, and cable length is often known. The total cable length might be used for rough loss estimations in a grid area, however for detailed loss calculations the cable length data has to be completed with data on load variations at every node. Today load variations cannot be easily obtained.

In this chapter power losses are considered, not energy losses. It is very interesting to observe the differences in power losses at different load levels. The large loss variations indicate the difficulties in predicting the energy losses accurately, without actual hourly metering. Data on power losses does not contain sufficient information for detailed monthly energy loss estimations since the power variations during the month are not known.

6 Conclusions

According to the results obtained by the loss estimation methods used by the Grid Settlement Group today, the losses vary widely between different networks and within each network during different months. Models are used for annual energy consumption breakdown by month. Different models are used for different types of customers; however it is not possible to create a model that is exact. Still today, consumers are partly responsible for data collection. Loss variations calculated by grid settlement are very likely to be influenced by errors, and this can possibly explain a great deal of the loss variations.

Near future methods of automatic monthly metering are likely to reduce errors and secure more accurate loss estimations. It will however still be necessary to know what loss levels to expect, in order to detect errors. To make the transition to new metering systems smoother, it would be valuable to know what loss levels to expect already before full-scale-usage of monthly read meters.

There are uncertainties in the Facilplus calculations; the methods used are approximate. Another disadvantage is that there is no possibility to calculate monthly energy losses. Fatal errors in the database used by Facilplus, limited access to values of annual energy losses to the OBY grid area only. The Facilplus simulations of OBY, at different load levels, with different choices of Velander tables and different values of Larsson's constant indicate that the losses as percentage values do not vary very much. According to the performed Facilplus calculations the losses in OBY can be expected to reach 2.7% to 3.1% of the energy fed into the network. No documentation on Facilplus is available. The only way to learn about the program and the significance of different choices is to find people who know the program. Of course there is also the time consuming method of trial and error.

PSS\E seems to generate reliable results, but since the used input load data was generated from Facilplus the data accuracy depends on the accuracy of Facilplus and the quality of data in SAP. The documentation of line and cable length in Facilplus is detailed and no significant errors seem to be involved in the cable data. Load data errors might be significant since this data was obtained by network calculations. PSS\E only calculates power losses, if the purpose is to estimate energy losses; models for power consumption patterns during a month have to be used. No-load losses are not considered. To draw models in PSS\E is very time consuming; it is not realistic to draw all 10 kV grids, nor the 400 V grids. The conclusion is that PSS\E is not a suitable tool for loss calculations in extended distribution networks.

The results obtained by Facilplus (2.7% - 3.1%) for the OBY area indicates that the loss values of 4% and above from the grid settlement is slightly too high. However this cannot be taken for granted. The results obtained by the Grid Settlement Group might be correct while the results from Facilplus might be too low. Facilplus only calculates technical losses. One possible explanation for high grid settlement values compared to Facilplus values could be that non-technical losses are included in the grid settlement results but not in the Facilplus results. There are also several conceivable, known and unknown, sources of errors both in grid settlement and Facilplus.

The higher losses obtained by grid settlement for UVI compared to OBY, can be explained by using the PSS\E simulations where losses in OBY was compared to losses in OBY with doubled cable length. In reality, UVI has twice as long cables as OBY on 10 kV level as well as on 400 V level. The simulations in PSS\E showed that on 10 kV level, losses increase remarkably if line length is doubled. The 400 V level could unfortunately not be simulated in PSS\E.

The software tools available today are not reliable enough for throughout analysis of monthly energy losses. The quality of data also needs to be improved to provide accurate basis for computer calculations and simulations.

As stated in the beginning, the aim for this thesis was:
-To study data for a couple of real grid areas.
-To study a couple of grid areas using network calculation software.
-To study one grid area in detail.

The aim was achieved in the sense that settlement data for a couple of real grid areas were studied. Only one of them was successfully studied in detail using calculation software and computer simulations, since fatal data errors prevented complete network calculations in the other grid areas. The results of the simulations and network calculations turned out to be of lower quality than expected in the beginning of the work with this thesis, since available software tools and data proved to be less applicable than expected. It is a major disadvantage that calculation of monthly energy losses is not possible.

7 Suggestions for Future Research

This thesis has focused on studying ways and means for E.ON Elnät to improve its knowledge on reasonable energy loss levels using existing tools and data. This knowledge improvement is crucial to obtain accurate reference values to the results of grid settlement. In this project it has been shown that the tools and data available today are not sufficient for detailed studies of monthly energy losses. Accurate estimation of monthly losses has in this thesis proved to be more challenging than anticipated. Further research is required to create methods and models that can be useful when evaluating the results from grid settlement. In the process of completing this thesis ideas and impulses have emerged. These ideas are outlined below and might be used as inspiration when designing further loss calculation projects.

Facilplus is quite complicated software, which can be used for a wide range of activities. To be able to use software effectively within any organization, software documentation is crucial. It is recommended that E.ON Elnät acquires or develops documentation on Facilplus.

Improved calculation tools with more options in Facilplus, is essential if Facilplus is to be used for loss analysis and other complicated analyses. When monthly energy meters are introduced it would be valuable to implement a monthly loss calculation feature, based on the measured energy consumption. Another possible way to acquire monthly energy data, which could be implemented already today, would be to add a model for breakdown of yearly energy consumptions by month. The disadvantage of this method might be introduction of errors, similar to those present in grid settlement. The alternative would be to acquire or develop alternative software for energy loss calculations.

The disadvantage when using PSS\E for extended networks is the time-consuming network drawing and data editing. It would be valuable to have the opportunity to import data files to PSS\E. Another difficulty is to calculate the energy losses from the power losses obtained by PSS\E. This can only be resolved by the use of an accurate model to estimate the power loss related to time for the entire network.

Frequently measured average input power on substation level and load power on consumer level would provide sufficient data for detailed energy loss calculations. If power input and output were carefully measured, the power loss would be the difference between them. Then the energy losses would be calculated by assuming the power to be constant during each hour and add all hourly energy losses during a month to obtain monthly energy losses. Today input power data for every substation; every hour is available from the Operation Group. Load power is currently not hourly measured for most consumers. Large investments in measurement equipment would be necessary to obtain required accurate load data. This is expensive and only justifiable for a small grid area. The calculated energy losses in combination with data on total cable length and breakdown of customers by customer category would probably be applicable for more general conclusions. This would form a first step in the development of an accurate model for energy loss estimations that could be used in any arbitrary grid.

It is recommended that further studies of losses relate to each substation instead of relating to each grid area. By studying losses related to each substation instead of each grid area errors in metering and estimation methods would easier be detected and properly dealt with.

Loss calculation is complicated, and time consuming. To perform valid calculations and to obtain accurate results it would be helpful to organize the quest for extended knowledge on loss variations into different subprojects. Each subproject could be an object for a master thesis or another kind of project. One useful idea might be to initiate separate studies of 10 kV and 0.4 kV level networks. Depending on available tools it is probably preferable to start studying only one grid at the chosen voltage level. The organization of loss variation research within limited subprojects would facilitate studies in detail and with a high degree of accuracy.

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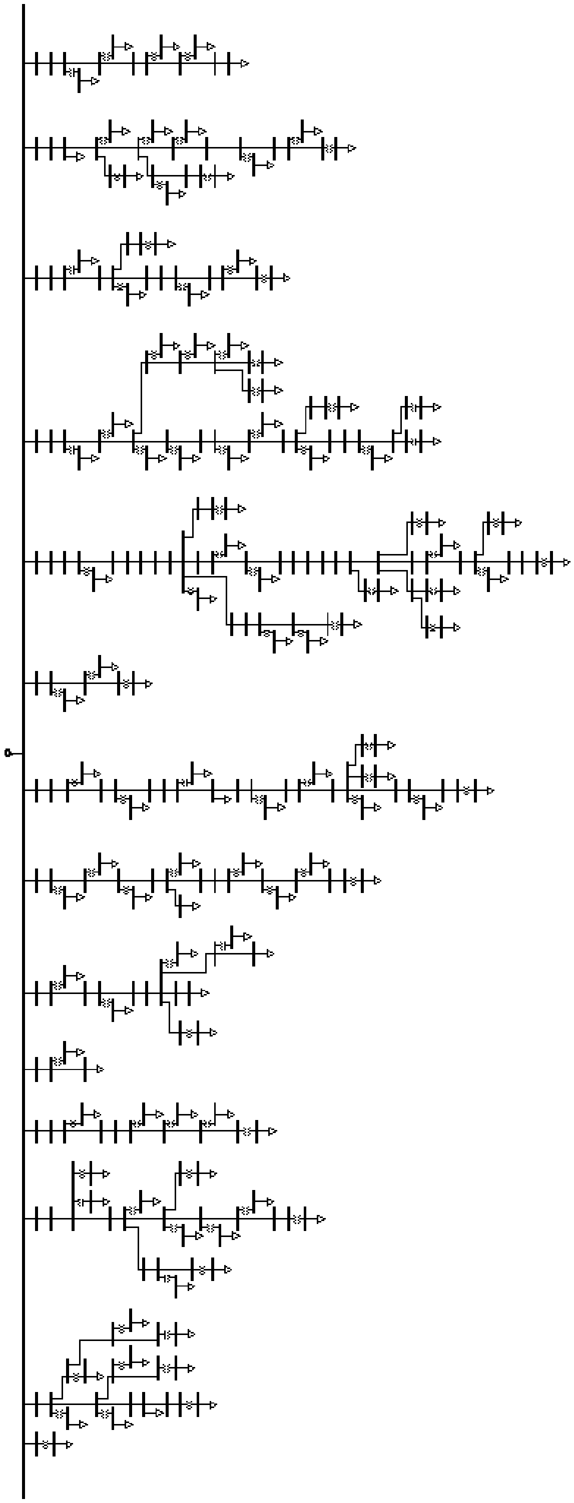
Appendix A: PSS\E Diagram Image



Appendix B: Derivation of Quantities Required by PSS\E

Transformer data

The transformer data available in Facilplus is related to the base of each transformer. PSS\E requires transformer data related to the system base. The equations used to obtain required quantities are presented below. The calculations using these equations were performed in an Excel sheet.

Relation between impedance in per unit, impedance base and impedance in Ohm

$$Z_{pu} = \frac{Z_{\Omega}}{Z_{base}} \tag{B-1}$$

Relation between impedance in Ohm, impedance in per unit related to transformer base, and impedance base of transformer

$$Z_{\Omega} = Z_{pu,trafobase} \cdot Z_{trafobase} \tag{B-2}$$

Combining equation B-1 and equation B-2 results in

$$Z_{pu} = \frac{Z_{pu,trafobase} \cdot Z_{trafobase}}{Z_{base}} \tag{B-3}$$

Where

$$Z_{base} = \frac{U_{base}^2}{S_{base}} \tag{B-4}$$

and

$$Z_{trafobase} = \frac{U_{HVside}^2}{S_{rated}} \tag{B-5}$$

The equation used for the calculations in the Excel file is

$$Z_{pu} = Z_{pu,trafobase} \cdot \frac{S_{base}}{S_{rated}} \tag{B-6}$$

For the transformer in distribution substation OBY-044 only rated power was given.
For the transformers in substation OBY-090 and OBY-100 no data was available. Rated power for OBY-090 and OBY-100 was chosen to 500 kVA since this is the most common transformer rating in the OBY grid area.

Once the rated power was decided additional data was collected from Standard Typstationer, Typskåp, Transformatorer (undated) which is a booklet containing standard data to be used in Facilplus.

Cable data

Given: Resistance $R_{\Omega/km}$ [Ω/km]
Inductance $L_{mH/km}$ [mH/km]
Capacitance $C_{\mu F/km}$ [μF/km]
Required: Resistance R_{pu} [p.u.]
Inductive reactance X_{pu} [p.u.]
Susceptans B_{pu} [p.u.]

The cable data is not given in the units that Facilplus requires. A derivation of required quantities is performed below. The calculations using these equations were performed using the software Excel.

The impedance Z consists of resistance R and reactance X.

$$Z = R + j \cdot X \tag{B-7}$$

The admittance Y consists of conductance G and susceptance B.

$$Y = G + j \cdot B \tag{B-8}$$

The admittance is the inverse of the impedance.

$$Y = \frac{1}{Z} \tag{B-9}$$

Per unit values are required. The impedance base, Z_{base}, used for per unit calculations for resistance, inductance and capacitance can be written

$$Z_{base} = \frac{U_{base}^2}{S_{base}} \tag{B-10}$$

When studying inductance and capacitance the relation between angular frequency ω and frequency f is needed.

$$\omega = 2 \cdot \pi \cdot f \tag{B-11}$$

The resistance for the cables is given in Ohm/km; PSS\E requires resistance in per unit. The total resistance of a cable is the resistance per kilometre multiplied by the length of the cable, l.

$$R = R_{\Omega/km} \cdot l \tag{B-12}$$

Relation between resistance in per unit R_{pu} and resistance in Ohm R

$$R_{pu} = \frac{R}{Z_{base}} \tag{B-13}$$

The formula used in the Excel file is a combination of equation B-12 and equation B-13

$$R_{pu} = \frac{R_{\Omega/km} \cdot l}{Z_{base}} \tag{B-14}$$

The inductance of the cables is given in mH/km; PSS\E requires reactance in per unit.
The total inductance of a cable is the inductance per kilometre multiplied by the length of the cable l.

$$L = L_{H/km} \cdot l \tag{B-15}$$

The inductive reactance X_L is defined as ω multiplied by the inductance L.

$$X_L = \omega \cdot L \tag{B-16}$$

Relation between inductive reactance in per unit and inductive reactance in Ohm

$$X_{L,pu} = \frac{X_L}{Z_{base}} \tag{B-17}$$

The formula used in the Excel file is a combination of equation B-15, equation B-16 and equation B-17

$$X_{L,pu} = \frac{\omega \cdot L_{H/km} \cdot l}{Z_{base}} \tag{B-18}$$

The capacitance is given in μF/km; PSS\E requires susceptance in per unit.
The total capacitance of a cable can be calculated as the capacitance per kilometre multiplied by the cable length.

$$C = C_{F/km} \cdot l \tag{B-19}$$

The capacitive reactance X_C is defined as the inverse of angular frequency ω multiplied by capacitance C

$$X_C = \frac{1}{\omega \cdot C} \tag{B-20}$$

Relation between susceptance B and capacitance C

$$B = \omega \cdot C \tag{B-21}$$

A combination of equation B-20 and equation B-21, results in the following formula for the susceptance B

$$B = \frac{1}{X_C} \tag{B-22}$$

Relation between capacitive reactance in per unit and in Ohm

$$X_{C,pu} = \frac{X_C}{Z_{base}} \qquad \text{(B-23)}$$

Equation B-22 rewritten in per unit

$$B_{pu} = \frac{1}{X_{C,pu}} \qquad \text{(B-24)}$$

The susceptance in per unit can be obtained by combining equation B-23 and equation B-24.

$$B_{pu} = \frac{Z_{base}}{X_C} \qquad \text{(B-25)}$$

From equation B-19, equation B-20 and equation B-25, the following equation can be obtained (which also was used in the Excel file)

$$B_{pu} = \omega \cdot C_{F/km} \cdot l \cdot Z_{base} \qquad \text{(B-26)}$$