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L237 Fjärås – Förlanda, Planning and Construction

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

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

This report is investigating how to find a way to improve the planning and construction of a new planned grid. An already existing grid, which is located between Fjärås and Förlanda south of Kungsbacka, is used in this report as a base of study. The material used in the old existing grid is investigated. By comparing old material with new, the differences in cost can be determined. This can for example be different cables in the grid. By using only the necessary information, mainly coordinates and loads, a new grid should be possible to construct in a fast and easy way. The result should be a proposal for a shortest way to customer. It should also give information about the new proposed grid, how much the voltage dip is, and cable size. All this can be accomplished by a program made for this task. By using this program, the planning and inspection can be done at a much faster rate.

Keywords: Planning, Construction, Distribution, Grid, Newton-Raphson, Gauss-Seidel

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Gothenburg, Sweden — Peter Angberg

January 7, 2007

Introduction

This Master of Science Thesis is made for Fortum Service AB[1] Elnät[2] Sverige and Fortum Distribution in Kungsbacka. Elnät Sverige is a unit that is working with construction and maintenance of distribution networks all around Sweden. Fortum Service biggest customer are Fortum, Vattenfall and E.ON.

Historically the net owners have controlled how the distribution network was constructed. Nowadays more of the construction and planning are handed over to Fortum. The company thinks that in the future more of the owners will leave the work, both forming and building of the distribution network, over to them. Then it is important that both the forming and building is made cost efficiently, otherwise they will lose important customers.

The thesis is about how Fortum Service wants to study the way distribution networks are constructed today, and after that see if and how they could obtain better solutions on planning and construction. The different things that can be made is to calculate on different types of networks (overhead lines, cables) or on the different types of stations (transformer stations, substations, low voltage grid), to be able to see where changes can be made. This could mean changing parts, use other, cheaper parts in the network or remove parts that shouldn't be there. It can also be about thinking in another way than what the company is doing today. To be able to make this report, one should be able to know how to calculate on networks and to know how they are constructed. This is important in such a way that the electrical demands are fulfilled

[1] Swe: Aktiebolag, Eng: Jointstock Company
[2] Eng: Grid

when changes are proposed, but also be able to find different changes in the grid. The goal is of course to increase the profit of the company.

To study a distribution network and how it can be changed, an area which is located between Fjärås and Förlanda is used. The location is south of Kungsbacka, beneath the lake Lygnern. This is one of many projects that Fortum are working on today, which makes it even more interesting. Due to several problems with the grid, a decision to rebuild it has been made. With this grid a revision is made how the area can be reconstructed, and studied in different ways in order to find the best solution. When the new improved network is finished a comparison with the old network is made. This will show what difference the changes has made.

Chapter 1

Background

Fortum is the leading company in electric distribution in the Nordic countries. It is also the second largest in power generation. A very positive improvement is that 93% of all power that was generated in the year 2005 didn't cause any CO_2[1] emissions. [1]

Fortum is supplying electricity to approximately 1.4 million customers in the Nordic region, which is located in Sweden, Finland, Norway and Estonia. In Sweden the grid is placed in Stockholm, Hälsingland, Värmland, Bergslagen, Närke, Västergötland, Bohuslän and Halland. They also have 136 400km cables and overhead lines at 0.4-20kV. The number of distribution transformers is 51 900. The regional grid consists of 7 600km cables and overhead lines, and is at a voltage level between 20-220kV. The average interruption time during a year is two hours per customer. The goal for 2012 is to reduce it to less than one hour per year. Fortum is approximately investing seven billion kr during a five year period. Some of this money is going to be used to change overhead lines to ground cables. The improvement of approximately 10 000km of grid is planned. They are also very interested in the environmental aspects. The company are financing activities and undertaking different projects which all of them are aiming towards decreasing the environmental affects, and the most efficient possible housekeeping. [2]

[1] Carbon dioxide

This thesis is made for Fortum Service and Fortum Distribution, which are different partners within the Fortum corporation. Previously, together with the net owners, Fortum Service AB was one company. Few years ago the company changed and today they are working only as a contract company.

1.1 Limitations

The limitations in this report are to study the planning and construction, and find a way to improve it. Because the study is only in the planning and construction state some assumptions are made to get reasonable values for a new planned grid. The calculations is focused on the 10kV grid. The voltage 10.5kV is used for the examined network. New placements of transformer stations are not made, this because the requirement of being out in the field and see where they should be placed is then needed. The loads are still in the same location, which means that if a transformer station is replaced it would probably be done so in a nearby region. The program that is made, and explained in this report, can only draw straight lines between transformer stations. Using this aid a new planned grid can be drawn by hand. The idea is to make the program draw everything automatically on a map from the beginning, which can give an example directly. The time for this thesis work is not enough to finish everything, but gives a proposal of how it can work. When having all the lengths and loads for the new planned grid, the other part of the program will give important facts about the grid. Here the calculations give the voltage dip, short circuit currents, losses, cost and more. How the calculations are made and its limitations are written in more detail in the report.

1.2 Grid construction in short

Planning is the first thing to start with when constructing a new grid. This is done by a preparer, which looks at both the environment on maps and out in nature, to see where it is possible to build a new electric grid. There's a lot of money that can be saved if this part is done correctly. When the planning is done it is time for inspection. Here it is necessary to look at the grid again to see if it is possible to lay a cable through the landscape without any problems. Some planned lines might have to be changed here. The next step is to check with all the landowners if it is possible to get a clearance to have a cable through their property. This part is very time consuming, because the planned grid might be very large, and some customers don't want any cables through their land. The best thing to do is to construct the grid using nearby roads. This simplifies a lot of things as it is easier and a lot faster to let the machinery work on roads instead of in the terrain. If there's an error somewhere, it is much easier to repair if the cable is close at hand. Another very important thing to look for is protected areas. The cables can't go through such areas because there might be a risk of environmental damage.

The working process for dimensioning of a reconstruction on local countryside grid is also interesting. First of all an analysis and judgement is made whether the net is a future 10 or 20kV grid. If the voltage is changed from 10 to 20kV a lower conductor area can be used. When the grid area is planned electrical calculations are made with the assumptions for maximum population load plus expected growth within the cost estimation time. Before the reconstruction is made customers that are located more privately should be asked if they want to keep their connection. A judgement should be made for the actual grid if some areas are acceptable for maintenance and fault tracing, and also if the line is located near highly populated areas.

Some methods that can be used in evaluation:

- Ploughing of ground cable
- Changing lines on existing poles
- Changing coated conductors on existing poles
- Changing the voltage from 10 to 20kV to use a lower conductor area for cables.

When reconstructing overhead lines it is important that undersized and rotten poles is strengthened or changed. To reduce errors in the grid, surrounding nature should be trimmed down. The basic alternative is not to change the overhead lines over continuous open distances like farmland, meadow or mire. [5]

1.3 Interruptions and other problems on the existing grid

A lot of overhead lines are used in the grid today. This is something that needs to be reduced. In the beginning of 2005 a hurricane, called Gudrun, went through Sweden. This hurricane arrived from the Atlantic Ocean between the 8th and 9th of January and affected the northern part of Europe. A lot of trees fell down due to powerful winds, and the electric grid in southern Sweden sustained a lot of damage. The night to the 9th of January 341 000 households in Sweden where out of power. Ringhals and Barsebäcks nuclear power plants had to stop their production because of several cable fractures in combination with large amounts of salt that came in from the ocean with the wind, called salt storm, and covered the interlocking installation plant at Ringhals, which increased the risk of flashover. Four days after the storm 100 000 households where still out of power. Two weeks after the storm 25 000 households where out of power, and after three weeks 10 000 households. Due to wet snow that had fallen onto the temporarily placed overhead lines, the cables where pulled down due to the weight. It took about 40 days until all on the mainland had their power back. One of the most affected areas was Hallands county, which is the location of the grid which is used in this report. [15]

The grid needs to be modified to withstand natural catastrophes. One thing that can be made to reduce the damage is to use cables because they are buried into the ground. All new projects are demanding that most of the grid are ground cables. Overhead lines should only be used if it is not possible to bury the cable, and in that case the lines should be isolated. It is of course more expensive, but in the long run more economically reasonable. If all the cables where buried into the ground from the beginning, the damage on the electric grid would not be as extensive as it was after the hurricane. If there's a similar hurricane in the future hopefully the amount of damage is not repeated. The cost of such a failure is too high.

Looking at the failure report on the examined grid there are a lot of other errors that has been recorded. When looking at the history of disruptions there are some failures due to wind and trees. Isolators and valve conductors have been replaced on some parts. Also some cables have failed. In appendix, see section 8.1 on page 45, the failure report is shown.

Chapter 2

Planning

South of Kungsbacka beneath the small lake Lygnern is a high voltage grid that needs to be rebuilt. The line goes between Fjärås and Förlanda.

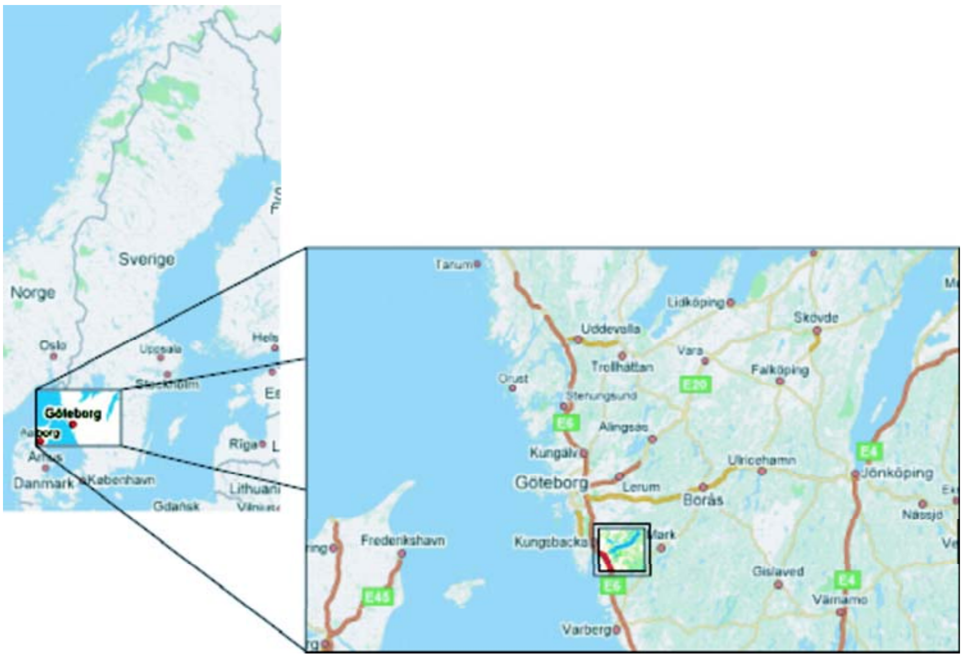

Figure 2.1: Location of the electric grid [3]

Where the area is located is shown in figure 2.1. A photographic picture over the Fjärås-Förlanda area is taken from Google Map, see figure 2.2. The nature is mixed;

we can see that there are clear areas but interspersed by a lot of trees. There are also a lot of small lakes in the area. When building a new electric grid all the surrounding area will affect how the line grid is planned.

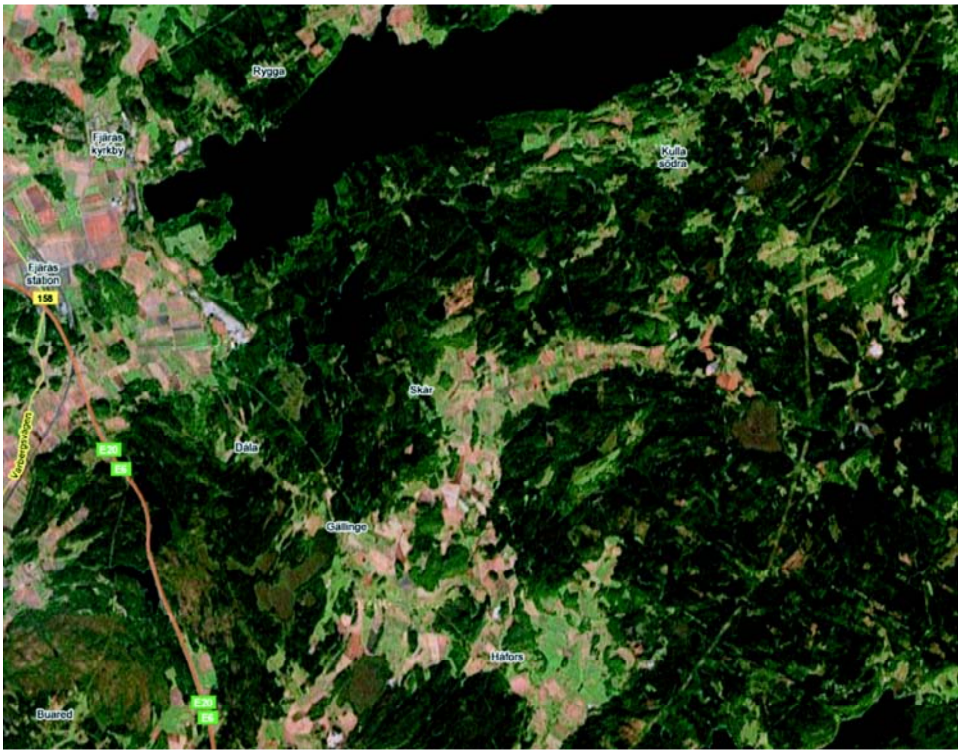

Figure 2.2: Fjärås - Förlanda [3]

2.1 The existing grid

The 10kV line grid that is going to be rebuilt now consists of 50 10/0.4kV transformers. The existing grid that is going to be changed can be seen in figure 2.3. The name of the line Fortum has given it is L237, which is shown in red color. Large interlocking installations is located at Duvehed and also close at Idala. The transformation of the voltage is from 130/10kV at Idala and 55/10kV at Fjärås. Close surrounding grids are also shown in the figure in light blue.

The blue dots represent the 10/0.4kV transformers. The red and light blue lines

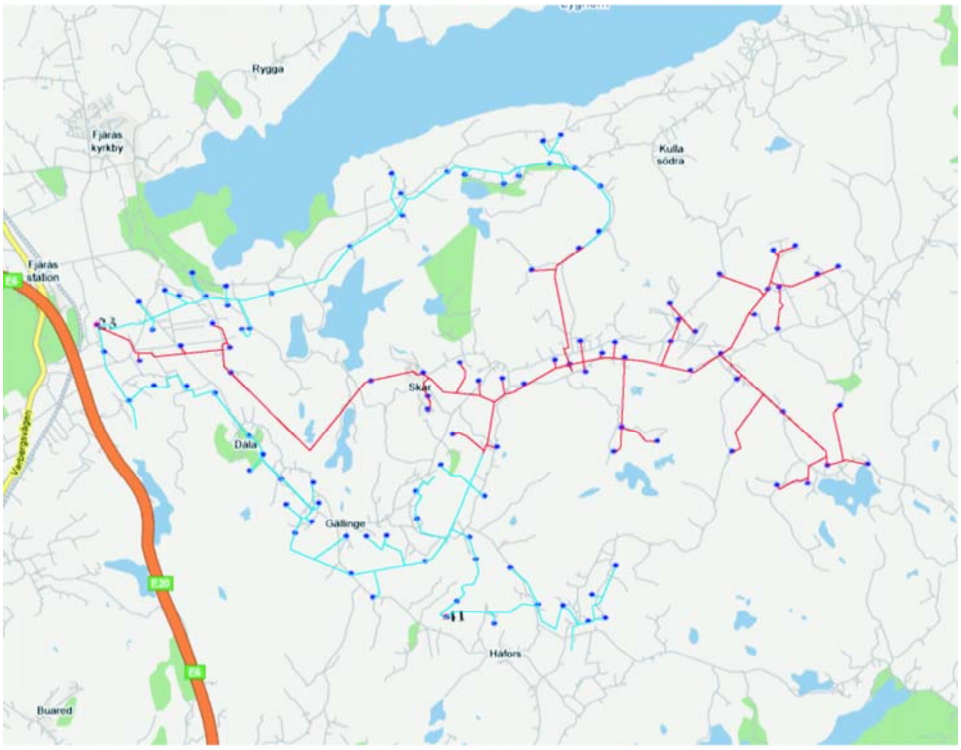

Figure 2.3: The existing grid today [3]

represent the 10kV line grid. One problem with this grid is that most of the cables are overhead lines. The failure risk probability is something that needs to be reduced. There are a lot of errors that have been recorded and can be seen in appendix, see section 8.1 on page 45. The network is also old, which also gives a good reason to update the grid.

The grid is large and there might be a good idea to optimize the grid line length to customer. Due to the long distance to the customers far away, the voltage dip is to high in the existing grid. There are no capacitor batteries which can help to raise the voltage. One way is to only study maps and see where there might be better alternative roads to construct the grid, then measure all the length on the maps. With all the possible choices this is very time consuming. When a new grid is planned there might be a good idea to have something that can help find the best solution a little bit faster. In the end, controlling and correcting the planned grid is needed and it is of course good to have something that can assist in this task.

Some parts of the existing grid will only be renewed, other parts will be dismantled and rebuilt. It is therefore good to see if some of the lines are correctly placed. As an outside observer the only necessary information is the coordinates and loads. By using this information a new grid can be constructed. Because this is a reconstruction of an already existing grid, changes will only be made to the 10kV grid. Many transformers are assumed to be left alone. In reality many transformers are replaced with new ones, which might mean new placements and maybe more transformers, where some might be larger. Also a reconstruction of the low voltage grid at 400V is usually made, which is not examined in this report. All the loads will still be in the same areas, and therefore the placement of new transformers will not differ much. If changing the middle voltage from 10kV to 20kV fewer transformer stations will be needed. Also a lower conductivity area on cables can be used.

2.2 New planned grid

To get fresh ideas a program is created in Matlab. Let's assume that no information is given how the grid looks like and go from there. First of all, all the coordinates for the grid transformers are written down and then implemented into a text file. When plotting the coordinates the result becomes as can be seen in figure 2.4. The information about all coordinates has been taken out manually, using a program called FieldView, for this report and can deviate slightly from the real values. Fortum has all the coordinate information if needed for other grids. This data was not given, and all coordinates were therefore needed to be taken out manually. Using the coordinate data that already is written down there would be no need for taking out coordinates manually, and a new grid can be planned much faster. If a planner has taken out coordinates for new transformer stations in the grid it can be implemented and used when using the program to give an example how the grid should be constructed.

All the transformers needs to be linked together in some way. By ignoring the fact that

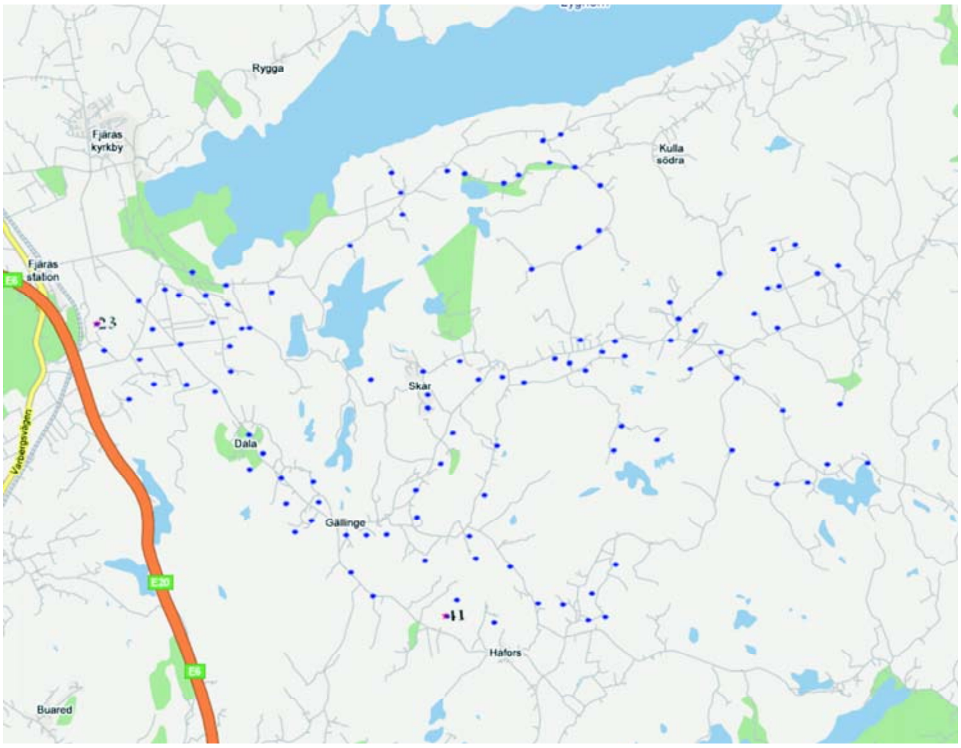

Figure 2.4: Coordinates for the 12/0.4kV transformers [3]

there are trees and water in the area, connecting all the transformers with straight lines is done. It is of course not possible in real life to construct the grid with only straight lines due to nature and economics, but the different ways will give examples as how to construct the new grid. When limiting the max length for a straight line it will limit the number of roads from one transformer to another. Seen in figure 2.5 the dark blue colored lines is showing the connection from transformers on the grid that is going to be reconstructed. Other colored lines is showing connections from transformers on nearby grids. This part of the program can be constructed in a better way. The idea is to use a real map and instead of straight lines the program should locate all the roads. Using the roads the program should work in the same way. This would give a much faster and more accurate idea as to how the grid should be constructed, and the planner would get an estimate as to how much it would cost quickly.

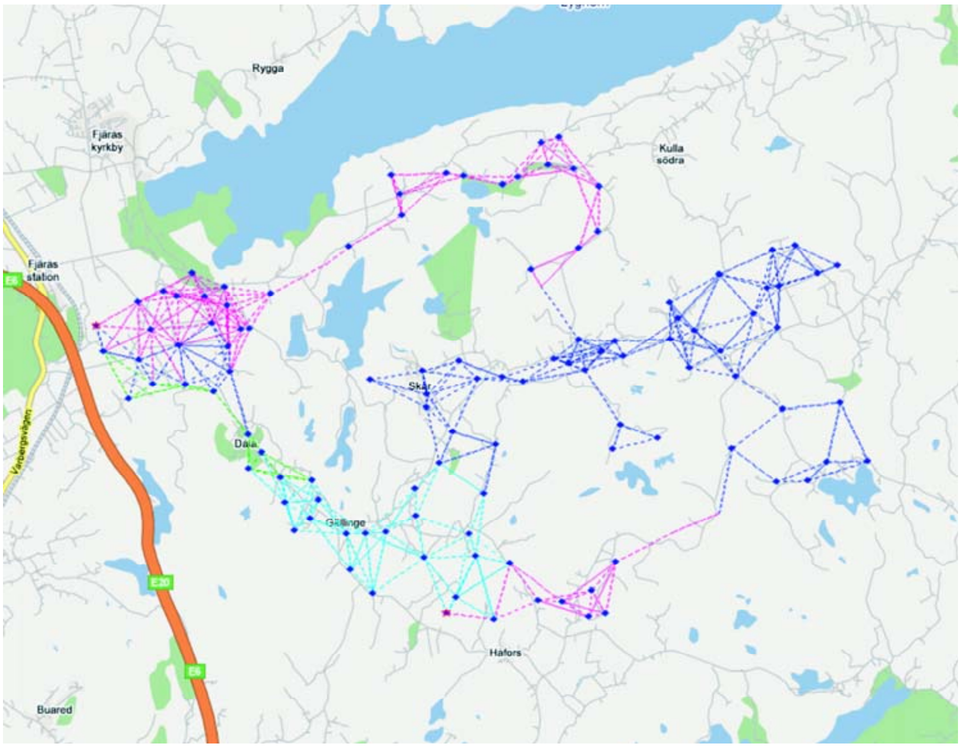

Figure 2.5: Lines between transformers [3]

The next thing is to find the shortest path to each and every transformer. This is done by using an algorithm called Dijkstra, see section 8.11.1 on page 68.

The Dijkstra algorithm needs a starting point. From there it will measure the length to each marked point, which in this case are all the transformer stations. The length is then saved. Next time when measuring the length to another transformer station the previous length is added to the new lengths, which will be compared with other distances. The shortest distance will be the one which the Dijkstra algorithm is using. Continuing using this measuring technique the result will be as seen in figure 2.6. With help of this result a good start for a new grid can be planned. By looking at the result after Dijkstras algorithm, and at the same time at more detailed maps, roads can be found for the cables. This is of course the first planning state. There are probably many different things that will come up when controlling if the planned grid is approved. It is maybe not possible, or a good idea, to put a cable at a certain

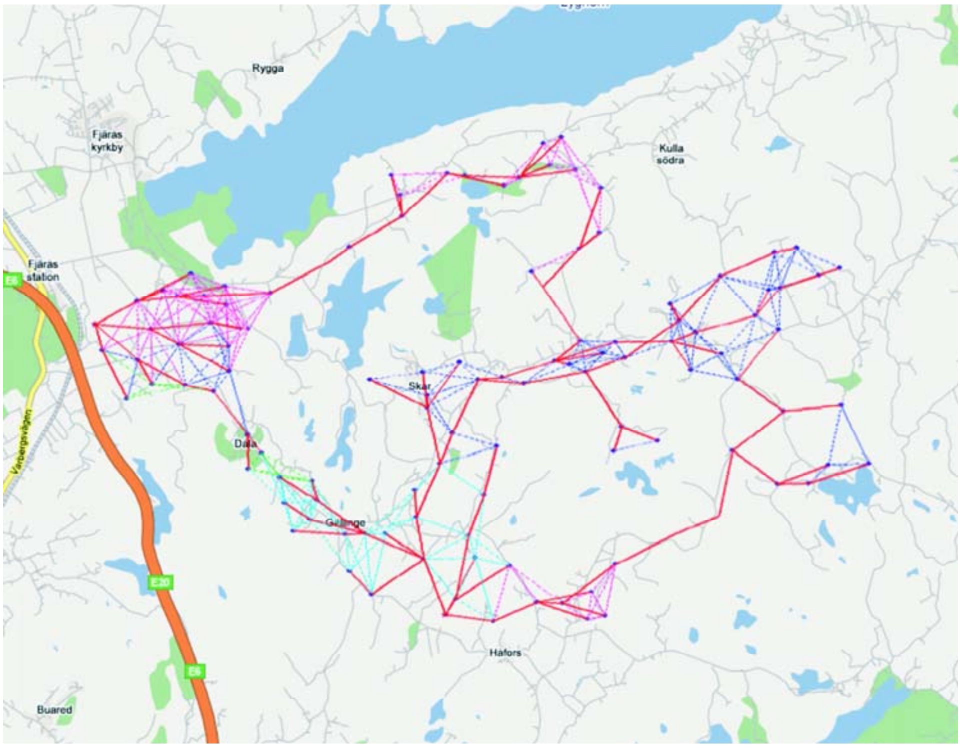

Figure 2.6: The result of Dijkstras algorithm [3]

place where an overhead line is a better solution. Straight lines are only used here because making the program find the roads by itself would take more time.

To decrease the interruption frequency most of the cables should be buried into the ground. This decreases for example the possibilities for lightning strikes on the electric grid. The climate is changing and there might be storms coming in the future, which could disrupt the grid. If overhead lines are used, trees can cause damage when falling. The weather conditions in Sweden are tough on the high voltage equipment. If the cables are buried many factors that have an effect on the grid will decrease. During winter time when snow is lying on branches they become heavy. This extra weight could make the branch lean on to the voltage line if the surrounding nature is not trimmed down. This could lead to a phase fault. New overhead lines are isolated, which prevents this kind of faults. Universal cables like AXCES, which can be used in water, ground and as overhead lines is an example of what can be used. In the chapter about material more information about cables is shown. A cheaper solution is to replace the old cables, which are not isolated, with new ones. If a fault occurs on an overhead line it's a lot easier, and cheaper, to repair than if they where ground cables. In the end it is the customer that have to pay for how much guarantee that company can give that the interruption frequency is low. Cables are more expensive than overhead lines, but will lower the interruptions and errors on the grid.

Most of the existing grid is overhead lines. In the planning stage the new grid should consist mostly of ground cables. A lot of time was therefore spent to find different paths for the construction. To reduce the cost, and simplify for the workers, following roads is something that should be considered. Following roads are not always the best alternative, but because the alternatives to construct the grid can be many, the limitations for the program would be to follow roads. An important implementation in the program would be that the user of the program can decide that a cable must go through a certain terrain because this is already determined. This can be made graphically by letting the user draw a line where the cable or overhead line must go. If there's not too much terrain, new and shorter ways could be chosen. If some part of the grid is not to be changed, the old overhead lines is then replaced with poles and isolated lines. This will help during the winter if something falls onto it as the reduction of phase faults is improved. Thereby in figure 2.7 the new planned grid is shown. The idea for a finished program is to make it draw the grid itself similar to the grid shown in figure 2.7. The result would give all important facts that is needed to be compared with the old grid. Because this result is made manually more detailed maps is shown in appendix, see section 8.13 on page 106.

Going out looking at the existing network is of course very important. Only looking at maps will not give the best solution. Some of the places that have been chosen might not be usable. Looking at the grid in real life will also show if and where the grid is old and damaged. Old transformers can be changed, which also gives an opportunity to find better placements for them. Permission from all the landowners is also a fact. This can also change the planning scheme because some customers don't want the 10kV cables going through their land.

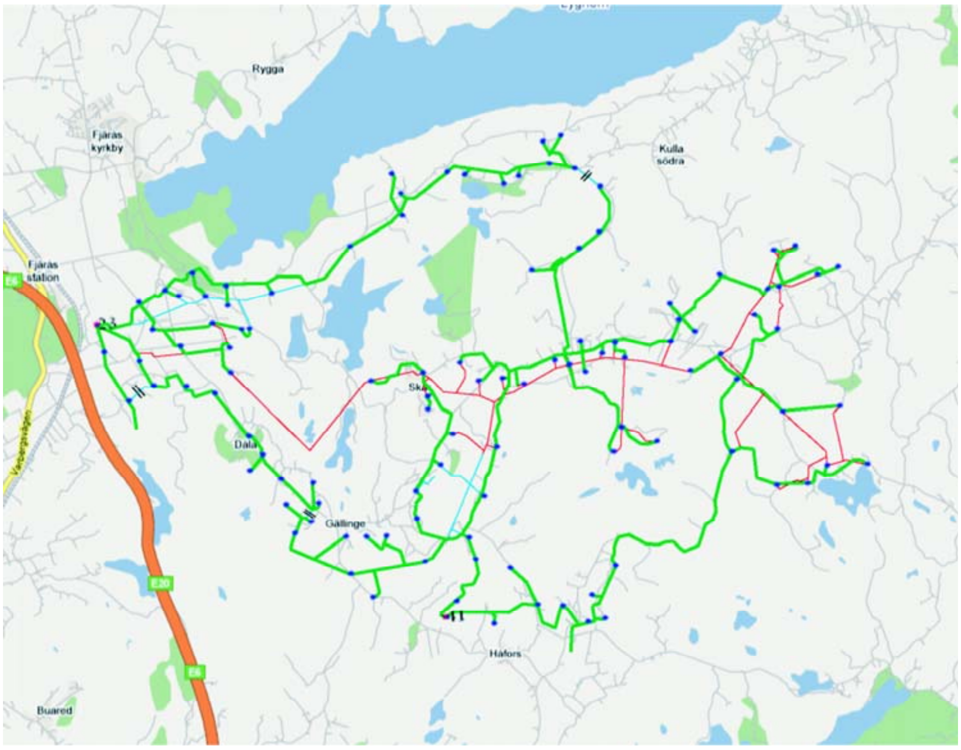

Figure 2.7: New planned grid [3]

When the new grid is planned an electrical scheme can be constructed. This will make it easier to calculate on the grid. In the chapter about calculations the electrical scheme is used to determine various data that is needed.

Chapter 3

Calculations

To understand what kind of material is needed in the grid some calculations must be made. The voltage should not deviate more than $\pm 5\%$, according to Fortum. Within this limit no capacitor bank is inserted into the grid to increase the voltage.

The old grid has a higher voltage dip than 5%, which is one reason why it should be reconstructed. Figure 2.7 shows one example how the new grid can be. The grid has been formed based on Dijkstras algorithm, which has been explained in the chapter about planning. Continuing with that example, an electric scheme of the grid can now be constructed. In appendix, figure 8.2, all the loads efficiencies and cable lengths has been written down. The active efficiencies P_j are known for all the loads. These values are given from Fortum and are approximated values based on customer's efficiency usage. The reactive power Q_j is not given, but it is approximated using the power factor 0.95. For larger load the power factor is approximated with 0.85. These values have been chosen after a meeting with Bo Larsson on Fortum Distribution. The network is large, and calculating everything by hand is not the most practical thing to do. Because all the alternatives how the grid and landscape can be if is important to have a method that can handle all different alternatives how the grid is constructed. Without complicating everything too much, the cables and overhead lines capacitance is neglected. For long transmission lines the capacitance is more important.

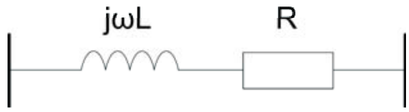

Figure 3.1: Short transmission line

In figure 3.1 a model of a short line cable is represented. This model is accurate enough to get a result that doesn't deviate to much from the real values. The capacitance has the affect to raise the voltage in the grid, and without it the voltage dip can become a little less than the real value. But the result will still be useful because the grid length is not long enough to cause any high effects due to the small capacitance that is in the cables. Continuing with the model, a way to solve the voltage dip is the next step. The model should be able to calculate fast and accurate for large and complicated grids. Two different methods are used for comparison, Gauss-Seidel and Newton-Raphson algorithm. These will be studied later in this chapter. Another important part that the method should calculate is the three phase short circuit over the grid. This can be used when determining cables, fuses and overcurrent protection which are located all over the grid.

At Fortum there are different programs that are used; two of them are Netkoll and facilplus. These programs will give a lot of information about for example fuses and short circuit in the grid. The programs are used after the planning and inspection. When the planner knows how the grid looks like, a very detailed calculation has to be made. This is the part which is done using the mentioned programs. In this report, calculations have been made with the Matlab program to establish important information about the grid. The program that is constructed in this report is something that can help the planner to determine where the new grid should be placed. The difference between Netkoll, facilplus and the constructed program, which is described in this report, is when they are used. The new program is used in the first state, and the other two are used later after planning and inspection. Basically a new planned grid will be shown as an example, and also give some information about the grid. Netkoll and facilplus can be used after both the planning and inspection, which will give more detailed information. At that stage all cable lengths, and which cables are placed where, is known. That makes it easier to build up a more accurate model of the grid.

3.1 Voltage dip

To calculate everything by hand would take a lot of time. Two methods calculating all bus voltages are therefore compared, Gauss-Seidel and Newton-Raphson algorithm.

3.1.1 Gauss-Seidel algorithm

Only using the power flow equations, and making some calculations, the following formula is derived:

$$u_k^{(v+1)} = \frac{P_k^{(v)} - iQ_k^{(v)}}{y_{kk}(u_k^{(v)})^*} - \frac{1}{y_{kk}} \sum_{\substack{j=1 \\ j \neq k}}^{n} y_{kj} u_j^{(v)} \tag{3.1}$$

After a few iterations all bus voltages should be known. In appendix the Gauss-Seidel algorithm is explained in more detail, see section 8.4 on page 49. The Matlab program is also shown, see page 72.

The problem with this algorithm is that if the grid is large the number of iterations will increase. The error might be large, and the result is not good enough for a large grid, but the algorithm is very easy to construct. If the time is limited this would be considered.

3.1.2 Newton-Raphson algorithm

The Newton-Raphson algorithm is using the derivative when determining all bus voltages. In appendix a more detailed explanation as to how this algorithm is used and calculated, see section 8.5 on page 52.

This method is much more accurate, and it will solve the problem a lot faster. This is the reason why this should be used. It is based on using the derivative on the power flow equations. This will determine the result much faster and more accurate. When the grid is large and complex the need of a better mathematical method is needed and that is why Newton-Raphson algorithm is used. As previously stated the Gauss-Seidel algorithm is not good enough when the grid is large. Gauss-Seidel algorithm has easy math involved, and can be constructed very fast. The Newton-Raphson algorithm is a little more complex. To solve this more maths is needed. If a fast and not too accurate solution is needed the Gauss-Seidel algorithm is actually the best one. If, on the other hand, a more accurate solution is needed the Newton-Raphson algorithm should be used. Later when testing different kinds of cables in the grid, which will give for example the voltage dip, the Newton-Raphson algorithm is then used for calculations.

3.2 Comparison between Gauss-Seidel and Newton-Raphson algorithms

Looking at the error based on the voltage and angle, when using the Gauss-Seidel algorithm, the result is represented in figure 3.2. For each loop, the new voltage result, which has been calculated from the iteration, is compared to the previous voltage. The difference is not much, but the result is not accurate enough to get good values.

With Newton-Raphson, at the same error comparison after 7 iterations, the error is $1.8 \cdot 10^{-12}$, compared to Gauss-Seidel where the error is $9.4 \cdot 10^{-5}$.

Because the result should be given fast and accurate the Newton-Raphson method is used. The big difference is that the algorithm for Gauss-Seidel is much easier and faster to construct. If only approximate results is needed and a code must be constructed the Gauss-Seidel is much easier to make. The Newton-Raphson algorithm

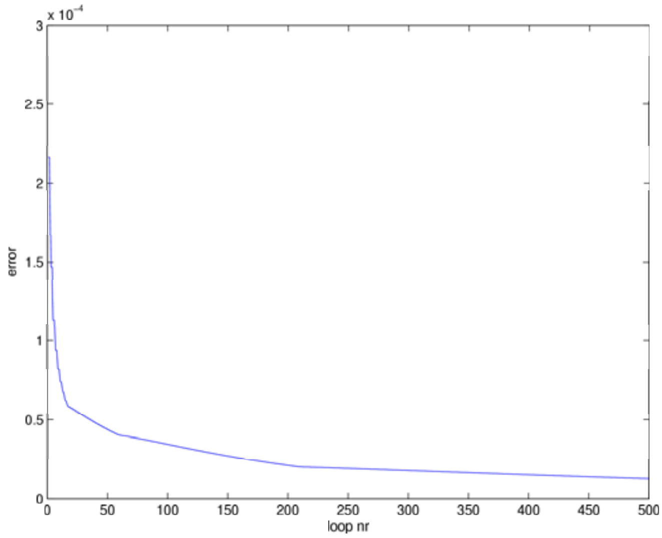

Figure 3.2: Gauss-Seidel error

needs a little more time when constructing it but because the final result should be able to solve more complicated grids, the Newton-Raphson metod is the one that should be used.

3.3 Cable size

If the maximum load is known at a customer, the current can be calculated. This maximum current can be used to determine which cable is needed. Different cables have different characteristics. The cable has to withstand the current in the cable. In cable data on page 67 the maximum continuous load current I_b is shown. If a short circuit happens the allowed overload on the cable can handle approximately 130% for a short moment. This means that for a cable ACJJ 240 where I_b is 345 the limit would be 450A for a short moment. For a smaller conductivity area the resistivity is larger. This will give a smaller short circuit current longer away on the cable. The data about the cables will give the maximum short circuit current over the time period of one second. The short circuit current should not be larger than this value. If a short circuit is occurring close at the transformer station, the size of the short

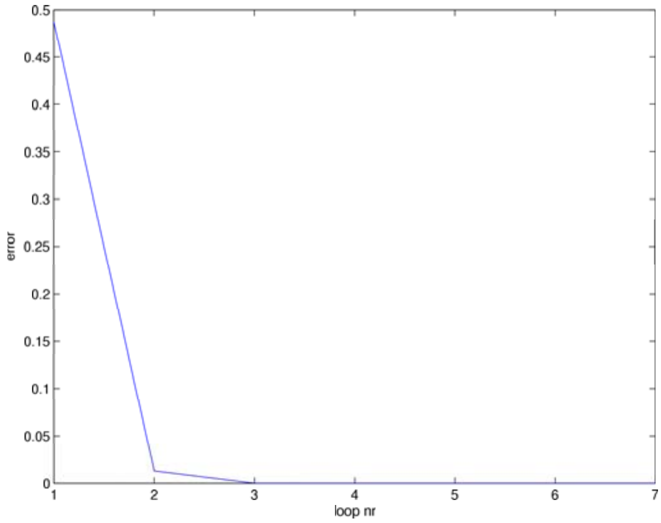

Figure 3.3: Newton-Raphson error

circuit current is larger. The fuse that is protecting the cable should be able to stop the current fast enough for it not to exceed that value.

It is important to know that when a fault occurs the cables should not break, which fuses and relays will help to prevent. Studying the short circuit currents, information can be gathered to determine which fuse should be chosen. If a large industry wants to increase their power consumption, the cables need to withstand it. Increasing the power consumption a larger main fuse is needed. The electric company needs to be told because they need to check if the actual grid is built to manage the larger load efficiency. It is the industry that needs to determine which size the main fuse should be. The main fuse is located by the load. The fuse that is placed in the transformer station has the characteristics that it should be able to trigger within 5 seconds. If the fault is occurring nearby the transformer station, the fuse will go off a lot faster than 5 seconds, this due to the high short circuit current that occurs. This time will give the maximum fuse. If it is too large the fuse might not trigger as fast as it should. This might lead to other problems in the grid. This is the part where the selectivity comes in. The fault should be isolated from the rest of the customers on the grid. Studying the short circuit current the maximum fuse size can be calculated.

This is based on the max 5 seconds trigger value. The cable data gives a value based on how much current it can withstand for a short moment. The fuse should break the current fast enough that the cable is not damaged.

The program, which is constructed for this report, is using the amount of efficiency that flows in the cables. Approximately 70% of the rated max efficiency, that the cable can withstand, should be used when determining cable. At Fortum 90% is used when determining cables, due to increased costs. Cable data gives the value of rated current. This can be calculated into rated efficiency.

3.4 Short circuit current

The short circuit current can be used to determine the overcurrent protections, which will be placed in the grid. Thermal stresses and where the short circuit is occurring are important factors that are used when determining the relay. The short circuit efficiency on the low voltage side of the used distribution plant is taken from used data, which can be seen in appendix at section 8.6 on page 56, where the calculations are shown.

The calculations that are made are calculated within the 10kV grid. Using the given short circuit efficiency S_{k1}, which is shown in figure 3.4, the approximated value for the short circuit current can be calculated at all buses. To get the additional short circuit value for the low voltage at 400V, the maximum length for the cables is assumed to be 150m to customer from the transformer station. The first 100m the cable FCJJ is used, and for the last 50m EKKJ is used. This assumption is to give approximate values if a short circuit is located close at the load location. To determine exactly what kind of conductor area it is important to look at the cable data and see how much power can be transferred through it. The next step is to see if it can withstand a short circuit for approximatly one second, different values for cables are shown. How to determine which cable to use is written in more detail in the chapter on cable size on page 21, section 3.3. Also the size of the fuses, which are placed in all the transformation stations, is determined based on the short circuit current. By using a fuse melt time table or graph, the right size can be determined, see section 3.4.3 on page 27.

3.4.1 Dimension of relay in distribution plant

The short circuit current size in the 10kV distribution plant or on an outgoing line is going to be dependent on a number of factors; short circuit power in the 55kV grid (referring to distribution plant 23), the transformers rated data, short circuit voltage and actual operation mode. The voltage size in the calculations is 10.5kV, this because the voltage level on the grid between Fjärås and Förlanda is at this level. In the report the standard of 10kV is used in the text.

At normal operation mode for Fjärås (distribution plant 23) the short circuit power is $S_k = 108MVA$. If data for the distribution plant was known the short circuit power S_{kn} could be calculated.

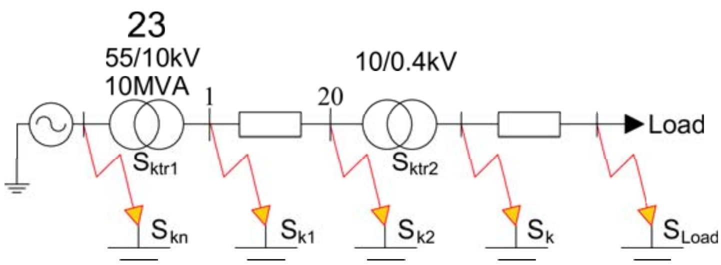

Figure 3.4: Short circuit powers

$$\left.\begin{matrix} S_n\ [MVA] \\ e_r\ [\%] \end{matrix}\right\} S_{ktr}$$

$$S_{ktr} = \frac{S_n}{e_r} \tag{3.2}$$

$$S_k = \frac{S_{ktr} \cdot S_{k2}}{S_{ktr} + S_{k2}} \tag{3.3}$$

The transformers short circuit data is not known, and neither is the short circuit power for the high voltage grid S_{kn}. The value S_{k1} is instead given in a data sheet, which can be seen in the appendix.

Using the short circuit power the short circuit current can be calculated. In the following calculations the values are taken from when the grid is consisting of only AXCEL 95. Changing the cables all over the grid will change the result. This is only done to illustrate how the calculations are made.

$$I_{k1} = \frac{S_{k1}}{\sqrt{3} \cdot 10k} \approx 6.7kA \tag{3.4}$$

The thermal stress that the short circuit current is making is also the time which the short circuit current is allowed to be turned on. The time is also dependent on where the short circuit is occurring, how the over current protection is constructed and how many selectivity steps the protection is embodying. [9]

To correctly dimension the distribution plant it has to be able to withstand the largest possible short circuit current, which is now calculated to 6.7kA, seen in equation (3.4).

Continuing with the overcurrent protection, the constant time relays the actual time tripping is assumed to be one second. The short circuit currents (1-second value) can then be calculated using equation (3.5) and the dynamical stresses can be calculated using equation (3.6). [9]

$$I_{kt} = I_k \cdot \sqrt{t_k} = [t_k = 1] = I_{k1} \cdot 1 = 6.7kA \tag{3.5}$$

$$I_{kd} = I_k \cdot 2.5 = I_{k1} \cdot 2.5 = 16.8kA \tag{3.6}$$

The overcurrent protection can now be determined using the calculated values based on time tripping and dynamical stresses.

3.4.2 Fuse dimensioning

The short circuit furthest away on the 10kV grid from the distribution plant (Fjärås 23) can be determined as follows. The lowest calculated short circuit current based on the 10kV grid is 1.57kA, which can be seen in the charts on page 62.

$$|S_{k1-2}| = \sqrt{3}|U_h||I_{k1-2}| = \sqrt{3}\cdot 10.5k \cdot 1.57k \approx 28.6MVA \quad (3.7)$$

$$S_{k2} = \frac{S_{k1-2}\cdot S_{kn}}{S_{k1-2}+S_{kn}} = 22.5MVA \quad (3.8)$$

$$\Rightarrow I_{k2} = \frac{22.5M}{\sqrt{3}\cdot 10.5k} \approx 1.2kA \quad (3.9)$$

The short circuit current I_{k1-2} is more closely explained in appendix, see section 8.6 on page 56. I_{k1-2} is a LLLG fault, and calculating the two-phase fault approximately can be done as follows:

$$I_{k2-2phase} \approx 0.86\cdot I_{k2} \approx 0.86\cdot 1.2k \approx 1kA \quad (3.10)$$

This result is the two-phase short circuit current for bus nr 20 on grid 23 (Fjärås), see figure 8.2 on page 56.

Also, at the low voltage side (400V) the short circuit current I_k can be calculated. Calculating this, some transformer data is needed. Due to no information given about the 10/0.4kV transformer at bus 20, the value on the short circuit reactance e_k is approximately 3.2%, as per the following calculations:

$$S_{ktr2} = \frac{S_b}{e_r} = \frac{100}{0.032} = 3.1MVA \quad (3.11)$$

$$S_k = \frac{S_{k2}\cdot S_{Sktr}}{S_{k2}+S_{Sktr}} = 2.7MVA \quad (3.12)$$

The short circuit current is calculated for the high voltage side of the transformer.

$$
\begin{aligned}
I_k &= \frac{2700k}{\sqrt{3} \cdot 10k} = 156A && (3.13)\\
I_{k-2phase} &= 0.86 \cdot 156 = 134A && (3.14)
\end{aligned}
$$

When calculating on the longest 10kV line, plus transformer, the short circuit power is 1.7MVA, which will as a consequence give a two-phase short circuit on approximately 82A, referred to the high voltage side.

To determine the short circuit current the furthest away, the low voltage cable plus the service line must be included in the calculations. The assumption that the low voltage cable can be a maximum of 100m, and the service line is 50m as the longest. If assumed that a FCJJ $50mm^2$ is used for the low voltage cable and EKKJ $25mm^2$ for the service line, the result will show that the short circuit current will be 69A, referred to the 10kV side, which is shown in appendix section 8.8 on page 60. The two-phase fault will then be approximately 59A, using a similar method to that used in equation (3.14). With help of fuse characteristics the time for the fuse to trip should be approximately 5 seconds. The tripping time should not be larger than this value. The information about tripping time is the one Fortum is using when calculating on their grids.

3.4.3 Fuses, relay and selectivity

The fuse size can be known after calculating the short-circuit current. Another very important factor is the selectivity. The fuses should help isolating the error, and thereby minimizing an interruption for many customers. Depending on the load size different fuses is put in on the high voltage side of the transformer. On the low voltage side the power is divided into more cables. For each cable a fuse is put in. Based on calculations a minimum recommendation on fuse size is given from the program. If there is a large industry, more than one cable can be placed towards it.

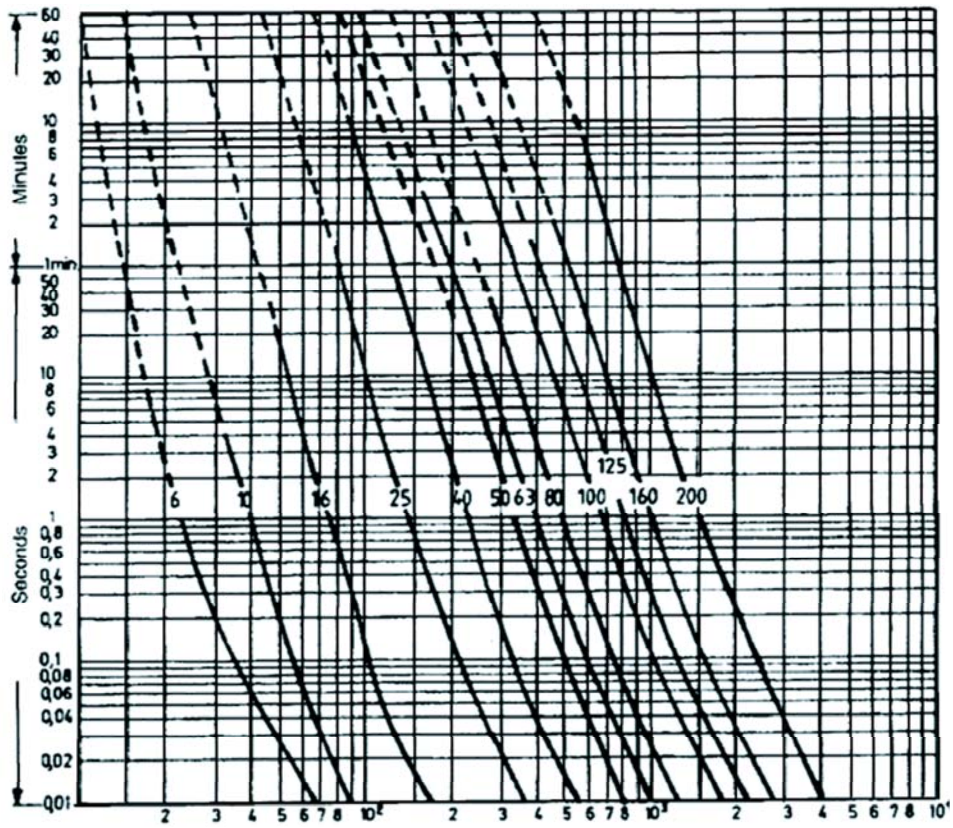

Figure 3.5: Fuses melt time [8]

To make the selectivity for the grid, melt time curves is useful. Different brands of fuses and relays will have different characteristics. There are a lot of different types of fuses on the market, which can make it hard to find out which one is the best. In the chapter on materials more details about this will be written.

The melt time curves for typical 10-20kV subarea fuses is shown in figure 3.5. The x-coordinate is prospective current and y-coordinate is melt time. The fuses may not trigger at marked time where the lines are dotted.

Continuing looking at bus 20, which is the farthest away from the distribution plant, according to given data from the charts on page 61 the min fuse on 10kV side is 6A. If a two-phase fault occurs the current will become 59A as previously calculated.

Looking at figure 3.5 the time for the fuse to break is approximately 0.015 seconds.

3.5 Voltage level change

If the transmission in the system should be improved there are two options. The first thing is to strengthen the grid; the second is to raise the voltage level. It will cost a lot to raise the voltage level, this because a lot of parts in the grid have to be changed. The interlocking installation is probably not changed in this report. But if in another network the old one is removed and replaced, it might be a good idea to check if increasing the voltage to a higher level is possible. By increasing the voltage level the current will decrease, which will decrease the losses in the grid. In the future a lot of loads will increase. Most of the investigations show that only very small economical profits can be made with conventional loads. But if electricity is used to cover all the heat demand in a large area, the load will increase and the higher voltage level at 24kV is both a technical and economical advantage. [9]

Chapter 4

Material

Cables, Overhead lines, Circuit-breakers, interlocking installations and Fuses are some materials that need to be placed in the grid.

On the existing 10kV grid, which is studied, information about what kind of relay protection is used, has been given from Henric Johansson, who is an investigating engineer with the responsibility area relays and selectivity investigations on Fortum Distribution in Kungsbacka. The relays on the outgoing 10kV lines there are modern statistical relay protections of typ Siemens 7SJ62. They are adjusted into constant time and use two over voltage steps, and also with a function for directed earth faults including the intermittent function. More information about this relay protection can be found at the Siemens homepage [4].

4.1 Cables

When looking at different cables it is important to know what the notation is for the different cables. The standards is established by CENELEC[1]. In Sweden there is SEK[2] which determine the Swedish standards. For cables the Swedish standard

[1]European Committee for Electrotechnical Standardization
[2]Swe: Svenska Elektiska Kommisionen Eng: Swedish Electrical Commission

SS 424 17 02 is used when determining what kind of material is used in cables.

Looking at old grids in general, the normal type of cables at low voltage grid was EKKJ, FKKJ and AKKJ, which has both isolation and a cover of PVC[3]. The PVC material is used widely all over the world. Approximately half of all PVC that is manufactured is used in construction. The material can replace material like wood, concrete and clay in many areas. How the PVC is affecting the environment is still under investigation. [16]

The old grid is constructed with some cables. The data for these cables is shown in appendix on page 67. The total length for the old grid is approximately 68km. The most common cable is ALMGSI which can be seen in figure 4.2. Looking at each cable type the FEAL $62mm^2$ is the most common, seen in figure 4.1.

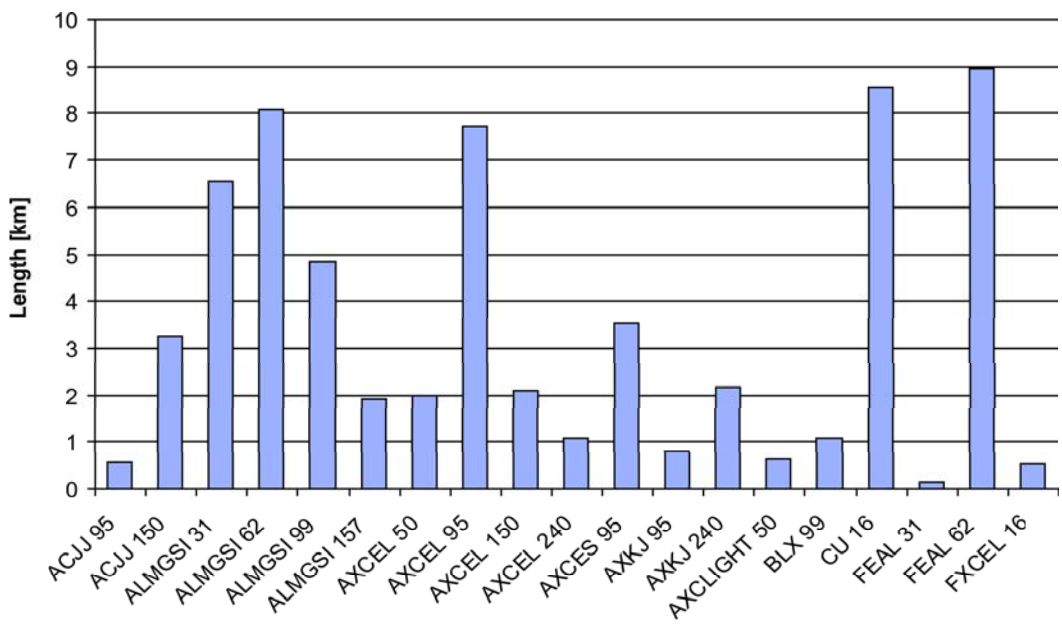

Figure 4.1: Lengths of cables used in old grid

The new grid should have approximately 80% of ground cable. After studying the old grid, it is noted that only 32% of the 10kV grid consists of ground cable. The

[3]polyvinyl chloride

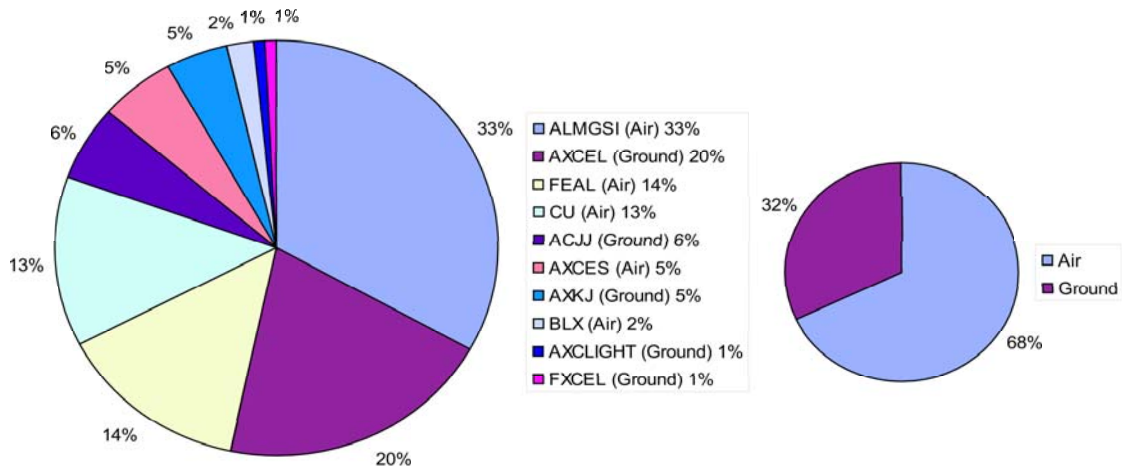

Figure 4.2: A circle diagram showing percentage of cable usage on old grid.

other 68% are overhead lines.

The difference when using cable instead of overhead lines is that the capacitive earth fault current is increasing in the order of 30-50 times the magnitude. This will lead to higher demands on compensation and the refractivity for the connecting devices. The most common way to reduce the earth fault current size is to connect an earthing reactor between the earthed neutral system point and zero. If an earth fault occurs a current with reverse phase will compensate the earth fault current completely or partly. [13]

These days an alternative has been found to the old overhead lines at 10 and 20kV, it's the BLX cable. The BLX is a line based on polyethylene isolation, which is built in the same way as ordinary overhead transmission line. The exception is a reduced phase distance. It can withstand trees that have fallen onto the line for a while. This means that the reparation of the line doesn't have to be done immediately. The customers will still be able to get their power delivered without any interruptions. [9]

The old grid has approximately 2% (1 km) BLX installed. The B stands for aluminium alloy which is the conductor, L stands for polyethylene (PE) which is the isolation and the X stands for PVC, with oval cross section, which is the mantle. [14]

ALMGSI which is the most common cable in the old existing grid is overhead transmission lines. The material is consisting of aluminium (Al), magnesium (Mg) and silicon (Si).

Today the standard cable that is used at Fortum is AXCEL, for the 10kV grid. Sometimes the AXCE cable is used instead. Instead of using overhead lines ground cable should be used in those places that are possible. The AXCEK is the same as AXCEL except that it is used in a fire classified location and is weighs almost 10% more.

Some cables are universal, which means that they can be used both in ground, water and air. These are EXCEL, FXCEL and AXCES. Ericsson is manufacturing these cables. These cables have some very important characteristics. They must be able to withstand a lot of different environments. The cables should be able to be ploughed into the ground. Comparing the universal cables against the BLX, which is an overhead transmission line, the inductive voltage drop is much lower. This is because the BLX has approximately $0.4\Omega/km$ and the EXCEL/AXCES has $0.09\Omega/km$ in reactance. This means that the universal cable can be inserted in grids that have problems with the voltage quality. The universal cable can be used as a overhead line, which means that not much work has to be done. Generally the universal cable needs less maintenance than a bare cable or BLX. [13]

There are a lot of different alternatives of cables out in the market. Choosing which one is the most appropriate is important. The cables should be able to deliver the amount of power that different customers need, and without interruptions. The trend is showing that need controlled maintenance is more important than time controlled maintenance. All cables should therefore be insulated. The cables should also withstand a short circuit for a short moment. If a short circuit happens at a location a circuit breaker should stop the electricity. This is important because the cables can only withstand a certain amount of high current for a short while.

Chapter 5

Cost

The program should be able to give the costs. The planner should get a rough idea how much the new grid is going to cost. This value can later be compared to the real result. The ebr catalogue shows the costs for different planning stages. [10]

The first planning stage, which is very rough, the first P1 part is used from the ebr catalogue. This is the one which is used for the program. The costs are very roughly made, which makes it easier to get a realistic value. The grid between Fjärås and Förlanda is in focus in this report. The cost will therefore be focused on the 10kV part. In the existing grid approximately 68% of the grid is overhead cables. The new planned grid will have more ground cables. There are three alternatives, the first one is the cost within a town, the second one is in a densely builtup area and the last one in the countryside. The region in which the actual planning is made, is in the countryside. Because the new grid is located in the countryside, the cost will be much lower than if it was located within a town. There are also two different kinds of cables that are mentioned, PEX[1] and N1XV. The PEX cable is for the 10kV and the N1XV is for the 0.4kV. The cost is, for now, only focusing on the 10kV grid, and not on the 0.4kV. The result will therefore only give the cost for the high voltage grid. The cost for the low voltage grid can become high. If the total length of all the low voltage cables is known it is easy to add, the cost of these to the total sum. This

[1]PEX is cross-linked Polyethylene. Material is used as isolation in cables.

is something the program at this moment can't give, but can be considered in the future if a more detailed solution is wanted.

For the overhead voltage lines there is one option for the 10kV, which is shown with work code G122. The cable EXCEL that is often used at Fortum is a 20kV cable. This is used because the customers want it. The most common cable is the EXCEL $95mm^2$, which costs approximately 368 000kr/km. The problem with this cable is that it is hard to work with. The $70mm^2$ overhead line cable that is constructed for the 10kV is easier to handle, and could replace the over dimensioned cable. But in the end the customer is the one that determines which cable should be used. The cost of a $70mm^2$ overhead line cable is 292 000kr/km. Of course one type of cable can't be placed everywhere. In the beginning of the grid there might be a good reason to have a stronger cable. Further away smaller cables can be used because not the same amount of power is distributed there.

Differential relays and other costs have to be inserted manually afterwards. Due to differences in grids the costs will differ. The details will not be considered in the calculations.

5.1 Transformer station cost

Let's assume that all transformers are replaced in the new grid. This will lead to another large cost. Operation work, Grid stations, with transformers and maintenance work are also considered. Considering the grid which is connected to interlocking installation 23, close at Fjärås, there are 169 grid stations with different sizes of transformers installed.

G159	Trafo and indicators	Cost [kr/unit]
21	12/0.4kV Trafo 800kVA	78 400
22	12/0.4kV Trafo 500kVA	56 900
23	12/0.4kV Trafo 315kVA	42 300
24	12/0.4kV Trafo 200kVA	30 700
25	12/0.4kV Trafo 100kVA	22 800
26	12/0.4kV Trafo 50kVA	17 900

The need for grid stations to be placed is also needed, which will lead to the following costs.

G152	Grid station	Cost [kr/unit]
22	12/0.4kV Grid station 2x800kVA	362 000
23	12/0.4kV Grid station 800kVA	180 000
24	12/0.4kV Grid station 315kVA	94 400

Adding all the costs for all 169 grid stations and transformers the total cost would be approximately 22 million kr. The removal of the old ones is not included. A lot of the transformers that are in the grid are probably not replaced, but if all where the cost would be large. The idea for the program is to allow the user to let it know if a transformer is going to be replaced or not. With help of that information the cost of the new grid will be more accurate.

5.2 Cost of overhead lines and cabels

The total length of the new grid, seen in figure 2.7 with green color, is approximately 86km. If AXCEL 95mm^2 is used all over, just to make it easy, the cost would be 266 000kr/km. This price is taken from the ebr catalogue, work code G146-14. [10] This is the cable that is made for 20kV, but is used for the 10kV grid. The reason, as previously told, is because the customers want this cable the most, according to Fortum. The total sum of this will therefore become approximately 23 million kr.

5.3 Other costs

Other costs that can be included are optocable, disconnectors, road lighting, customer- and marketing service, grid service, maintenance, and so on. If cables are overhead lines, maintenance on the forest would be appropriate. But because the grid is mostly ground cables this is not in the same cost size as it was before. The old grid needs to be dismantled, which means that this is also a cost that needs to be considered. This is something that the program can't do. The program now does not know how the old grid looks like. What is done in this report is made manually, which means that all the cable lengths and types have been written down, and then calculated on.

All the mentioned costs can be inserted, if wanted in a later state. But for now, only the cost for new transformer stations and cables are considered.

Chapter 6

Result

The result for the planning program on the grid between Fjärås and Förlanda is shown and discussed. The inspection part can be made after the program has given an example as to how the grid can be constructed.

6.1 Comparison with the old grid

The old existing grid is consisting of approximately 68% overhead lines. The amount of overhead lines needs to be reduced. Using cables instead of overhead lines will result in a more reliable energy distribution. The grid also has a large voltage dip because of its size. The largest calculated voltage dip is -10.65%, which can be seen in the tables shown in appendix. This is one of the reasons that the grid should be reconstructed. The voltage levels need to be higher. In the new example for constructing the grid, which can be seen in figure 8.2, there are some large changes. A large part of the grid has been handed over to the interlocking installation 41 close at Idala. This will help reducing the voltage drop. Using only AXCEL $95mm^2$ the voltage drop will become a maximum of -1.37% for the grid that is connected to interlocking installation 23, which is located close at Fjärås. The grid now is connected to the interlocking installation 41 will now have the largest voltage dip -3.29%. The longest distance out to customer is approximately 19.0km with the old grid, and for the new grid approximately 12.5km. The limit for voltage drop is -5% at Fortum, which the new proposed grid is within. The calculations that are made to get these results have been determined with the Newton-Raphson algorithm, which is explained earlier in the report. The electrical schemes of the grids can be seen in appendix page 47 and 48.

6.2 Planning program

The idea for the planning program is to simplify the planning process. If a planning is already made the program can show the shortest path to customer, and also give a cost example. This can be used when comparing results. The program itself will show how much the voltage dip is at all buses in the examined grid.

There are some things that the program needs to be able to give a solution:

- Customer power
- Transformer station size and location
- Interlocking installation short circuit current, size and location

The location of all transformer stations, the coordinates, is needed. Also the size of each transformer station is needed, for short circuit current calculations. The maximum load that is consumed from a customer, must be given to be able to calculate which cables and fuses are needed. The interlocking installation, where the voltage is transformed to the 10kV grid, the short circuit current and placement is needed. The short circuit current can now be determined for all buses, which can be used to determine for example the relays which are placed in the 10kV grid. Knowing all placements for all transformers a grid can be drawn with help of the program.

After giving all data that is needed to the program a solution will be calculated. The result for the new planned grid which is made in this report can be seen in appendix page 61.

6.3 Future updates

The program that has been written is made in Matlab. The next step is to make it more useful to other users. A graphical interface has to be made. The next step would therefore be to make the program in, for example Java, which can simply be used by a lot of users. This means that the user doesn't have to buy any expensive programs to be able to use this. The map part of the program is also something that needs to be upgraded. The algorithm to find the shortest way to customer works, but more detailed maps are needed. Better maps over the area can be used to make the programable to follow roads, which mean a faster and more accurate solution is given.

The cable selection is something that also should be inserted in the program. The idea for this is that the program is going to give an example what kind of cable that should be placed, and where. Having information about cables, and how much power that can be transferred through it can be used to determine this. Some small adjustments need to be done at this part.

6.4 Conclusion

There are still a lot of changes and programming left to make this program useful to other users. Knowing how the program works it is easy to make changes and use the program. The next step is therefore to make the program simple to use. A graphical interface should be constructed to make it easier to operate. The time from having nothing at all to a complete planning proposal should not take much time at all. If a planner only want to look at a new area to construct a grid, this program should give an approximate solution, and of course fast. In the previous section about future updates some parts that need to be improved are mentioned. When and if this program is finished it can help the planner to finish the work a lot faster. The grids all over Sweden need to be updated and rebuilt. The program can be quite advanced when finished, but easy to use. For now a simple prototype is finished. The calculation part is made correctly, and continuing with some more advanced map systems the program can be finished.

Hopefully this program will provide a better and more accurate grid construction.

Chapter 7

Summary

The thesis work Fortum wanted, was to study how the distribution network is constructed today, and after that see if and how they could obtain better solutions on planning and construction. This was the only information that was given from the beginning, which made this thesis very interesting to work with. No rules to follow and new ideas are wanted. The idea from the beginning was to study different material, if they could be replaced and find better ones. The problem was that information about prices is very hard to get. The price is settled based on different contracts the companies makes. Due to lack of material insight it was very hard to find better and more price worthy materials than the already existing material. Based on the fact that no program was handed over, an idea to make another program was in mind. The result became quite interesting. The program that has been constructed can help the planner to shorten the planning process, or just give a cost proposal to compare if a new grid already is planned. The program is still not completed, but a lot is finished. The code and idea which is explained in the report is made in detail. Hopefully the program will be finished in the near future. For now the program has no graphical interface, which will make it very hard to use for other users. The next step for the program is to fix this, and also improve the map grid construction part. Hopefully everyone will see the fully functional program in the market in the near future.

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Chapter 8

Appendix

8.1 Reported errors on existing grid

The work management has assembled some interruption statistics for the old existing grid. Some of these errors are represented below.

20041026: A tree has fallen on street. The high voltage has been taken out of use to remove tree safely. The interruption time is 1 hour and 47 minutes until customers get their power back. 380 customers are affected.

20050108: A tree has fallen on line and the line is broken. The interruption time is 3 days 23 hours and 3 minutes. 410 customers are affected.

20050112: A transformer stops working. Lack of maintenance is the cause of this. The interruption time is 21 minutes. 456 customers are affected.

20050112: Error at the same place. The interruption time is 16 hours and 22 minutes. 456 customers are affected.

20050113: A tree has fallen on line and the line is broken. The interruption time is 4 hours and 28 minutes. 456 customers are affected.

20050114: A tree has fallen on line and the line is broken. The interruption time is

5 hours and 40 minutes. 163 customers are affected.

20050518: Cause unknown. The interruption time is 3 hours and 33 minutes. 155 customers are affected.

20060131: Old overhead transmission cable has been broken. The cable end has been burned. Reason for this is lack of maintenance. The interruption time is 5 hours and 26 minutes. 424 customers are affected.

20060208: Cause unknown. The interruption time is 44 minutes. 76 customers are affected. Later the same day another interruption happens. The interruption time is 46 minutes. 76 customers are affected.

20060212: Cause unknown. The interruption time is 3 minutes. 386 customers are affected. Later same day another error occurs, due to earth fault currents breakers that have been disconnected. This time 898 customers are affected.

20060213: Cause unknown. The interruption time is 2 hours and 5 minutes. Fault that occurred yesterday (20060212) is still making problems. The fault is found in a fuse devise. 898 customers are affected.

20060219: Isolator and surge diverter are replaced. 1699 customers are affected. The customers have had power all the time due to redirected power supply. The interruption time is 3 hours and 3 minutes. Two other times during that day there is maintenance at the same place. The interruption times the other times are 1 minute and 5 minutes.

20060324: Cause unknown. The interruption time is 1 hour and 37 minutes. 162 customers affected.

20060326: Two fault with cause unknown. Interruption times for these are each 1 minute. 386 customers are affected. The third fault is caused by a bird that has created a short circuit. The interruption time is 2 hours and 30 minutes. Also here 386 customers are affected.

8.2 Electrical scheme for old grid

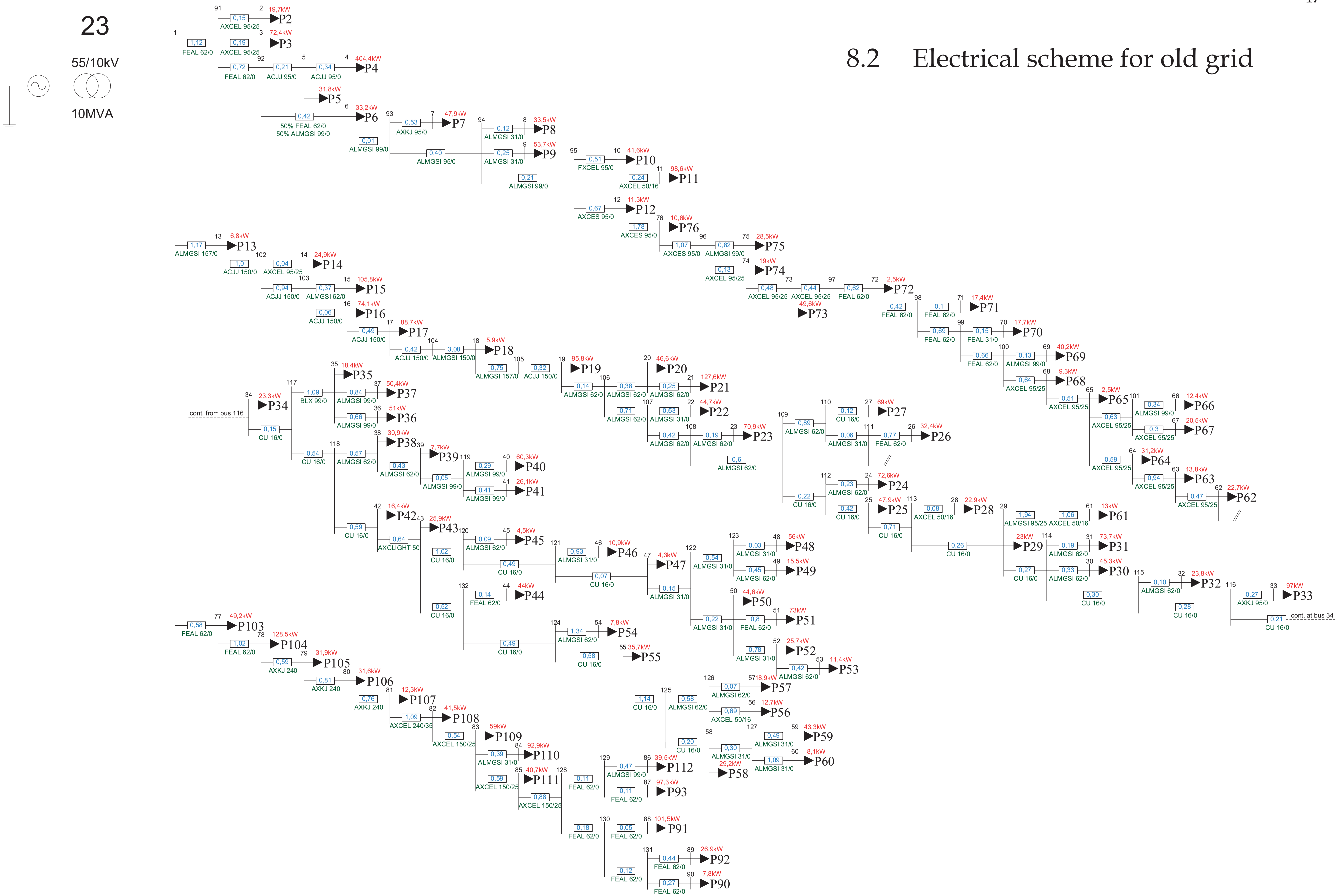


Figure 8.1: Electrical scheme for old grid

8.3 Electrical scheme for new grid

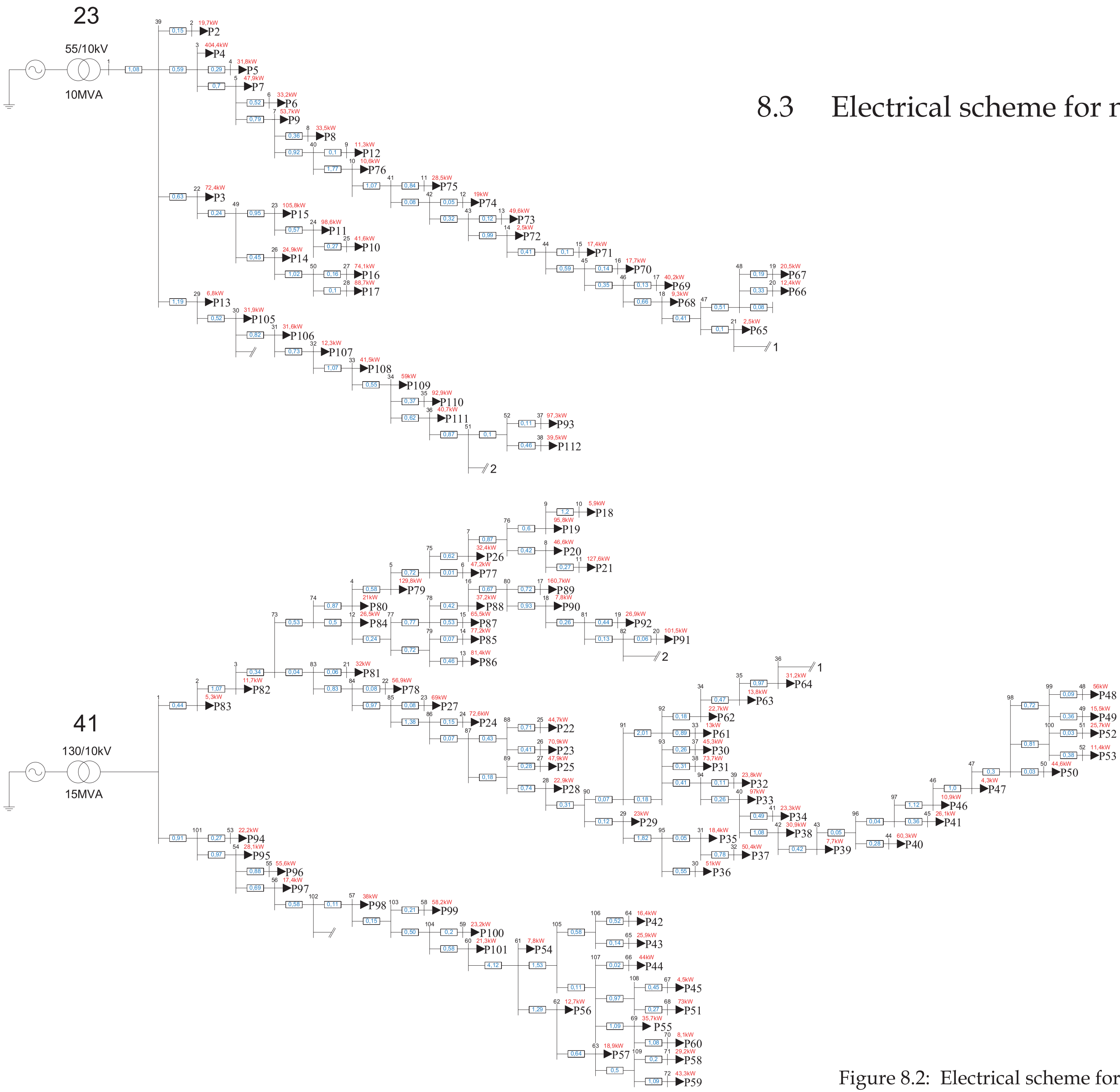


Figure 8.2: Electrical scheme for new grid

8.4 Gauss-Seidel

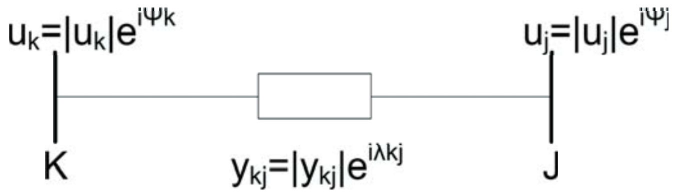


Figure 8.3: Cable or line between two buses

Calculating all voltages over the grid the Gauss-Seidel algorithm can be of use. In figure 8.3 a simple model is shown and represents a cable or a overhead line between two buses.

y_{kk} = Sum of admittances to node k.

y_{kj} = Sum of admittances between j and k.

and if $k \neq j$ the admittance should be with a negative sign.

n =total number of buses

The power flow equations are now used.

$$S = \sqrt{3}\, U_h I_f^* \tag{8.1}$$

$$P_k = \sum_{j=1}^{n} |y_{kj}||u_k||u_j| \cos(\psi_k - \psi_j - \lambda_{kj}) \tag{8.2}$$

$$Q_k = \sum_{j=1}^{n} |y_{kj}||u_k||u_j| \sin(\psi_k - \psi_j - \lambda_{kj}) \tag{8.3}$$

Let's look into the first equation (8.1), which give us the following:

$$
\begin{aligned}
(8.1) \Rightarrow S &= \sqrt{3}\, u_h \Big(\frac{u_f}{z}\Big)^* = \sqrt{3}\, u_h\, y^* \frac{u_h^*}{\sqrt{3}} = u_h\, y^* u_h^* && (8.4)\\
\Rightarrow S_k &= P_k - iQ_k = \sum_{j=1}^{n} u_k\, y_{kj}^* u_j^* && (8.5)\\
\Rightarrow S_k^* &= P_k^* - iQ_k^* = \sum_{j=1}^{n} u_k^*\, y_{kj} u_j && (8.6)
\end{aligned}
$$

Equation (8.6) can also be seen as follows:

$$
\begin{pmatrix} S_1^* \\ \vdots \\ S_k^* \\ \vdots \\ S_n^* \end{pmatrix} = \begin{pmatrix} y_{11}u_1^* & \dots & y_{1k}u_1^* & \dots & y_{1n}u_1^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{k1}u_k^* & \dots & y_{kk}u_k^* & \dots & y_{kn}u_k^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{n1}u_n^* & \dots & y_{nk}u_n^* & \dots & y_{nn}u_n^* \end{pmatrix} \begin{pmatrix} u_1 \\ \vdots \\ u_k \\ \vdots \\ u_n \end{pmatrix}
$$

Continuing with equation (8.6), and extending it, will give an equation that later can be iterated.

$$
(8.6) \Rightarrow S_k^* = u_k^* \sum_{j=1}^{n} y_{kj} u_j = u_k^* y_{kk} u_k + u_k^* \sum_{\substack{j=1 \\ j\neq k}}^{n} y_{kj} u_j \qquad (8.7)
$$

Using the result in (8.7) the voltage u_k is expressed as follows:

$$
\Rightarrow u_k = \frac{S_k^* - u_k^* \sum\limits_{\substack{j=1 \\ j\neq k}}^{n} y_{kj} u_j}{y_{kk} u_k^*} = \frac{P_k - iQ_k}{y_{kk} u_k^*} - \frac{1}{y_{kk}} \sum_{\substack{j=1 \\ j\neq k}}^{n} y_{kj} u_j \qquad (8.8)
$$

The equation for Gauss-Seidel is:

$$u_k^{(v+1)} = \frac{P_k^{(v)} - iQ_k^{(v)}}{y_{kk}(u_k^{(v)})^*} - \frac{1}{y_{kk}} \sum_{\substack{j=1 \\ j \neq k}}^{n} y_{kj} u_j^{(v)} \tag{8.9}$$

To construct the algorithm following steps has been used. The reference for this is taken from Power System Design course, which was held Thursday 1:st of December 2004. A Matlab code was then constructed after these steps.

1. Define: The buses, and known and unknown variables.
2. Set the reference bus voltage as $1\angle 0°$ and give initial values to the unknowns.
3. Write down the admittance matrix for the network.
4. Write the general form of G.S. iterative equation.

$$u_k^{(v+1)} = \frac{P_k^{(v)} - iQ_k^{(v)}}{y_{kk}(u_k^{(v)})^*} - \frac{1}{y_{kk}} \sum_{\substack{j=1 \\ j \neq k}}^{n} y_{kj} u_j^{(v)}$$

5. Start the iteration for each bus, the power flow equations are used to calculate the powers (if unknowns):

$$P_k^{(v)} = \sum_{j=1}^{n} |y_{kj}||u_k^{(v)}||u_j^{(v)}| \cos(\psi_k^{(v)} - \psi_j^{(v)} - \lambda_{kj})$$
$$Q_k^{(v)} = \sum_{j=1}^{n} |y_{kj}||u_k^{(v)}||u_j^{(v)}| \sin(\psi_k^{(v)} - \psi_j^{(v)} - \lambda_{kj})$$

6. Update the variables to continue with next iteration.
7. Compare two successive solutions to reach a required accuracy.

The problem with this algorithm is that the grid can't be too large. The grid that is examined in this report might be too large for this algorithm, and the error gives an inaccurate result.

8.5 Newton-Raphson

The Newton-Raphson algorithm is more accurate than Gauss-Seidel algorithm. The power flow equations (PFE) are used here.

$$P_k = \sum_{j=1}^{n} |y_{kj}||u_k||u_j| \cos(\psi_k - \psi_j - \lambda_{kj}) \quad (8.10)$$

$$Q_k = \sum_{j=1}^{n} |y_{kj}||u_k||u_j| \sin(\psi_k - \psi_j - \lambda_{kj}) \quad (8.11)$$

n =total number of buses

The voltages on all buses in the grid is wanted. We know one bus voltage, which is called the swingbus, and this is 1 pu. The voltage angle is then $\psi_1 = \psi_{ref} = 0$. All the other buses $(n-1)$ has angles ψ_j.

The first thing is to assume all bus voltages, $|u_j|\angle\psi_j$, which are not known. Comparing the assumed values to the real one will give a small error, which can be described as $\Delta|u_j|\angle\Delta\psi_j$.

We need to find the roots for equation (8.10) and (8.11). The total efficiencies in the circuit should be zero, which means that the following equations should be solved:

$$P_k = 0 \quad (8.12)$$

$$Q_k = 0 \quad (8.13)$$

The roots is now wanted. Using the assumed value on voltages, and adding the error, the roots are found. If the values on all voltages are correct, both the active and reactive efficiencies in equation (8.10) and (8.11) will become zero. Call the PFE based on calculated values of a first guess f_{pk} and f_{qk}.

$$P_k = f_{pk} = f_{pk}(\psi_j^{(0)} + \Delta\psi_j, u_j^{(0)} + \Delta u_j) = 0 \qquad j = 1, \ldots, n \tag{8.14}$$

$$Q_k = f_{qk} = f_{qk}(\psi_j^{(0)} + \Delta\psi_j, u_j^{(0)} + \Delta u_j) = 0 \qquad j = 1, \ldots, n \tag{8.15}$$

If equation (8.14) and (8.15) is $f(x+\Delta x) = 0$, then the root is $x+\Delta x$. When $\Delta x \rightarrow 0$ the root $x + \Delta x \rightarrow x$, and the real values are found.

The next step is to make an Taylor expansion, only using first derivatives.

$$P_k = f_{pk}(\psi_j^{(0)}, |u_j|^{(0)}) + \cdots + \left(\frac{\delta f_{pk}}{\delta \psi_j}\right)^{(0)} \Delta\psi_j^{(0)} + \cdots + \left(\frac{\delta f_{pk}}{\delta |u_j|}\right)^{(0)} \Delta|u_j|^{(0)} + \cdots \tag{8.16}$$

$$Q_k = \underbrace{f_{qk}(\psi_j^{(0)}, |u_j|^{(0)})}_{First\ guess} + \underbrace{\cdots + \left(\frac{\delta f_{qk}}{\delta \psi_j}\right)^{(0)} \Delta\psi_j^{(0)} + \cdots + \left(\frac{\delta f_{qk}}{\delta |u_j|}\right)^{(0)} \Delta|u_j|^{(0)} + \cdots}_{Error} \tag{8.17}$$

$(1 + 2n)$ terms are used in equation (8.16), and also in (8.17).

Assume that both P_k and Q_k are known values. f_{pk} and f_{qk} are calculated values based on first guesses. Next thing is to compare the real value P_k and the calculated one f_{pk}.

$$\Delta P_k^{(0)} = P_k - f_{pk}(\psi_j^{(0)}, |u_j|^{(0)}) = \cdots + \left(\frac{\delta f_{pk}}{\delta \psi_j}\right)^{(0)} \Delta\psi_j^{(0)} + \cdots + \left(\frac{\delta f_{pk}}{\delta |u_j|}\right)^{(0)} \Delta|u_j|^{(0)} + \cdots \tag{8.18}$$

$$\Delta Q_k^{(0)} = Q_k - f_{qk}(\psi_j^{(0)}, |u_j|^{(0)}) = \cdots + \left(\frac{\delta f_{qk}}{\delta \psi_j}\right)^{(0)} \Delta\psi_j^{(0)} + \cdots + \left(\frac{\delta f_{qk}}{\delta |u_j|}\right)^{(0)} \Delta|u_j|^{(0)} + \cdots \tag{8.19}$$

Now, the values in equation (8.18) and (8.19) is the power mismatches. The equations can be written in a $(2n \times 2n)$ matrix.

$$\underbrace{\begin{pmatrix} \Delta P_1^{(0)} \\ \vdots \\ \Delta P_n^{(0)} \\ \hline \Delta Q_1^{(0)} \\ \vdots \\ \Delta Q_n^{(0)} \end{pmatrix}}_{\Delta X} = \underbrace{\left(\begin{array}{ccc|ccc} \left(\frac{\delta f_{p1}}{\delta \psi_1}\right)^{(0)} & \dots & \left(\frac{\delta f_{p1}}{\delta \psi_n}\right)^{(0)} & \left(\frac{\delta f_{p1}}{\delta |u_1|}\right)^{(0)} & \dots & \left(\frac{\delta f_{p1}}{\delta |u_n|}\right)^{(0)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\delta f_{pn}}{\delta \psi_1}\right)^{(0)} & \dots & \left(\frac{\delta f_{pn}}{\delta \psi_n}\right)^{(0)} & \left(\frac{\delta f_{pn}}{\delta |u_1|}\right)^{(0)} & \dots & \left(\frac{\delta f_{pn}}{\delta |u_n|}\right)^{(0)} \\ \hline \left(\frac{\delta f_{q1}}{\delta \psi_1}\right)^{(0)} & \dots & \left(\frac{\delta f_{q1}}{\delta \psi_n}\right)^{(0)} & \left(\frac{\delta f_{q1}}{\delta |u_1|}\right)^{(0)} & \dots & \left(\frac{\delta f_{q1}}{\delta |u_n|}\right)^{(0)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\delta f_{qn}}{\delta \psi_1}\right)^{(0)} & \dots & \left(\frac{\delta f_{qn}}{\delta \psi_n}\right)^{(0)} & \left(\frac{\delta f_{qn}}{\delta |u_1|}\right)^{(0)} & \dots & \left(\frac{\delta f_{qn}}{\delta |u_n|}\right)^{(0)} \end{array}\right)}_{J} \underbrace{\begin{pmatrix} \Delta \psi_1^{(0)} \\ \vdots \\ \Delta \psi_n^{(0)} \\ \hline \Delta |u_1|^{(0)} \\ \vdots \\ \Delta |u_n|^{(0)} \end{pmatrix}}_{\Delta U}$$

The matrix written in a simpler form:

$$\left[\Delta X^{(v)}\right] = \left[J^{(v)}\right]\left[\Delta U^{(v)}\right] \tag{8.20}$$

First iteration with first guesses when $v = 0$.

$$v = 0 \rightarrow \left[\Delta X^{(0)}\right] = \left[J^{(0)}\right]\left[\Delta U^{(0)}\right] \tag{8.21}$$

The $[\Delta X]$ is known due to assumed values, which then are corrected with the iteration. The Jacobian matrix $[J]$ is also known and is calculated from first guessed values. This means that $[\Delta U]$ is wanted, and the matrix equation (8.21) needs to be solved.

$$(8.21) \;\; \Rightarrow \;\; \left[\Delta U^{(0)}\right] = \left[J^{(0)}\right]^{-1}\left[\Delta X^{(0)}\right] \tag{8.22}$$

After solving equation (8.22) both $\Delta\psi_j^{(0)}$ and $\Delta|u_j|^{(0)}$ are known. This will lead to a second guess.

$$\begin{aligned} \psi_j^{(1)} &= \psi_j^{(0)} + \Delta\psi_j^{(0)} && (8.23) \\ |u_j|^{(1)} &= |u_j|^{(0)} + \Delta|u_j|^{(0)} && (8.24) \end{aligned}$$

The new calculated values on all buses can now be used for another iteration. This should be repeated until tolerated errors are reached.

$$\left.\begin{aligned} \Delta P^{(v)} &= \varepsilon_{pk} \\ \Delta Q^{(v)} &= \varepsilon_{qk} \end{aligned}\right\} Tolerated\ errors$$

Now the voltages should be accurate enough. And the last thing is to calculate both the active (P_1) and reactive (Q_1) efficiencies at the swingbus.

This method is much more accurate than the Gauss-Seidel algorithm. It is also alot faster. The Newton-Raphson algorithm can be used for larger grids. This method has some limitations. The capacitances in the cables is neglected. Looking at the voltage dip, enough accuracy is given when only using the resistance and inductance data from cables.

8.6 Short circuit current

For example the short circuit (LLLG, 3-phase to ground) current is calculated for bus 5 at interlocking installation 23.

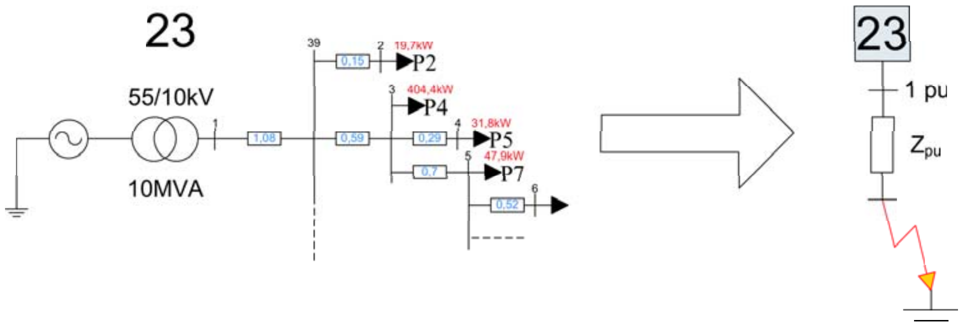


Figure 8.4: Short circuit current at bus 5

Let's assume that the cable AXCEL 95 is used, this will give the resistance $0.32\Omega/km$ and inductance $0.3mH/km$. The cable length to bus 5 is 1.96km, see figure 8.2.

$$Z_{km} = 0.32 + i \cdot 2\pi \cdot 50 \cdot 0.3 \cdot 10^{-3}\Omega/km \quad (8.25)$$

$$Z = Length \cdot Z_{km} = 1.96 \cdot Z_{km} \approx 0.6 + i0.18 \quad (8.26)$$

It is of course not necessary to use pu (per unit) calculations for this example, but when calculating for all buses it is easier to use pu. $S_B = 10MVA$ and $U_B = 10kV$.

$$Z_{pu} = \frac{Z}{Z_B} = \frac{Z}{\left(\frac{U_B^2}{S_B}\right)} \quad (8.27)$$

$$Z_{pu} \approx \frac{0.6 + i0.18}{\left(\frac{(10 \cdot 10^3)^2}{10 \cdot 10^6}\right)} \approx 0.063 + i0.018pu \quad (8.28)$$

It is now easy to calculate the short circuit current. The voltage over the cable is 1pu, which will give the following result:

$$I_{pu} = \frac{1}{Z_{pu}} \approx \frac{1}{0.063 + i0.018} \approx 14.7 - i4.3pu \quad (8.29)$$

$$|I_k| = |I_{pu}| \cdot |I_B| = |I_{pu}| \cdot \frac{|S_B|}{\sqrt{3}|U_B|} \quad (8.30)$$

$$|I_k| \approx |14.7 - i4.3| \cdot \frac{|10M|}{\sqrt{3}|10k|} \approx 8.83kA \quad (8.31)$$

This can't be done manually for each bus, that would take for ever. Instead using the admittance matrix the short circuit current for each bus can be determined.

To calculate the admittance matrix the following needs to be done. First of is to construct the grid. Between bus i and bus j the impedance is Z_{ij}. The admittance can then be calculated.

$$Y_{ij} = \frac{1}{Z_{ij}} \quad (8.32)$$

Building the admittance matrix is done as follows:

$$y_{bus} = \begin{pmatrix} y_{11} & \cdots & y_{1k} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{k1} & \cdots & y_{kk} & \cdots & y_{kn} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{kn} & \cdots & y_{nk} & \cdots & y_{nn} \end{pmatrix}$$

Where

$$y_{ij} = -Y_{ij} \quad i \neq j \quad (8.33)$$

$$y_{ii} = Y_{i1} + Y_{i2} + \cdots + Y_{in} \quad i = j \quad (8.34)$$

Now the impedance matrix can be calculated.

$$z_{bus\,ij} = \frac{1}{y_{bus\,ij}} \tag{8.35}$$

$$Z_{pu\,ij} = z_{bus\,ij} \tag{8.36}$$

$$I_{pu\,ij} = \frac{1}{Z_{pu\,ij}} \tag{8.37}$$

The short circuit current at bus i will therefore become the following:

$$|I_{k\,i}| = |I_{pu\,ii}| \cdot |I_B| = |I_{pu\,ii}| \cdot \frac{|S_B|}{\sqrt{3}|U_B|} \tag{8.38}$$

In Matlab subsection 8.12.11 on page 102 in Appendix the code for short circuit current is shown.

8.7 Active losses in grid

This is the last thing that is done. Knowing all voltages and impedances the following calculations is used.

$$S = 3U_f I_f^* \tag{8.39}$$

$$\Rightarrow S = 3U_f \left(\frac{U_f}{Z}\right)^* \tag{8.40}$$

$$\Rightarrow S = \frac{3U_f U_f^*}{Z^*} = \frac{3U_f^2}{Z^*} = P + iQ \tag{8.41}$$

The real part of the apparent power is now easy to extract. This is done between all buses. The total losses for the grid is then given.

In Matlab subsection 8.12.12 on page 103 in Appendix the code for Losses is shown.

8.8 Fuse Dimensioning calculations

The low voltage is here assumed to be consisting of two types of cables, the first one is a FCJJ 50mm^2, and the other one EKKJ 25mm^2.

$$
\begin{aligned}
Z_{FCJJ50\_100m} &= 0.0350 + j0.0085\Omega && (8.42)\\
Z_{EKKJ25\_50m} &= 0.0365 + j0.0181\Omega && (8.43)\\
Z_{lowTot} &= Z_{FCJJ50\_100m} + Z_{EKKJ25\_50m} = 0.0715 + j0.0265\Omega && (8.44)
\end{aligned}
$$

This is transformed into per units.

$$Z_{pu} = \frac{Z}{Z_b} = \frac{0.0715 + j0.0265}{\frac{400^2}{10M}} = 4.5 + j1.7\,pu \quad (8.45)$$

The short circuit power can then be calculated.

$$|S_{klow}| = \frac{|S_b|}{|Z_{pu}|} = 2.1MVA \quad (8.46)$$

Using this total short circuit power for the furthest load point can be calculated. The short circuit current calculated for the 10kV side is then calculated accordingly:

$$
\begin{aligned}
S_{ktot} &= \frac{S_{klow} \cdot S_k}{S_{klow} + S_k} = \frac{2.1M \cdot 2.7M}{2.1M + 2.7M} \approx 1.2MVA && (8.47)\\
I_{ktot} &= \frac{S_{ktot}}{\sqrt{3} \cdot 10k} \approx 69A && (8.48)
\end{aligned}
$$

8.9 Charts

	AXCEL 95 (23)						
Bus nr	Ik 1-2 [kA]	Udip [%]	Sk [MVA]	Ik [10kV side,kA]	Ik load [10kV side, A]	min fuse [10kV side, A]	min fuse [400V side, A]
2	14,77	-0,62	77,04	4,24	67,91	6	35
3	10,88	-0,78	69,87	3,84	67,80	25	315 x 2
4	9,27	-0,79	65,83	3,62	67,73	6	50
5	7,67	-0,88	60,86	3,35	67,62	6	80
6	6,29	-0,88	55,54	3,05	67,49	6	50
7	5,75	-0,96	53,13	2,92	67,43	6	80
8	5,16	-0,96	50,23	2,76	67,34	6	50
9	4,35	-1,03	45,65	2,51	67,17	6	20
10	3,11	-1,16	37,09	2,04	66,76	6	16
11	2,34	-1,25	30,54	1,68	66,29	6	50
12	2,58	-1,24	32,69	1,80	66,47	6	35
13	2,44	-1,26	31,48	1,73	66,37	6	80
14	2,19	-1,30	29,07	1,60	66,16	6	6
15	2,06	-1,32	27,82	1,53	66,04	6	35
16	1,92	-1,34	26,42	1,45	65,89	6	35
17	1,86	-1,35	25,72	1,41	65,81	6	63
18	1,76	-1,36	24,70	1,36	65,68	6	16
19	1,59	-1,37	22,81	1,25	65,42	6	35
20	1,57	-1,37	22,59	1,24	65,39	6	20
21	1,68	-1,36	23,79	1,31	65,56	6	6
22	10,63	-0,73	69,28	3,81	67,79	6	160
23	6,27	-0,83	55,45	3,05	67,49	6	160
24	5,24	-0,86	50,61	2,78	67,35	6	160
25	4,86	-0,86	48,60	2,67	67,28	6	63
26	7,57	-0,79	60,53	3,33	67,62	6	50
27	5,08	-0,84	49,77	2,74	67,32	6	160
28	5,16	-0,84	50,23	2,76	67,34	6	160
29	8,01	-0,79	62,01	3,41	67,65	6	10
30	6,51	-0,86	56,49	3,11	67,52	6	50
31	5,03	-0,96	49,55	2,72	67,31	6	50
32	4,19	-1,04	44,66	2,46	67,13	6	20
33	3,36	-1,16	39,02	2,15	66,87	6	63
34	3,05	-1,21	36,64	2,01	66,73	6	100
35	2,87	-1,22	35,20	1,94	66,64	6	160
36	2,76	-1,24	34,28	1,89	66,58	6	63
37	2,37	-1,28	30,83	1,70	66,32	6	100
38	2,27	-1,28	29,86	1,64	66,23	6	63
39	16,83	-0,62	79,83	4,39			
40	4,45	-1,03	46,29	2,55			
41	2,63	-1,24	33,12	1,82			
42	2,60	-1,24	32,85	1,81			
43	2,48	-1,26	31,84	1,75			
44	2,08	-1,32	28,06	1,54			
45	1,95	-1,34	26,72	1,47			
46	1,88	-1,35	25,98	1,43			
47	1,69	-1,36	23,97	1,32			
48	1,62	-1,37	23,11	1,27			
49	9,32	-0,76	65,97	3,63			
50	5,31	-0,84	51,00	2,80			
51	2,44	-1,27	31,45	1,73			
52	2,41	-1,27	31,15	1,71			

Bus nr	AXCEL 95 (41) Ik 1-2 [kA]	Udip [%]	Sk [MVA]	Ik [10kV side,kA]	Ik load [10kV side, A]	min fuse [10kV side, A]	min fuse [400V side, A]
2	41,30	-0,33	121,54	6,68	68,31	6	10
3	12,04	-1,13	87,22	4,80	68,04	6	20
4	5,59	-1,71	59,77	3,29	67,60	6	35
5	4,74	-1,80	54,10	2,97	67,45	10	200
6	3,99	-1,88	48,32	2,66	67,27	6	80
7	3,52	-1,95	44,37	2,44	67,12	6	50
8	2,81	-2,05	37,82	2,08	66,80	6	80
9	2,74	-2,04	37,05	2,04	66,76	6	160
10	2,32	-2,05	32,66	1,80	66,46	6	10
11	2,70	-2,06	36,68	2,02	66,74	10	200
12	6,31	-1,66	64,06	3,52	67,69	6	50
13	4,23	-1,75	50,23	2,76	67,34	6	160
14	4,65	-1,74	53,40	2,94	67,43	6	160
15	4,11	-1,82	49,33	2,71	67,31	6	100
16	4,22	-1,85	50,16	2,76	67,33	6	63
17	3,19	-1,95	41,42	2,28	66,99	10	250
18	3,07	-1,96	40,36	2,22	66,94	6	16
19	2,75	-1,97	37,18	2,04	66,76	6	50
20	2,86	-1,97	38,26	2,10	66,83	6	160
21	9,32	-1,39	78,15	4,30	67,93	6	50
22	6,49	-1,71	65,07	3,58	67,71	6	100
23	4,82	-2,06	54,63	3,00	67,47	6	100
24	3,48	-2,52	44,07	2,42	67,11	6	160
25	2,89	-2,57	38,61	2,12	66,85	6	80
26	3,04	-2,57	40,02	2,20	66,92	6	160
27	3,25	-2,60	41,95	2,31	67,01	6	80
28	3,00	-2,78	39,63	2,18	66,90	6	35
29	2,80	-2,87	37,69	2,07	66,79	6	16
30	2,05	-2,95	29,67	1,63	66,22	6	80
31	2,17	-2,94	31,06	1,71	66,34	6	35
32	1,99	-2,95	28,94	1,59	66,15	6	80
33	1,95	-2,93	28,44	1,56	66,10	6	20
34	2,11	-2,93	30,30	1,67	66,27	6	35
35	2,00	-2,94	29,04	1,60	66,16	6	20
36	1,80	-2,95	26,76	1,47	65,93	6	50
37	2,64	-2,91	36,08	1,98	66,70	6	80
38	2,62	-2,92	35,89	1,97	66,69	6	160
39	2,55	-2,97	35,09	1,93	66,64	6	35
40	2,49	-3,00	34,54	1,90	66,60	6	160
41	2,34	-3,01	32,86	1,81	66,48	6	35
42	2,17	-3,11	31,04	1,71	66,34	6	50
43	2,07	-3,14	29,86	1,64	66,23	6	16
44	1,99	-3,15	28,99	1,59	66,15	6	100
45	1,97	-3,15	28,69	1,58	66,13	6	50
46	1,82	-3,21	26,92	1,48	65,94	6	16
47	1,65	-3,26	24,89	1,37	65,71	6	10
48	1,50	-3,30	22,97	1,26	65,44	6	100
49	1,47	-3,30	22,55	1,24	65,38	6	25
50	1,60	-3,28	24,29	1,34	65,63	6	80
51	1,50	-3,29	22,92	1,26	65,44	6	50
52	1,46	-3,29	22,38	1,23	65,35	6	20
53	15,40	-0,17	95,54	5,25	68,12	6	35
54	9,67	-0,35	79,46	4,37	67,95	6	50
55	6,58	-0,36	65,58	3,61	67,72	6	100

56	7,07	-0,45	68,15	3,75	67,77	6	35
57	5,57	-0,55	59,66	3,28	67,60	6	63
58	5,02	-0,58	56,02	3,08	67,51	6	100
59	4,42	-0,63	51,73	2,84	67,38	6	35
60	4,05	-0,70	48,82	2,68	67,29	6	35
61	2,11	-1,12	30,35	1,67	66,28	6	16
62	1,84	-1,16	27,14	1,49	65,97	6	20
63	1,72	-1,18	25,78	1,42	65,81	6	35
64	1,62	-1,23	24,45	1,34	65,65	6	25
65	1,67	-1,23	25,15	1,38	65,74	6	50
66	1,77	-1,23	26,34	1,45	65,88	6	80
67	1,56	-1,25	23,69	1,30	65,55	6	10
68	1,58	-1,26	24,00	1,32	65,59	6	160
69	1,60	-1,24	24,27	1,33	65,62	6	63
70	1,46	-1,25	22,48	1,24	65,37	6	16
71	1,62	-1,20	24,45	1,34	65,65	6	50
72	1,50	-1,21	22,94	1,26	65,44	6	63
73	9,82	-1,38	80,04	4,40			
74	7,64	-1,57	70,93	3,90			
75	3,99	-1,88	48,39	2,66			
76	3,01	-2,02	39,73	2,18			
77	5,82	-1,70	61,21	3,37			
78	4,67	-1,80	53,57	2,95			
79	4,73	-1,74	54,01	2,97			
80	3,65	-1,91	45,53	2,50			
81	2,95	-1,97	39,12	2,15			
82	2,88	-1,97	38,52	2,12			
83	9,62	-1,39	79,27	4,36			
84	6,68	-1,71	66,11	3,64			
85	4,92	-2,06	55,37	3,04			
86	3,58	-2,52	44,97	2,47			
87	3,54	-2,54	44,55	2,45			
88	3,26	-2,56	42,11	2,32			
89	3,42	-2,59	43,49	2,39			
90	2,85	-2,86	38,21	2,10			
91	2,82	-2,88	37,90	2,08			
92	2,15	-2,93	30,80	1,69			
93	2,75	-2,91	37,14	2,04			
94	2,59	-2,97	35,50	1,95			
95	2,19	-2,94	31,21	1,72			
96	2,06	-3,15	29,72	1,63			
97	2,05	-3,15	29,62	1,63			
98	1,61	-3,28	24,34	1,34			
99	1,51	-3,30	23,11	1,27			
100	1,50	-3,29	22,97	1,26			
101	19,97	-0,17	103,63	5,70			
102	5,77	-0,54	60,87	3,35			
103	5,33	-0,57	58,09	3,19			
104	4,65	-0,63	53,40	2,94			
105	1,79	-1,22	26,61	1,46			
106	1,70	-1,23	25,42	1,40			
107	1,77	-1,23	26,38	1,45			
108	1,62	-1,25	24,48	1,35			
109	1,65	-1,19	24,81	1,36			

	Old Grid (only 23)						
Bus nr	Ik 1-2 [kA]	Udip [%]	Sk [MVA]	Ik [10kV side,kA]	Ik load [10kV side, A]	min fuse [10kV side, A]	min fuse [400V side, A]
2	6,65	-0,87	57,07	3,14	67,53	6	6
3	7,30	-0,88	59,55	3,27	67,59	6	35
4	4,31	-1,43	45,45	2,50	67,16	6	160
5	4,68	-1,38	47,60	2,62	67,25	25	315 x 2
6	4,15	-1,48	44,43	2,44	67,12	6	50
7	3,71	-1,49	41,53	2,28	66,99	6	50
8	3,40	-1,58	39,29	2,16	66,88	6	80
9	3,15	-1,59	37,39	2,06	66,78	6	50
10	2,65	-1,69	33,37	1,83	66,52	6	80
11	2,49	-1,71	31,95	1,76	66,41	6	63
12	3,08	-1,68	36,89	2,03	66,75	6	160
13	12,73	-0,76	73,64	4,05	67,86	6	20
14	8,79	-1,23	64,46	3,54	67,70	6	10
15	5,42	-1,69	51,55	2,83	67,38	6	50
16	6,78	-1,69	57,58	3,17	67,55	6	160
17	6,05	-1,89	54,51	3,00	67,47	6	160
18	2,62	-3,75	33,08	1,82	66,50	6	160
19	2,26	-4,28	29,79	1,64	66,23	6	10
20	2,01	-4,47	27,33	1,50	65,99	6	160
21	1,91	-4,49	26,31	1,45	65,88	6	80
22	1,61	-5,08	23,08	1,27	65,46	10	200
23	1,68	-5,42	23,86	1,31	65,57	6	80
24	1,47	-5,96	21,46	1,18	65,20	6	160
25	1,40	-6,51	20,59	1,13	65,05	6	160
26	1,28	-5,70	19,09	1,05	64,76	6	80
27	1,40	-5,69	20,57	1,13	65,05	6	50
28	1,17	-7,43	17,80	0,98	64,47	6	100
29	1,12	-7,76	17,14	0,94	64,31	6	35
30	1,02	-8,10	15,86	0,87	63,96	6	16
31	1,04	-8,10	16,07	0,88	64,02	6	80
32	0,99	-8,42	15,44	0,85	63,83	6	160
33	0,94	-8,73	14,74	0,81	63,60	6	35
34	0,92	-8,92	14,44	0,79	63,50	6	160
35	0,83	-9,12	13,25	0,73	63,05	6	35
36	0,80	-9,13	12,77	0,70	62,84	6	35
37	0,79	-9,13	12,64	0,70	62,79	6	80
38	0,78	-9,52	12,54	0,69	62,74	6	80
39	0,75	-9,54	12,15	0,67	62,56	6	50
40	0,74	-9,55	11,94	0,66	62,46	6	16
41	0,73	-9,55	11,87	0,65	62,42	6	100
42	0,75	-9,83	12,10	0,67	62,53	6	50
43	0,72	-10,04	11,61	0,64	62,29	6	25
44	0,66	-10,18	10,82	0,60	61,85	6	50
45	0,62	-10,36	10,27	0,56	61,50	6	80
46	0,54	-10,52	8,97	0,49	60,55	6	10
47	0,59	-10,53	9,73	0,53	61,13	6	16
48	0,55	-10,62	9,09	0,50	60,64	6	10
49	0,52	-10,62	8,75	0,48	60,36	6	100
50	0,57	-10,61	9,39	0,52	60,88	6	25
51	0,54	-10,65	9,00	0,49	60,57	6	80
52	0,52	-10,64	8,74	0,48	60,35	6	160
53	0,51	-10,65	8,56	0,47	60,19	6	50
54	0,58	-10,27	9,57	0,53	61,01	6	20
55	0,59	-10,38	9,72	0,53	61,12	6	16

56	0,49	-10,56	8,18	0,45	59,84	6	63
57	0,50	-10,55	8,42	0,46	60,07	6	20
58	0,51	-10,56	8,54	0,47	60,17	6	35
59	0,47	-10,60	7,99	0,44	59,65	6	50
60	0,45	-10,59	7,62	0,42	59,26	6	63
61	0,91	-7,78	14,38	0,79	63,48	6	16
62	1,05	-2,35	16,22	0,89	64,06	6	20
63	1,08	-2,34	16,59	0,91	64,17	6	35
64	1,14	-2,33	17,40	0,96	64,37	6	20
65	1,18	-2,32	17,95	0,99	64,51	6	50
66	1,11	-2,33	16,95	0,93	64,26	6	6
67	1,12	-2,33	17,10	0,94	64,30	6	20
68	1,22	-2,30	18,44	1,01	64,62	6	35
69	1,26	-2,28	18,91	1,04	64,72	6	16
70	1,35	-2,22	19,98	1,10	64,94	6	63
71	1,53	-2,15	22,15	1,22	65,32	6	35
72	1,67	-2,10	23,72	1,30	65,55	6	35
73	1,96	-2,00	26,82	1,47	65,93	6	6
74	2,07	-1,96	27,88	1,53	66,05	6	80
75	1,85	-1,96	25,69	1,41	65,80	6	35
76	2,39	-1,85	30,95	1,70	66,33	6	50
77	16,43	-0,26	79,33	4,36	67,94	6	16
78	5,96	-0,70	54,08	2,97	67,45	6	80
79	5,47	-0,74	51,78	2,85	67,39	10	200
80	4,92	-0,81	48,92	2,69	67,29	6	50
81	4,49	-0,86	46,51	2,56	67,21	6	50
82	4,00	-0,94	43,45	2,39	67,08	6	20
83	3,69	-0,99	41,40	2,28	66,99	6	63
84	2,92	-1,03	35,63	1,96	66,67	6	100
85	3,41	-1,03	39,37	2,16	66,89	6	160
86	2,66	-1,10	33,45	1,84	66,52	6	63
87	2,85	-1,09	35,05	1,93	66,63	6	63
88	2,84	-1,10	34,98	1,92	66,63	6	100
89	2,47	-1,11	31,72	1,74	66,39	6	160
90	2,58	-1,10	32,72	1,80	66,47	6	50
91	7,88	-0,87	61,57	3,39			
92	4,94	-1,35	49,03	2,70			
93	4,14	-1,49	44,35	2,44			
94	3,66	-1,57	41,20	2,27			
95	3,45	-1,61	39,72	2,18			
96	2,10	-1,95	28,19	1,55			
97	1,87	-2,03	25,91	1,42			
98	1,56	-2,15	22,44	1,23			
99	1,40	-2,22	20,61	1,13			
100	1,28	-2,28	19,11	1,05			
101	1,14	-2,33	17,36	0,95			
102	8,94	-1,23	64,89	3,57			
103	6,88	-1,66	57,98	3,19			
104	5,53	-2,06	52,10	2,86			
105	2,32	-4,16	30,34	1,67			
106	2,19	-4,42	29,10	1,60			
107	1,89	-5,05	26,03	1,43			
108	1,74	-5,41	24,50	1,35			
109	1,66	-5,62	23,63	1,30			
110	1,44	-5,68	21,08	1,16			
111	1,42	-5,68	20,83	1,15			
112	1,56	-5,94	22,50	1,24			

113	1,18	-7,43	17,95	0,99
114	1,06	-8,09	16,36	0,90
115	1,00	-8,42	15,58	0,86
116	0,95	-8,72	14,91	0,82
117	0,89	-9,06	14,12	0,78
118	0,82	-9,47	13,08	0,72
119	0,75	-9,55	12,12	0,67
120	0,63	-10,36	10,32	0,57
121	0,59	-10,51	9,80	0,54
122	0,58	-10,57	9,59	0,53
123	0,55	-10,61	9,11	0,50
124	0,63	-10,27	10,33	0,57
125	0,52	-10,54	8,70	0,48
126	0,50	-10,55	8,45	0,46
127	0,50	-10,58	8,32	0,46
128	3,05	-1,08	36,68	2,02
129	2,95	-1,09	35,85	1,97
130	2,89	-1,10	35,33	1,94
131	2,79	-1,10	34,49	1,90
132	0,67	-10,17	10,92	0,60

8.10 Cable data

Cables in old grid is shown in the table below:

Type	F Area [mm^2]	N Area [mm^2]	R [Ω/km]	L [mH/km]	max Ib [A]	Ik phase [A]	Length [km]
ACJJ	95	0	0.32	0.31	205	9830	0.55
ACJJ	150	0	0.21	0.3	265	12300	3.23
ALMGSI	31	0	1.05	1.27	105	2900	6.56
ALMGSI	62	0	0.52	0	155	5900	8.09
ALMGSI	99	0	0.33	1.13	210	9400	4.84
ALMGSI	157	0	0.21	1.11	275	14900	1.92
AXCEL	50	16	0.64	0.33	170	4790	1.99
AXCEL	95	25	0.32	0.3	240	9000	7.74
AXCEL	150	25	0.21	0.28	310	14900	2.01
AXCEL	240	35	0.13	0.26	400	22600	1.09
AXCES	95	0	0.32	0.31	200	11000	3.52
AXKJ	95	0	0.32	0.3	240	8990	0.8
AXKJ	240	0	0.13	0.26	400	22600	2.16
AXCLIGHT	50	16	0.641	0.33	145	5200	0.64
BLX	99	0	0.33	1.13	210	9400	1.09
CU	16	0	1.11	1.27	90	2000	8.58
FEAL	31	0	1.07	1.2	100	2600	0.15
FEAL	62	0	0.53	1.12	150	5200	8.95
FXCEL	16	0	1.15	0.4	115	3000	0.51

The values of cable impedances has been measured at 20 °C, which means that the value can deviate some due to different temperatures. This is neglected due to that this study is only for planning state, which means that more detailed calculations is later used when the grid planning and inspection is finished.

8.11 Matlab code for used algorithms

The Matlab code for the used algorithms are shown in this section.

8.11.1 Dijkstras algorithm

```
clc;
clear;
M=load('Koordinater.txt');

n=length(M); %Number of stations
figure(1);
clf;
hold on;
for i=1:112
    plot(M(i,1), M(i,2),'MarkerSize',15,'Marker','.');
end
plot(M(1,1), M(1,2), 'rpentagram'); %Startpoint Transformerstation 23
text(M(1,1), M(1,2), num2str(23),'FontSize',15,'FontName','Times');
plot(M(102,1), M(102,2), 'rpentagram'); %Startpoint Transformerstation 41
text(M(102,1), M(102,2), num2str(41),'FontSize',15,'FontName','Times');

max = 1250; %Max range
figure(2)
clf;
hold on;
for i=1:n
    if i<=112
        plot(M(i,1), M(i,2),'MarkerSize',15,'Marker','.');
        text(M(i,1), M(i,2), num2str(i),'FontSize',15,'FontName','Times');
    end
    for j=1:n
        D(i,j) = sqrt((M(i,1) - M(j,1))^2 + (M(i,2) - M(j,2))^2);
        if D(i,j) <= max
            L(i,j) = 1;   %There is a link between stations;
            if (i>1 & i<13) | (j>1 & j<13)
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':','color','m');
            elseif i<60 | j<60
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':');
            elseif i<77 | j<77
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':','color','m');
            elseif i<94 | j<94
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':','color','c');
            elseif i<103 | j<103
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':','color','m');
```

```
            elseif i<113 | j<113
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':','color','g');
            else
                line([M(i,1) M(j,1)], [M(i,2) M(j,2)], 'LineStyle', ':','color','m');
            end
            if D(i,j)>0
                %text((M(i,1)+M(j,1))/2,(M(i,2)+M(j,2))/2, num2str(round(D(i,j)))
                %      ,'FontSize',7,'FontName','Times');
            end
        else
            L(i,j) = inf; %There is NOT a link between stations;
        end
    end
end
plot(M(1,1), M(1,2), 'rpentagram'); %Startpoint Transformerstation 23
plot(M(102,1), M(102,2), 'rpentagram'); %Startpoint Transformerstation 41

%W=Weighted adjacency matrix
for i=1:n
    for j=1:n
        if L(i,j)==1
            if D(i,j)==0
                W(i,j)=inf;
            else
                W(i,j)=D(i,j);
            end
        else
            W(i,j)=inf;
        end
    end
end

%Startvalues (all the stations are unvisited):
%Visited stations
visited(1,n)=0;
% It stores the shortest distance between each station and the source station;
distance(1,1:n)=inf;

%Startpoints
distance(1)=0; %23
visited(1)=1;

distance(102)=0; %41
visited(102)=1;

% visited(24)=1;
% visited(25)=1;
% visited(38)=1;
```

```
% visited(39)=1;

pause
%Dijkstra algorithm
while length(visited)~=sum(visited)

    %Part 1-------------------------------------------------------------
    %The first part is checking all the new distances to NOT visited stations
    temp=[];
    h=1;
    %i represent each station number
    for i=1:n
        if distance(i)~=(inf) && visited(i)==1
            %j represent the stations that we want to check if they are
            %connected to station i.
            for j=1:n
                if L(i,j)==1 && i~=j && visited(j)==0
                    temp(h,:)=[i j D(i,j)];
                    h=h+1;
                end
            end
        end
    end

    %Part 2-------------------------------------------------------------
    %We make a new temp which shows the total distance between each station
    %and the source station.
    temp2=[];
    if length(temp)>0
        for i=1:length(temp(:,1))
            if temp(i)~=0
                temp2(i,:)=[temp(i) temp(i,2) (distance(temp(i))+temp(i,3))];
            end
        end
    end

    %Part 3-------------------------------------------------------------
    %Now we need to check which distance is the shortest in temp2, and
    %after that set visited=1, insert new distance and color the line which
    %is used.
    h=1;
    for i=1:length(temp2)
        while h==1
            if temp2(i,3)==min(temp2(:,3))
                distance(temp2(i,2))=distance(temp2(i))+temp(i,3);
                visited(temp2(i,2))=1;
                h=0;
                %Color the line which gives the shortest way.
```

```
                line([M(temp2(i),1) M(temp2(i,2),1)], [M(temp2(i),2) M(temp2(i,2),2)],...
                    'Color','r','LineWidth',1.5, 'LineStyle','-');
            else
                i=i+1;
            end
        end
    end
end

%Now we want to know how the connection points are connected with the
%shortest line length. The above algorithm (Dijkstra) shows the shortest
%path from one station to the source station.
```

8.11.2 Gauss-Seidel algorithm

```
%The Gauss-Seidel Algorithm is used to calulate the voltages at all busses.
%The method for this algorithm is taken from lecture notes:
%Power System Design, Lecture 14 Tuesday 25/11-2005.

clear
clc

Ub=10e3;
Sb=10e6;
zb=(Ub^2/Sb);

%-----2-----
%Write down the admittance matrix for the network

%The admittance matrix, y (in pu)
run admittance23
y_abs=abs(y);
y_angle=angle(y);

nrOfBuses=length(y);

%-----1-----
%Define the buses, and known and unknown variables

%Active and Reactive power (in pu)
run PQpower23

%-----3-----
%Set the reference bus voltage as 1pu angle=0 and give initial values to the unknowns
run voltages23

h=0;

epsilon=0.05;
loop=0;
while loop<1000 && epsilon>1e-6
    loop=loop+1;
    %-----6-----
    %Update the variables to continue with next iterations

    if loop>1
        for k=1:nrOfBuses
            if busU(k)==0
                U(1,k)=U(2,k);
            end
        end
```

```
end

%-----4-----
%Write the general form of G.S. iterative equation

for k=1:nrOfBuses
    if busU(k)==0
        sumValue=0;
        for j=1:nrOfBuses
            if j~=k
                sumValue=sumValue+y(k,j)*U(1,j);
            end
        end

        U(2,k)=(1/y(k,k))*((P(k)-i*Q(k))/conj(U(1,k))-sumValue);
    end
end

%-----5-----
%Start the iteration for each bus, the PFE are used to calculate the
%powers (if unknowns).

%Approximated power values are reset
for k=1:nrOfBuses
    if busS(k)==0
        P(k)=0;
        Q(k)=0;
    end
end

%New estimate is calculated
for k=1:nrOfBuses
    for j=1:nrOfBuses
        if busS(k)==0
            P(k)=P(k)+y_abs(k,j)*abs(U(2,j))*abs(U(2,k))*...
                 cos(angle(U(2,k))-angle(U(2,j))-y_angle(k,j));
            Q(k)=Q(k)+y_abs(k,j)*abs(U(2,j))*abs(U(2,k))*...
                 sin(angle(U(2,k))-angle(U(2,j))-y_angle(k,j));
        end
    end
end

clc
BusNr_Voltage_Angle=[1 ;abs(U(2,1)); angle(U(2,1)).*180/pi]';
BusNr_P_Q=[1 ;P(1);Q(1)]'
loop

%-----7-----
```

```
    %Compare two successive solutions to reach a required accuracy
    epsilonU=U(2,:)-U(1,:);
    epsilonPsi=angle(U(2,:))-angle(U(1,:));

    h=h+1;
    epsilonUPsi(h)=max(abs([epsilonU epsilonPsi]));
    %plot(1:500, abs(epsilonUPsi(1:500)))
    epsilon=max(abs([epsilonU epsilonPsi]))

end

BusNr_Voltage_Angle=[1:length(y) ;abs(U(2,:)); angle(U(2,:)).*180/pi]'
BusNr_P_Q=[1 ;P(1) ;Q(1)]'
Number_Of_Loops=loop
```

8.11.3 Newton-Raphson algorithm

```
%The Newton-Raphson Algorithm is used to calulate the voltages at all busses.
%The method for this algorithm is taken from lecture notes:
%Power System Design, Lecture 15 Tuesday 29/11-2005. (see: Summary procedure nr)

clear
clc

Ub=10.5e3;
Sb=10e6;
zb=(Ub^2/Sb);

%Write down the admittance matrix for the network
%The admittance matrix, y (in pu)
run admittance23
y_abs=abs(y);
y_angle=angle(y);

nrOfBuses=length(y);

%Define the buses, and known and unknown variables
%Active and Reactive power (in pu)
run PQpower23
nrOfKnownBuses=sum(busS);

%------1------
%Decide an estimate of all 'U' and 'psi', which are not known.
%Set the reference bus voltage as 1pu angle=0 and give initial values to the unknowns
run voltages23

%h=0;

epsilon=0.05;
loop=0;
while loop<1000 && epsilon>1e-10
    loop=loop+1;
    %------2------
    %Calculate fpk(0) and fqk(0) using estimates made in '1'.
    %Use the PFE (Power Flow Equations)
    dP=zeros(1,nrOfBuses);
    dQ=zeros(1,nrOfBuses);
    for k=1:nrOfBuses; %Values at bus k is calculated
        if busS(k)==1
            %PFE; Power Flow Equation
            %fp(k) and fq(k) is calculated values based on estimates
            %Active Power
            fp=0;
```

```
        for j=1:length(y)
            fp=fp+y_abs(k,j)*abs(U(j))*abs(U(k))*cos(psi(k)-psi(j)-y_angle(k,j));
        end
        %Reactive Power
        fq=0;
        for j=1:length(y)
            fq=fq+y_abs(k,j)*abs(U(j))*abs(U(k))*sin(psi(k)-psi(j)-y_angle(k,j));
        end

        %------3------
        %Calculate the error in guess
        dP(k)=P(k)-fp;
        dQ(k)=Q(k)-fq;
    end
end
%------4------
%Calculate the Jacobian 'J'
%a) Take the first derivatives of fp(k) and fq(k) to psi(j) and U(j)
%b) Include the estimated values

%define functions
dPdU=zeros(nrOfBuses);
dPdpsi=zeros(nrOfBuses);
dQdU=zeros(nrOfBuses);
dQdpsi=zeros(nrOfBuses);
smallAngle=1e-10;

for k=1:nrOfBuses
    for j=1:nrOfBuses
        if busS(k)==1 && busS(j)==1
            %:.:.:.:.:.:.:.:.:.:.:.:.:.:.
            %dPdU------------------------
            if k==j
                for s=1:nrOfBuses
                    if k==s
                        if abs(cos(psi(k)-psi(s)-y_angle(k,s)))<smallAngle
                        else
                            dPdU(k,j)=dPdU(k,j)+y_abs(k,s)*2*abs(U(k))*...
                                      cos(psi(k)-psi(s)-y_angle(k,s));
                        end
                    else
                        if abs(cos(psi(k)-psi(s)-y_angle(k,s)))<smallAngle
                        else
                            dPdU(k,j)=dPdU(k,j)+y_abs(k,s)*abs(U(k))*...
                                      cos(psi(k)-psi(s)-y_angle(k,s));
                        end
                    end
                end
```

```
else
    if abs(cos(psi(k)-psi(j)-y_angle(k,j)))<smallAngle
    else
        dPdU(k,j)=y_abs(k,j)*abs(U(k))*...
                  cos(psi(k)-psi(j)-y_angle(k,j));
    end
end
%----------------------------

%:.:.:.:.:.:.:.:.:.:.:.:.:.:.
%dPdpsi----------------------
if k==j
    for s=1:nrOfBuses
        if k==s
            %The derivative is zero, nothing should be done.
        else
            if abs(sin(psi(k)-psi(s)-y_angle(k,s)))<smallAngle
            else
                dPdpsi(k,j)=dPdpsi(k,j)-y_abs(k,s)*abs(U(j))*abs(U(s))*...
                            sin(psi(k)-psi(s)-y_angle(k,s));
            end
        end
    end
else
    if abs(sin(psi(k)-psi(j)-y_angle(k,j)))<smallAngle
    else
        dPdpsi(k,j)=y_abs(k,j)*abs(U(j))*abs(U(k))*...
                    sin(psi(k)-psi(j)-y_angle(k,j));
    end
end
%----------------------------

%:.:.:.:.:.:.:.:.:.:.:.:.:.:.
%dQdU------------------------
if k==j
    for s=1:nrOfBuses
        if k==s
            if abs(sin(psi(k)-psi(s)-y_angle(k,s)))<smallAngle
            else
                dQdU(k,j)=dQdU(k,j)+y_abs(k,s)*2*abs(U(k))*...
                          sin(psi(k)-psi(s)-y_angle(k,s));
            end
        else
            if abs(sin(psi(k)-psi(s)-y_angle(k,s)))<smallAngle
            else
                dQdU(k,j)=dQdU(k,j)+y_abs(k,s)*abs(U(k))*...
                          sin(psi(k)-psi(s)-y_angle(k,s));
```

```
                    end
                end
            end
        else
            if abs(sin(psi(k)-psi(j)-y_angle(k,j)))<smallAngle
            else
                dQdU(k,j)=y_abs(k,j)*abs(U(k))*...
                          sin(psi(k)-psi(j)-y_angle(k,j));
            end
        end
        %----------------------------

        %:.:.:.:.:.:.:.:.:.:.:.:.:.:.
        %dQdpsi----------------------
        if k==j
            for s=1:nrOfBuses
                if k==s
                    %The derivative is zero, nothing should be done.
                else
                    if abs(cos(psi(k)-psi(s)-y_angle(k,s)))<smallAngle
                    else
                        dQdpsi(k,j)=dQdpsi(k,j)+y_abs(k,s)*abs(U(j))*abs(U(s))*...
                                    cos(psi(k)-psi(s)-y_angle(k,s));
                    end
                end
            end
        else
            if abs(cos(psi(k)-psi(j)-y_angle(k,j)))<smallAngle
            else
                dQdpsi(k,j)=-y_abs(k,j)*abs(U(j))*abs(U(k))*...
                            cos(psi(k)-psi(j)-y_angle(k,j));
            end
        end
        %----------------------------
    end
  end
end

%This removes the row and column that is not wanted

p=0;
for j=1:nrOfBuses
    if busS(j)==1
        p=p+1;
        x(p)=j;
    end
end
dPdpsi=dPdpsi([x],[x]);
```

```
dPdU=dPdU([x],[x]);
dQdpsi=dQdpsi([x],[x]);
dQdU=dQdU([x],[x]);

dP=dP([x]);
dQ=dQ([x]);

J=[dPdpsi dPdU;dQdpsi dQdU];

%------5------
%Inversion of 'J'
invJ=inv(J);

%------6------
%The result is dpsi and dU

%First the power matrix 'dPower' has to be created (dPower=J*dVoltage)
%After that dVoltage=invJ*dPower, which gives us the new dpsi and dU.
dPower=[dP';dQ'];
epsilon=max(abs(dPower));

dVoltage=invJ*dPower;

dpsi=dVoltage(1:length(dVoltage)/2)';
dU=dVoltage((1+length(dVoltage)/2):length(dVoltage))';

%h=h+1;
%epsilonUPsi(h)=max(abs([dU dpsi]));

%------7------
%Next estimate for new |U| and psi. [ U=|U|*e^i(psi) ]
psi=psi+[0 dpsi];
U=U+[0 dU];

%------8------
%Start again at point '2'

%------9------
%Repeat until tolerated errors are achieved

%Check------------------
%Calculate the P and Q at the swingbus
P(1)=0;
Q(1)=0;

for s=1:nrOfBuses
    P(1)=P(1)+y_abs(1,s)*abs(U(s))*abs(U(1))*cos(psi(1)-psi(s)-y_angle(1,s));
    Q(1)=Q(1)+y_abs(1,s)*abs(U(s))*abs(U(1))*sin(psi(1)-psi(s)-y_angle(1,s));
```

```
    end

    BusNr_Voltage_Angle=[1:length(y) ;U; psi.*180/pi]';
    BusNr_P_Q=[1 ;P(1) ;Q(1)]';
    loop;
    clc
    %------------------------
end

%------10------
%All voltages should be known now
BusNr_Voltage_Angle=[1:length(y) ;(U-1)*100; psi.*(180/pi)]'
%------11------
%Calculate the P and Q at the swingbus
P(1)=0;
Q(1)=0;
for s=1:nrOfBuses
    P(1)=P(1)+y_abs(1,s)*abs(U(s))*abs(U(1))*cos(psi(1)-psi(s)-y_angle(1,s));
    Q(1)=Q(1)+y_abs(1,s)*abs(U(s))*abs(U(1))*sin(psi(1)-psi(s)-y_angle(1,s));
end

BusNr_P_Q=[1 ;P(1) ;Q(1)]'

The_error=epsilon
Number_Of_Loops=loop
```

8.12 Matlab code for new grid

The matlab code for admittance matrix, power and voltages. To be able to run the following codes either the Gauss-Seidel or the Newton-Raphson algorithm must be combined.

8.12.1 Distribution plant 23: admittance23.m

```
%Length between buses in [km]
y=zeros(52);

y(1,39)=1.08;
y(39,2)=0.15;
y(39,3)=0.59;
y(3,4)=0.29;
y(3,5)=0.7;
y(5,6)=0.52;
y(5,7)=0.79;
y(7,8)=0.36;
y(7,40)=0.92;
y(40,9)=0.1;
y(40,10)=1.77;
y(10,41)=1.07;
y(41,11)=0.84;
y(41,42)=0.08;
y(42,12)=0.05;
y(42,43)=0.32;
y(43,13)=0.12;
y(43,14)=0.99;
y(14,44)=0.41;
y(44,15)=0.1;
y(44,45)=0.59;
y(45,16)=0.14;
y(45,46)=0.35;
y(46,17)=0.13;
y(46,18)=0.66;
y(18,47)=0.41;
y(47,21)=0.1;
y(47,48)=0.51;
y(48,19)=0.19;
y(48,20)=0.33;
y(39,22)=0.63;
y(22,49)=0.24;
y(49,23)=0.95;
y(23,24)=0.57;
y(24,25)=0.27;
y(49,26)=0.45;
```

```
y(26,50)=1.02;
y(50,27)=0.16;
y(50,28)=0.1;
y(39,29)=1.19;
y(29,30)=0.52;
y(30,31)=0.82;
y(31,32)=0.73;
y(32,33)=1.07;
y(33,34)=0.55;
y(34,35)=0.37;
y(34,36)=0.62;
y(36,51)=0.87;
y(51,52)=0.1;
y(52,37)=0.11;
y(52,38)=0.46;
%-----------------------------------------------------
for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=y(n,m)
            if y(m,n)>0
                y(n,m)=y(m,n);
            else
                y(m,n)=y(n,m);
            end
        end
    end
end

%The admittance matrix is created
%y is now consisting of the length values between buses.

%Cable AXCEL 95 is now used:
R=0.32;
L=2*pi*50*0.3e-3;
z=(R+i*L)/((Ub^2)/(Sb)); %pu/km

for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=0
            y(m,n)=1/(z*y(m,n));
        end
    end
end

%Diagonal
for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=0 && m~=n
```

```
            y(m,m)=y(m,m)+y(m,n);
        end
    end
end

%Correcting the sign
for m=1:length(y)
    for n=1:length(y)
        if m~=n
            y(m,n)=-y(m,n);
        end
    end
end
```

8.12.2 Distribution plant 23: PQpower23.m

```
%Approximated power values
P=zeros(1,nrOfBuses);
Q=zeros(1,nrOfBuses);

activePower=xlsread('P_load.xls');
%Known values
P(2)=activePower(2);
P(3)=activePower(4);
P(4)=activePower(5);
P(5)=activePower(7);
P(6)=activePower(6);
P(7)=activePower(9);
P(8)=activePower(8);
P(9)=activePower(12);
P(10)=activePower(76);
P(11)=activePower(75);
P(12)=activePower(74);
P(13)=activePower(73);
P(14)=activePower(72);
P(15)=activePower(71);
P(16)=activePower(70);
P(17)=activePower(69);
P(18)=activePower(68);
P(19)=activePower(67);
P(20)=activePower(66);
P(21)=activePower(65);
P(22)=activePower(3);
P(23)=activePower(15);
P(24)=activePower(11);
P(25)=activePower(10);
P(26)=activePower(14);
P(27)=activePower(16);
P(28)=activePower(17);
P(29)=activePower(13);
P(30)=activePower(105);
P(31)=activePower(106);
P(32)=activePower(107);
P(33)=activePower(108);
P(34)=activePower(109);
P(35)=activePower(110);
P(36)=activePower(111);
P(37)=activePower(93);
P(38)=activePower(112);

for m=2:nrOfBuses
    Q(m)=P(m)*tan(acos(0.95));
```

```
end

%pu, negative due to power direction out from bus.
P=-(1e3/Sb).*P;
Q=-(1e3/Sb).*Q;

%If bus power is known busS(x)=1, else busS(x)=0.
busS=ones(1,nrOfBuses);
busS(1)=0;
```

8.12.3 Distribution plant 23: voltages23.m

```
U=zeros(2,nrOfBuses);

%Swingbus; the bus with known values, pu calculations.
psi(1)=0;
U(:,1)=1; %1pu=12kV

%Initial values to the unknowns
for j=2:nrOfBuses
    U(1,j)=1;
    psi(j)=0*pi/180;
end

%If bus voltage is known busU(x)=1, else busU(x)=0.
busU=zeros(1,nrOfBuses);
busU(1)=1;
```

8.12.4 Distribution plant 41: admittance41.m

```
%Length between buses in [km]
y=zeros(109);

y(1,2)=0.44;
y(2,3)=1.07;
y(3,73)=0.34;
y(73,74)=0.53;
y(74,4)=0.87;
y(4,5)=0.58;
y(5,75)=0.72;
y(75,6)=0.01;
y(75,7)=0.62;
y(7,76)=0.87;
y(76,8)=0.42;
y(76,9)=0.6;
y(8,11)=0.27;
y(9,10)=1.2;
y(74,12)=0.5;
y(12,77)=0.24;
y(77,79)=0.72;
y(79,13)=0.46;
y(79,14)=0.07;
y(77,78)=0.77;
y(78,15)=0.53;
y(78,16)=0.42;
y(16,80)=0.67;
y(80,17)=0.72;
y(80,18)=0.93;
y(18,81)=0.26;
y(81,19)=0.44;
y(81,82)=0.13;
y(82,20)=0.06;
y(73,83)=0.04;
y(83,21)=0.06;
y(83,84)=0.83;
y(84,22)=0.08;
y(84,85)=0.97;
y(85,23)=0.08;
y(85,86)=1.38;
y(86,24)=0.15;
y(86,87)=0.07;
y(87,88)=0.43;
y(88,25)=0.71;
y(88,26)=0.41;
y(87,89)=0.18;
y(89,27)=0.28;
```

```
y(89,28)=0.74;
y(28,90)=0.31;
y(90,29)=0.12;
y(29,95)=1.82;
y(95,30)=0.55;
y(95,31)=0.05;
y(31,32)=0.78;
y(90,91)=0.07;
y(91,92)=2.01;
y(92,33)=0.89;
y(92,34)=0.18;
y(34,35)=0.47;
y(35,36)=0.97;
y(91,93)=0.18;
y(93,37)=0.26;
y(93,38)=0.31;
y(93,94)=0.41;
y(94,39)=0.11;
y(94,40)=0.26;
y(40,41)=0.49;
y(40,42)=1.08;
y(42,43)=0.42;
y(43,96)=0.05;
y(96,44)=0.28;
y(96,97)=0.04;
y(97,45)=0.36;
y(97,46)=1.12;
y(46,47)=1;
y(47,98)=0.3;
y(98,99)=0.72;
y(99,48)=0.09;
y(99,49)=0.36;
y(98,100)=0.81;
y(100,51)=0.03;
y(100,52)=0.38;
y(98,50)=0.03;
y(1,101)=0.91;
y(101,53)=0.27;
y(101,54)=0.97;
y(54,55)=0.88;
y(54,56)=0.69;
y(56,102)=0.58;
y(102,57)=0.11;
y(57,103)=0.15;
y(103,58)=0.21;
y(103,104)=0.50;
y(104,59)=0.2;
y(104,60)=0.58;
```

```
y(60,61)=4.12;
y(61,62)=1.29;
y(62,63)=0.64;
y(63,109)=0.5;
y(109,71)=0.2;
y(109,72)=1.09;
y(61,105)=1.53;
y(105,106)=0.58;
y(106,64)=0.52;
y(106,65)=0.14;
y(105,107)=0.11;
y(107,66)=0.02;
y(107,108)=0.97;
y(108,67)=0.45;
y(108,68)=0.27;
y(107,69)=1.09;
y(69,70)=1.08;
%-----------------------------------------------------
for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=y(n,m)
            if y(m,n)>0
                y(n,m)=y(m,n);
            else
                y(m,n)=y(n,m);
            end
        end
    end
end

%The admittance matrix is created
%y is now consisting of the length values between buses.

%Cable AXCEL 95 is now used:
R=0.32;
L=2*pi*50*0.3e-3;
z=(R+i*L)/((Ub^2)/(Sb)); %pu/km

for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=0
            y(m,n)=1/(z*y(m,n));
        end
    end
end

%Diagonal
for m=1:length(y)
```

```
    for n=1:length(y)
        if y(m,n)~=0 && m~=n
            y(m,m)=y(m,m)+y(m,n);
        end
    end
end

%Correcting the sign
for m=1:length(y)
    for n=1:length(y)
        if m~=n
            y(m,n)=-y(m,n);
        end
    end
end
```

8.12.5 Distribution plant 41: PQpower41.m

```
%Approximated power values
P=zeros(1,nrOfBuses);
Q=zeros(1,nrOfBuses);

activePower=xlsread('P_load.xls');
%Known values
P(2)=activePower(83);
P(3)=activePower(82);
P(4)=activePower(80);
P(5)=activePower(79);
P(6)=activePower(77);
P(7)=activePower(26);
P(8)=activePower(20);
P(9)=activePower(19);
P(10)=activePower(18);
P(11)=activePower(21);
P(12)=activePower(84);
P(13)=activePower(86);
P(14)=activePower(85);
P(15)=activePower(87);
P(16)=activePower(88);
P(17)=activePower(89);
P(18)=activePower(90);
P(19)=activePower(92);
P(20)=activePower(91);
P(21)=activePower(81);
P(22)=activePower(78);
P(23)=activePower(27);
P(24)=activePower(24);
P(25)=activePower(22);
P(26)=activePower(23);
P(27)=activePower(25);
P(28)=activePower(28);
P(29)=activePower(29);
P(30)=activePower(36);
P(31)=activePower(35);
P(32)=activePower(37);
P(33)=activePower(61);
P(34)=activePower(62);
P(35)=activePower(63);
P(36)=activePower(64);
P(37)=activePower(30);
P(38)=activePower(31);
P(39)=activePower(32);
P(40)=activePower(33);
P(41)=activePower(34);
```

```
P(42)=activePower(38);
P(43)=activePower(39);
P(44)=activePower(40);
P(45)=activePower(41);
P(46)=activePower(46);
P(47)=activePower(47);
P(48)=activePower(48);
P(49)=activePower(49);
P(50)=activePower(50);
P(51)=activePower(52);
P(52)=activePower(53);
P(53)=activePower(94);
P(54)=activePower(95);
P(55)=activePower(96);
P(56)=activePower(97);
P(57)=activePower(98);
P(58)=activePower(99);
P(59)=activePower(100);
P(60)=activePower(101);
P(61)=activePower(54);
P(62)=activePower(56);
P(63)=activePower(57);
P(64)=activePower(42);
P(65)=activePower(43);
P(66)=activePower(44);
P(67)=activePower(45);
P(68)=activePower(51);
P(69)=activePower(55);
P(70)=activePower(60);
P(71)=activePower(58);
P(72)=activePower(59);

for m=2:nrOfBuses
    Q(m)=P(m)*tan(acos(0.95));
end

%pu, negative due to power direction out from bus.
P=-(1e3/Sb).*P;
Q=-(1e3/Sb).*Q;

%If bus power is known busS(x)=1, else busS(x)=0.
busS=ones(1,nrOfBuses);
busS(1)=0;
```

8.12.6 Distribution plant 41: voltages41.m

```
U=zeros(2,nrOfBuses);

%Swingbus; the bus with known values, pu calculations.
psi(1)=0;
U(:,1)=1; %1pu=12kV

%Initial values to the unknowns
for j=2:nrOfBuses
    U(1,j)=1;
    psi(j)=0*pi/180;
end

%If bus voltage is known busU(x)=1, else busU(x)=0.
busU=zeros(1,nrOfBuses);
busU(1)=1;
```

8.12.7 Distribution plant 41: admittance23old.m

```
%Length between buses in [km]
y=zeros(132);

%Cables
%run cablesAXCEL95
run cables

y(1,91)=1.21*FEAL620;
y(91,2)=0.44*AXCEL9525;
y(91,3)=0.19*AXCEL9525;
y(91,92)=0.72*FEAL620;
y(92,5)=0.21*ACJJ950;
y(5,4)=0.34*ACJJ950;
y(92,6)=0.21*FEAL620+0.21*ALMGSI990;
y(6,93)=0.01*ALMGSI990;
y(93,7)=0.53*AXKJ950;
y(93,94)=0.4*ALMGSI990;
y(94,8)=0.12*ALMGSI310;
y(94,9)=0.25*ALMGSI310;
y(94,95)=0.21*ALMGSI990;
y(95,10)=0.51*FXCEL16;
y(10,11)=0.24*AXCEL5016;
y(95,12)=0.67*AXCES950;
y(12,76)=1.78*AXCES950;
y(76,96)=1.07*AXCES950;
y(96,75)=0.82*ALMGSI990;
y(96,74)=0.13*AXCEL9525;
y(74,73)=0.48*AXCEL9525;
y(73,97)=0.44*AXCEL9525;
y(97,72)=0.62*FEAL620;
y(72,98)=0.42*FEAL620;
y(98,71)=0.1*FEAL620;
y(98,99)=0.69*FEAL620;
y(99,70)=0.15*FEAL310;
y(99,100)=0.66*FEAL620;
y(100,69)=0.13*ALMGSI990;
y(100,68)=0.64*AXCEL9525;
y(68,65)=0.51*AXCEL9525;
y(65,101)=0.63*AXCEL9525;
y(101,66)=0.34*ALMGSI990;
y(101,67)=0.3*AXCEL9525;
y(65,64)=0.59*AXCEL9525;
y(64,63)=0.94*AXCEL9525;
y(63,62)=0.47*AXCEL9525;

y(1,13)=1.17*ALMGSI1570;
```

```
y(13,102)=1*ACJJ1500;
y(102,14)=0.04*AXCEL9525;
y(102,103)=0.94*ACJJ1500;
y(103,15)=0.37*ALMGSI620;
y(103,16)=0.06*ACJJ1500;
y(16,17)=0.49*ACJJ1500;
y(17,104)=0.42*ACJJ1500;
y(104,18)=3.08*ALMGSI1500;
y(18,105)=0.75*ALMGSI1570;
y(105,19)=0.32*ACJJ1500;
y(19,106)=0.14*ALMGSI620;
y(106,20)=0.39*ALMGSI620;
y(20,21)=0.25*ALMGSI620;
y(106,107)=0.71*ALMGSI620;
y(107,22)=0.53*ALMGSI310;
y(107,108)=0.42*ALMGSI620;
y(108,23)=0.19*ALMGSI620;
y(108,109)=0.26*ALMGSI620;
y(109,110)=0.89*ALMGSI620;
y(110,27)=0.12*CU160;
y(110,111)=0.06*ALMGSI310;
y(111,26)=0.77*FEAL620;
y(109,112)=0.22*CU160;
y(112,24)=0.23*ALMGSI310;
y(112,25)=0.42*CU160;
y(25,113)=0.71*CU160;
y(113,28)=0.08*ALMGSI620;
y(113,29)=0.26*CU160;
y(29,61)=1.94*AXCEL9525+1.06*AXCEL5016;
y(29,114)=0.27*CU160;
y(114,31)=0.19*ALMGSI620;
y(114,30)=0.33*ALMGSI620;
y(114,115)=0.3*CU160;
y(115,32)=0.1*ALMGSI620;
y(115,116)=0.28*CU160;
y(116,33)=0.27*AXKJ950;
y(116,34)=0.21*CU160;
y(34,117)=0.15*CU160;
y(117,35)=1.09*BLX990;
y(35,36)=0.66*ALMGSI990;
y(35,37)=0.84*ALMGSI990;
y(117,118)=0.54*CU160;
y(118,38)=0.57*ALMGSI620;
y(38,39)=0.43*ALMGSI620;
y(39,119)=0.05*ALMGSI990;
y(119,40)=0.29*ALMGSI990;
y(119,41)=0.41*ALMGSI990;
y(118,42)=0.59*CU160;
```

```
y(42,43)=0.64*AXCLIGHT50;
y(43,120)=1.02*CU160;
y(120,45)=0.09*ALMGSI620;
y(120,121)=0.49*CU160;
y(121,46)=0.93*ALMGSI310;
y(121,47)=0.07*CU160;
y(47,122)=0.15*ALMGSI310;
y(122,123)=0.54*ALMGSI310;
y(123,48)=0.03*ALMGSI310;
y(123,49)=0.45*ALMGSI310;
y(122,50)=0.22*ALMGSI310;
y(50,51)=0.8*FEAL620;
y(50,52)=0.78*ALMGSI310;
y(52,53)=0.42*ALMGSI620;
y(43,132)=0.52*CU160;
y(132,44)=0.14*FEAL620;
y(132,124)=0.49*CU160;
y(124,54)=1.34*ALMGSI620;
y(124,55)=0.58*CU160;
y(55,125)=1.14*CU160;
y(125,126)=0.58*ALMGSI620;
y(126,57)=0.07*ALMGSI620;
y(126,56)=0.69*AXCEL5016;
y(125,58)=0.2*CU160;
y(58,127)=0.3*ALMGSI310;
y(127,59)=0.49*ALMGSI310;
y(127,60)=1.09*ALMGSI310;

y(1,77)=0.58*FEAL620;
y(77,78)=1.02*FEAL620;
y(78,79)=0.59*AXKJ240;
y(79,80)=0.81*AXKJ240;
y(80,81)=0.76*AXKJ240;
y(81,82)=1.09*AXCEL24035;
y(82,83)=0.54*AXCEL15025;
y(83,84)=0.39*ALMGSI310;
y(83,85)=0.59*AXCEL15025;
y(85,128)=0.88*AXCEL15025;
y(128,129)=0.11*FEAL620;
y(129,86)=0.47*ALMGSI990;
y(129,87)=0.11*FEAL620;
y(128,130)=0.18*FEAL620;
y(130,88)=0.05*FEAL620;
y(130,131)=0.12*FEAL620;
y(131,89)=0.44*FEAL620;
y(131,90)=0.27*ALMGSI620;
%-----------------------------------------------------
for m=1:length(y)
```

```
    for n=1:length(y)
        if y(m,n)~=y(n,m)
            if y(m,n)>0
                y(n,m)=y(m,n);
            else
                y(m,n)=y(n,m);
            end
        end
    end
end

%The admittance matrix is created
%y is now consisting of the length values between buses.

for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=0
            y(m,n)=1/y(m,n);
        end
    end
end

%Diagonal
for m=1:length(y)
    for n=1:length(y)
        if y(m,n)~=0 && m~=n
            y(m,m)=y(m,m)+y(m,n);
        end
    end
end

%Correcting the sign
for m=1:length(y)
    for n=1:length(y)
        if m~=n
            y(m,n)=-y(m,n);
        end
    end
end
```

8.12.8 Distribution plant 41: PQpower23old.m

```
%Approximated power values
P=zeros(1,nrOfBuses);
Q=zeros(1,nrOfBuses);

P(1)=1;

activePower=xlsread('P_load.xls');
%Known values
nrOfKnownLoads=76;
for n=2:nrOfKnownLoads
    P(n)=activePower(n);
end

P(77)=activePower(103);
P(78)=activePower(104);
P(79)=activePower(105);
P(80)=activePower(106);
P(81)=activePower(107);
P(82)=activePower(108);
P(83)=activePower(109);
P(84)=activePower(110);
P(85)=activePower(111);
P(86)=activePower(112);
P(87)=activePower(93);
P(88)=activePower(91);
P(89)=activePower(92);
P(90)=activePower(90);

for m=2:nrOfBuses
    if P(m)>100
        Q(m)=P(m)*tan(acos(0.85));
    else
        Q(m)=P(m)*tan(acos(0.95));
    end
end

%pu, negative due to power direction out from bus.
P=-(1e3/Sb).*P;
Q=-(1e3/Sb).*Q;

%If bus power is known busS(x)=1, else busS(x)=0.
busS=ones(1,nrOfBuses);
busS(1)=0;
```

8.12.9 Distribution plant 41: voltages23old.m

```
%Swingbus; the bus with known values, pu calculations.
psi(1)=0;
U(:,1)=1; %1pu=10kV

%Initial values to the unknowns
for j=2:nrOfBuses
    U(1,j)=1;
    psi(j)=0;
end

%If bus voltage is known busU(x)=1, else busU(x)=0.
busU=zeros(1,nrOfBuses);
busU(1)=1;
```

8.12.10 Cable data

```
%Cable data

%---ACJJ---
R=0.32;
L=2*pi*50*0.31e-3;
ACJJ950=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.21;
L=2*pi*50*0.3e-3;
ACJJ1500=(R+i*L)/((Ub^2)/Sb); %pu/km

%---ALMGSI---
R=1.05;
L=2*pi*50*1.27e-3;
ALMGSI310=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.52;
L=2*pi*50*1.21e-3;
ALMGSI620=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.33;
L=2*pi*50*1.13e-3;
ALMGSI990=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.21;
L=2*pi*50*1.11e-3;
ALMGSI1500=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.21;
L=2*pi*50*1.11e-3;
ALMGSI1570=(R+i*L)/((Ub^2)/Sb); %pu/km

%---AXCEL---
R=0.32;
L=2*pi*50*0.3e-3;
AXCEL9525=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.64;
L=2*pi*50*0.33e-3;
AXCEL5016=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.21;
L=2*pi*50*0.33e-3;
AXCEL15025=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.13;
L=2*pi*50*0.26e-3;
AXCEL24035=(R+i*L)/((Ub^2)/Sb); %pu/km

%---AXCES---
R=0.32;
L=2*pi*50*0.31e-3;
AXCES950=(R+i*L)/((Ub^2)/Sb); %pu/km
```

```
%---AXKJ---
R=0.13;
L=2*pi*50*0.26e-3;
AXKJ240=(R+i*L)/((Ub^2)/Sb); %pu/km
R=0.32;
L=2*pi*50*0.3e-3;
AXKJ950=(R+i*L)/((Ub^2)/Sb); %pu/km

%---AXCLIGHT---
R=0.641;
L=2*pi*50*0.33e-3;
AXCLIGHT50=(R+i*L)/((Ub^2)/Sb); %pu/km

%---BLX---
R=0.33;
L=2*pi*50*1.13e-3;
BLX990=(R+i*L)/((Ub^2)/Sb); %pu/km

%---CU---
R=1.11;
L=2*pi*50*1.27e-3;
CU160=(R+i*L)/((Ub^2)/Sb); %pu/km

%---FEAL---
R=0.53;
L=2*pi*50*1.12e-3;
FEAL620=(R+i*L)/((Ub^2)/Sb); %pu/km
R=1.07;
L=2*pi*50*1.2e-3;
FEAL310=(R+i*L)/((Ub^2)/Sb); %pu/km

%---FXCEL---
R=1.15;
L=2*pi*50*0.4e-3;
FXCEL16=(R+i*L)/((Ub^2)/Sb); %pu/km
```

8.12.11 Short circuit current

```
%This file is run after either Gauss-Seidel or Newton-Raphson algorithm.
%Use of bus impedance matrix for fault analysis

%run 'filename' can be changed due to which admittance is used.
run admittance23
nrOfBuses=length(y)

%The admittance matrix is known, the only thing that needs to be done is to
%calculate the Zbus=y^(-1)

Zbus=inv(y([2:nrOfBuses],[2:nrOfBuses]));

%Next step is to calculate the shortcircuit current for each bus in the
%system.
Ik=0;
for m=1:nrOfBuses-1
    Ik(m)=1/Zbus(m,m);
    %from pu to kA values
    Ik(m)=abs(Ik(m))*(Sb/(sqrt(3)*Ub))/1000;
end

Sk1=108e6; %Given value

Ik12=abs(Ik);
Sk12=sqrt(3)*Ub*Ik12*1000;
Sk2=Sk1.*Sk12./(Sk1+Sk12);
Ik2=Sk2./(sqrt(3).*Ub);
%Trafo-----------
Sktr2=100e3/0.032; %100kVA trafo is assumed in grid, with reactive efficiency 3.2%
%----------------
Sk=Sk2.*Sktr2./(Sk2+Sktr2);
%Low voltage cables---
R=0.35;
L=2*pi*50*0.27e-3;
FCJJ50=(R+i*L); %omega/km
R=0.73;
L=2*pi*50*1.15e-3;
EKKJ25=(R+i*L); %omega/km
Zlow=FCJJ50*0.1+EKKJ25*0.05;
%---------------------
Zlowpu=Zlow/((400^2)/Sb);
Slow=Sb/abs(Zlowpu);
Sk_load=Slow.*Sk./(Slow+Sk);
Ik_load=Sk_load/(sqrt(3)*Ub); %referred to 10kV side

BusNr_Ik12_Sk2_Ik2_Ik=[2:nrOfBuses; Ik12; Sk2./1e6; Ik2./1e3; Ik_load]'
```

8.12.12 Active losses in grid

```
%This file is run after either Gauss-Seidel or Newton-Raphson algorithm. By
%using the calculated voltages at all buses losses can be calculated.

%run 'filename' can be changed due to which algorithm is used.
run NewtonRaphson23

z=0;
for m=1:nrOfBuses
    for n=1:nrOfBuses
        %Correcting the sign
        if m~=n
            y(m,n)=-y(m,n);
        else
            y(m,n)=0;
        end
        %Changing back to impedance
        if y(m,n)~=0
            z(m,n)=(1/y(m,n))*zb;
        else
            z(m,n)=0;
        end
    end
end

dP=0;
for m=1:nrOfBuses
    for n=1:nrOfBuses
        if m~=n & z(m,n)~=0
            if U(m)>U(n)
                U1=(U(m)*Ub)*exp(i*psi(m));
                U2=(U(n)*Ub)*exp(i*psi(n));
            elseif U(n)>U(m)
                U1=(U(n)*Ub)*exp(i*psi(n));
                U2=(U(m)*Ub)*exp(i*psi(m));
            else %In this case the voltages are the same
                lossless_line_between=[m,n]
                U1=(U(n)*Ub)*exp(i*psi(n));
                U2=(U(m)*Ub)*exp(i*psi(m));
            end
                Uh=U2-U1;
                S=(real(Uh)^2+imag(Uh)^2)/conj(z(m,n));
                dP(m,n)=real(S);
            end
        end
    end
end
```

```
%Calculation of total losses
dPtot=0;
for m=1:nrOfBuses
    for n=1:nrOfBuses
        if n<m
            dPtot=dPtot+dP(m,n);
        end
    end
end

Total_active_power_losses=dPtot
```

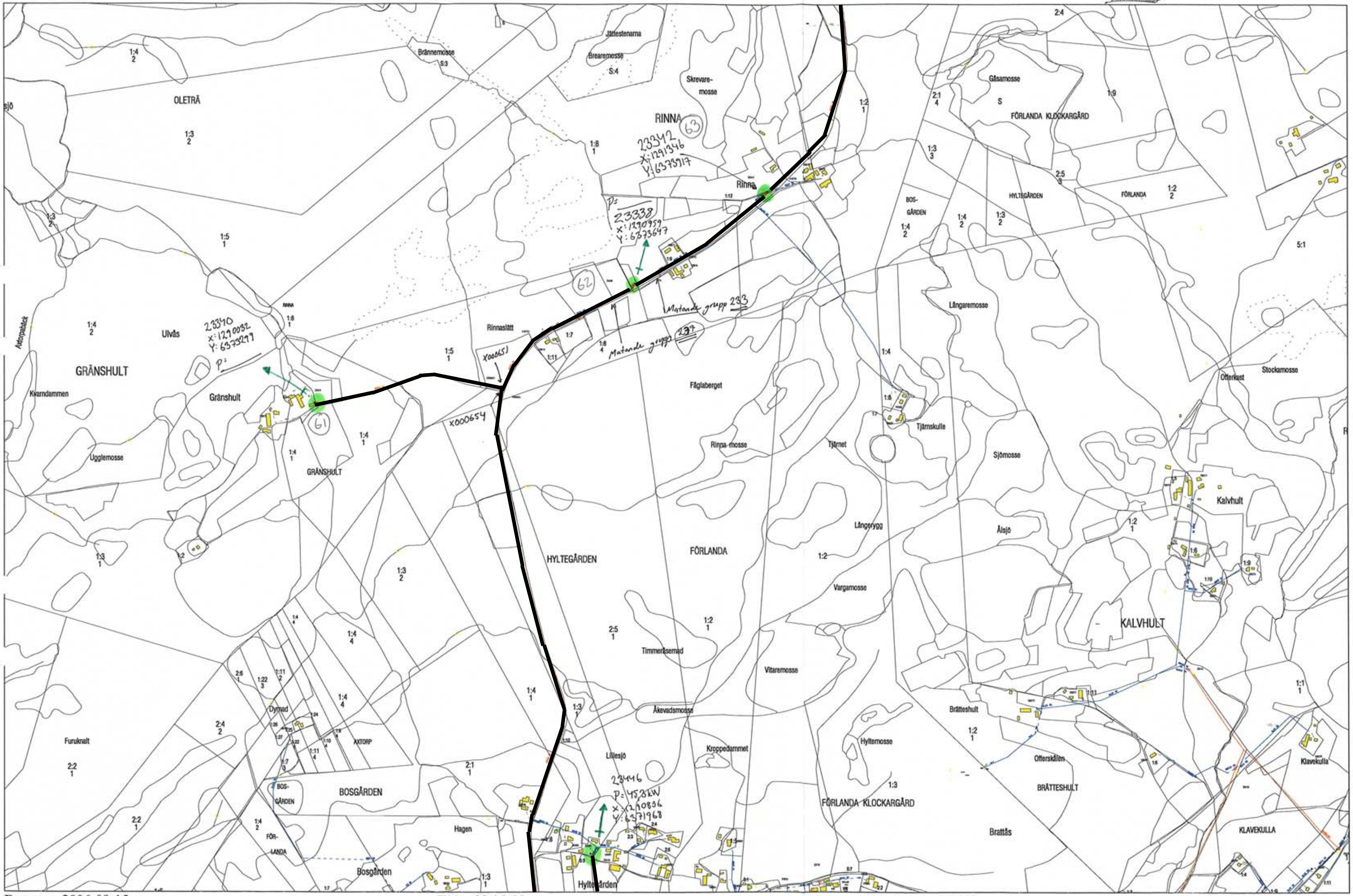
8.12.13 Determining fuses in transformer stations

```
%This program determines the lowest fuse size that a transformer station
%needs.

%run 'filename' can be changed due to which algorithm is used.
run NewtonRaphson23
run PQpower23
P=-(Sb/1e3).*P;

Imax=0;
for n=1:nrOfBuses
    Imax(n)=P(n)*1e3/(sqrt(3)*400);
end

%Fuse size is determined (up to 355A)
FuseSize=[6,10,16,20,25,35,50,63,80,100,160,200,250,315,355];
Fuse=zeros(1,nrOfBuses);
NrOfFuses=0;

for m=1:nrOfBuses
    NrOfFuses(m)=1;
    Fuse(m)=6;
    for n=1:length(FuseSize)-1
        if Imax(m)>FuseSize(n)
            Fuse(m)=FuseSize(n+1);
        end
    end

    if Imax(m)>Fuse(m)
        ImaxSplit=Imax(m)/2;
        for n=1:length(FuseSize)-1
            if ImaxSplit>FuseSize(n)
                Fuse(m)=FuseSize(n+1);
            end
        end
        NrOfFuses(m)=2;
        disp(['Bus nr ',num2str(m),...
              ' needs 2 cables with min fusesize ',num2str(Fuse(m)),'A'])
    end
end

BusNr_Imax_Fuse=[1:nrOfBuses; Imax; Fuse; NrOfFuses]'
```

Datum: 2006-09-28 **Tid:** 14:36:19 **Skala:** 1 : 10000

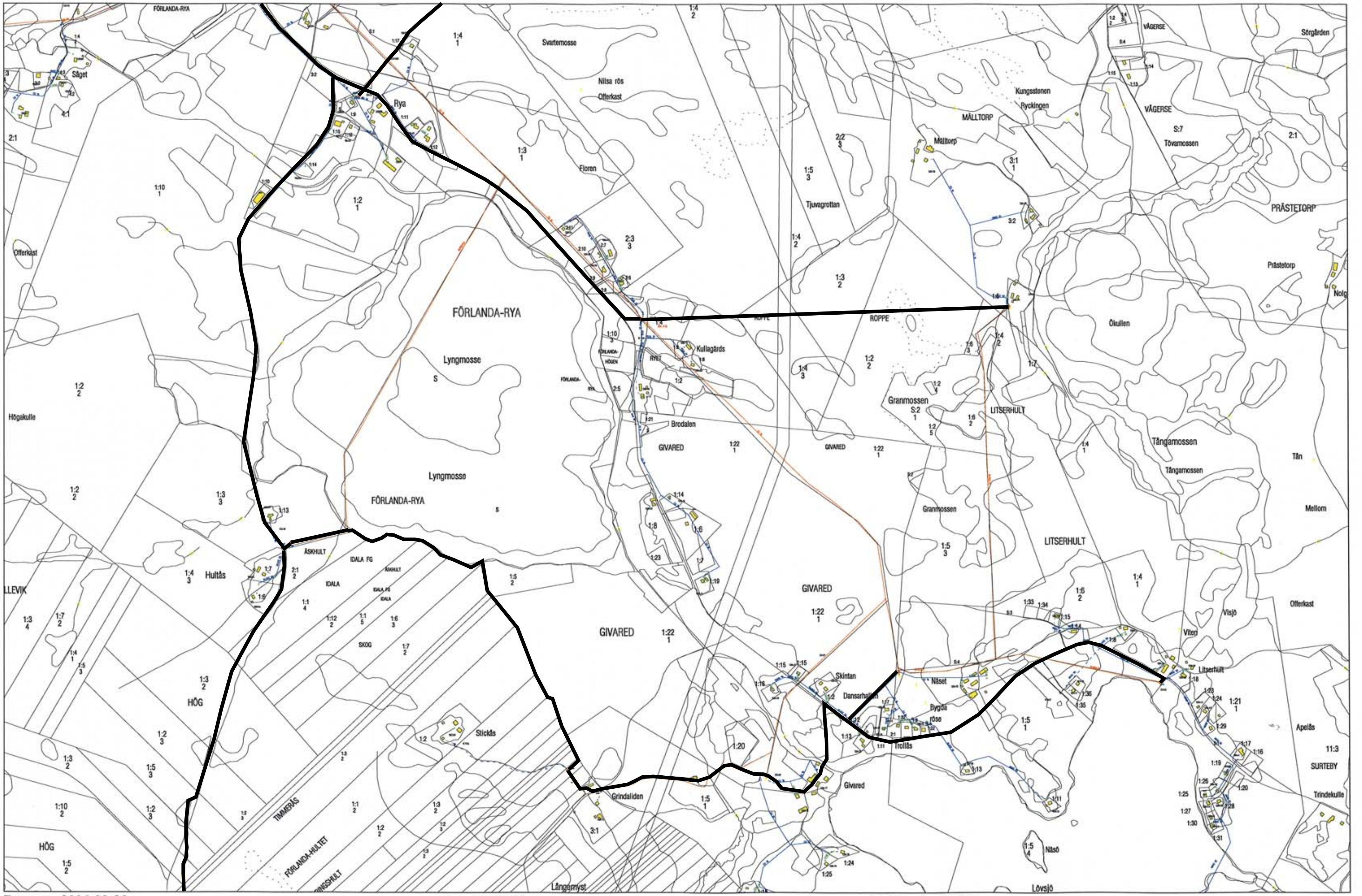
Birka Nät AB

Karta 9



Datum: 2006-09-15 Tid: 08:15:55 Skala: 1 : 10000

Birka Nät AB



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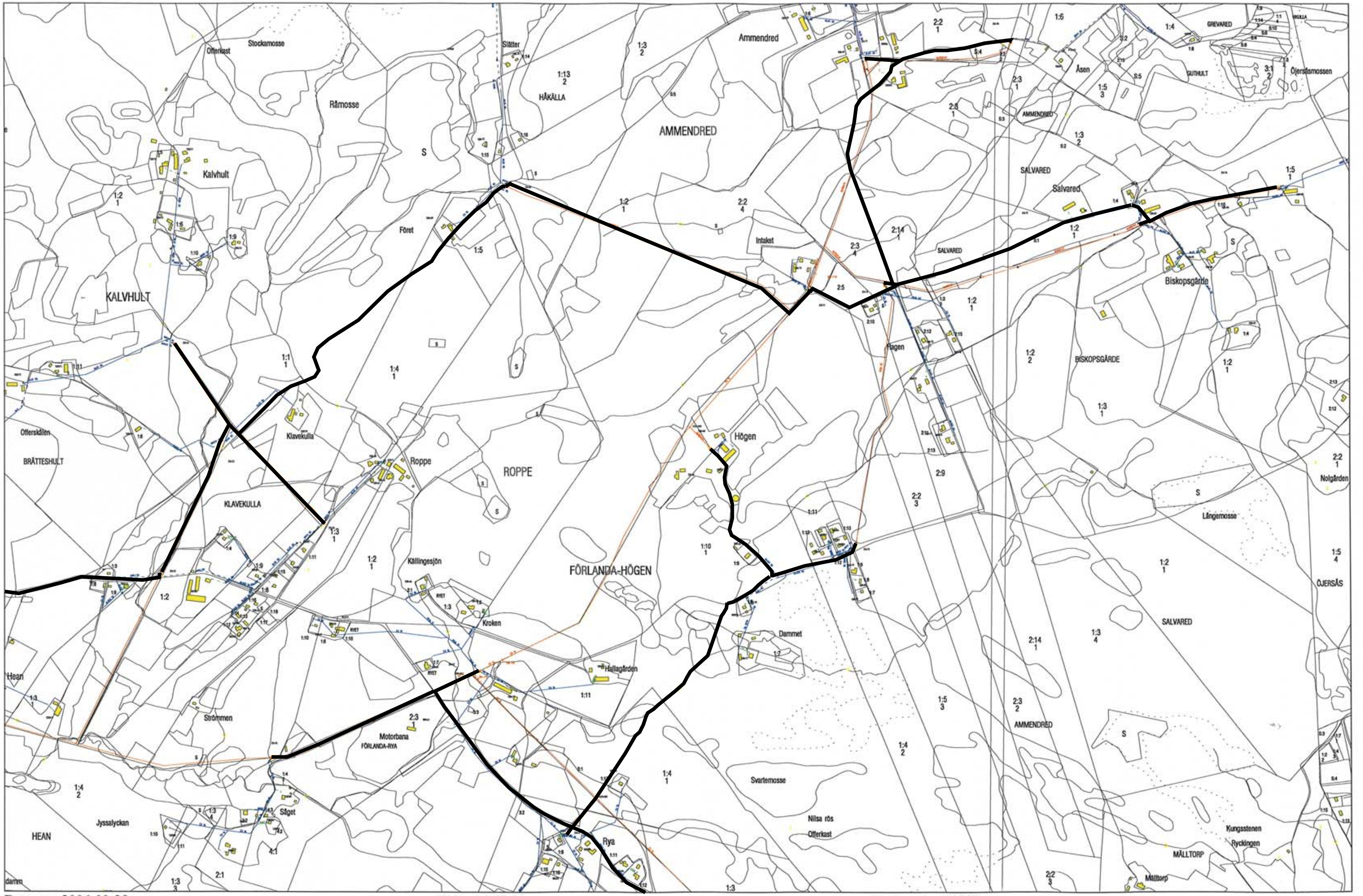
Birka Nät AB



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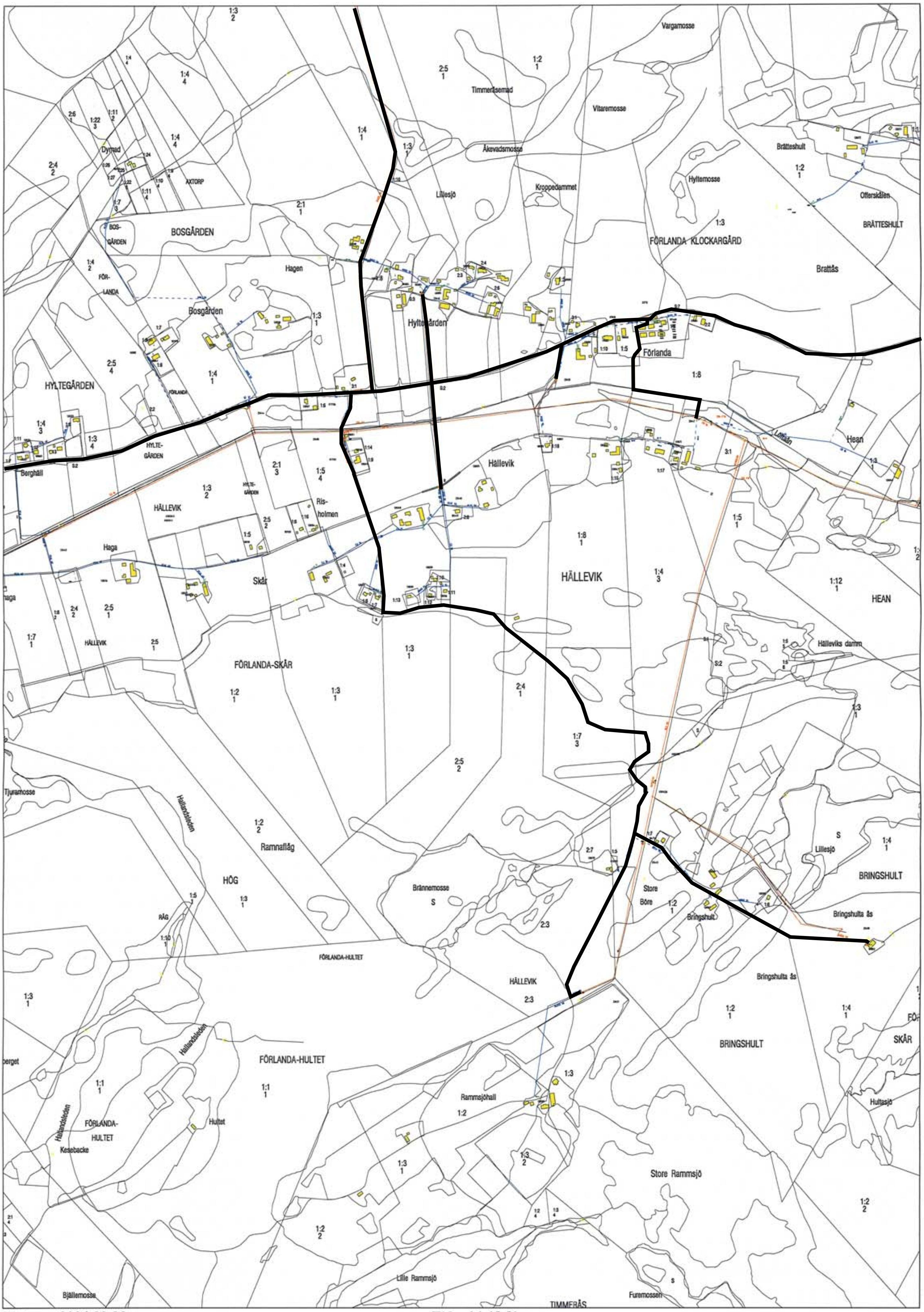
Birka Nät AB



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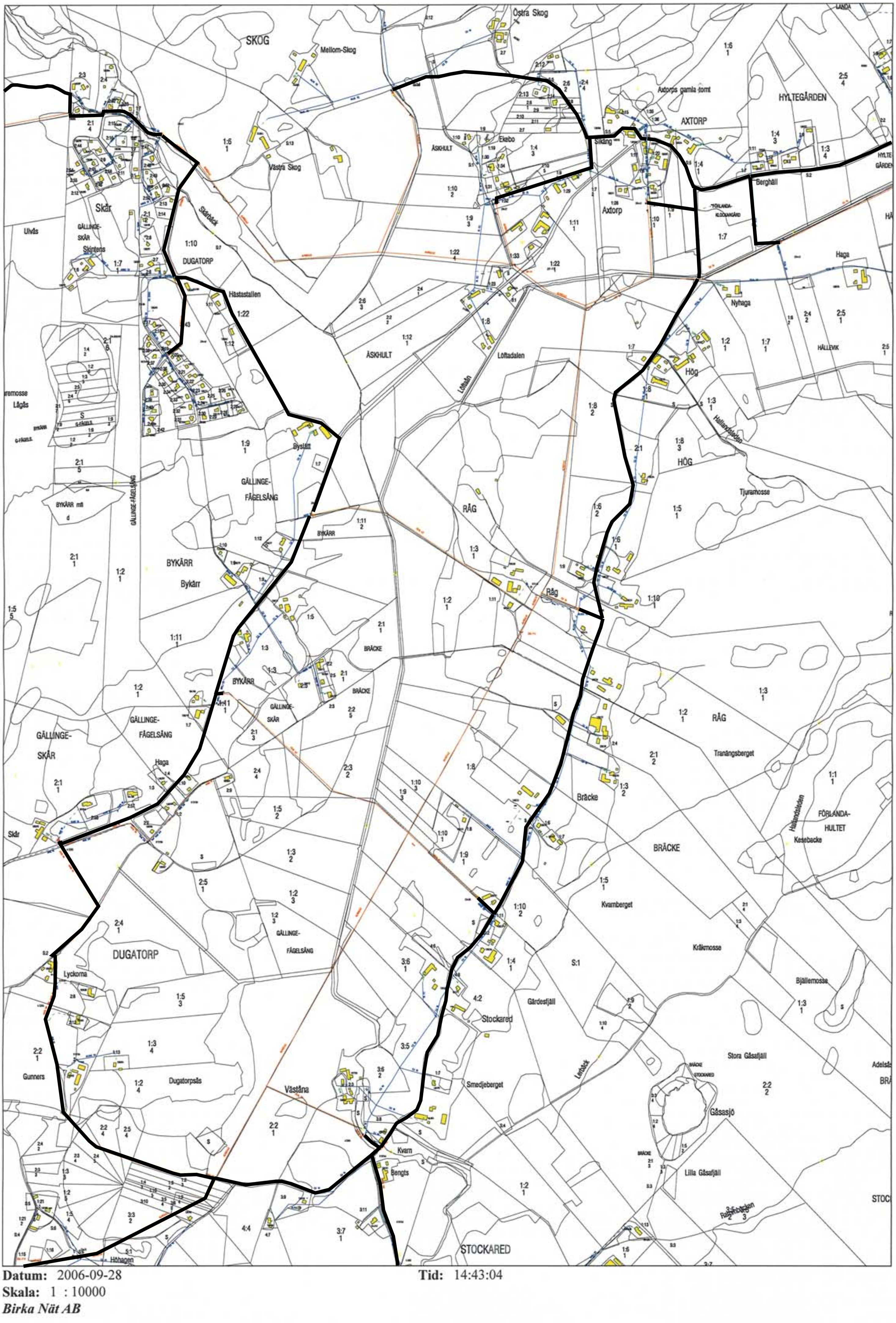
Skala: 1 : 10000

Birka Nät AB



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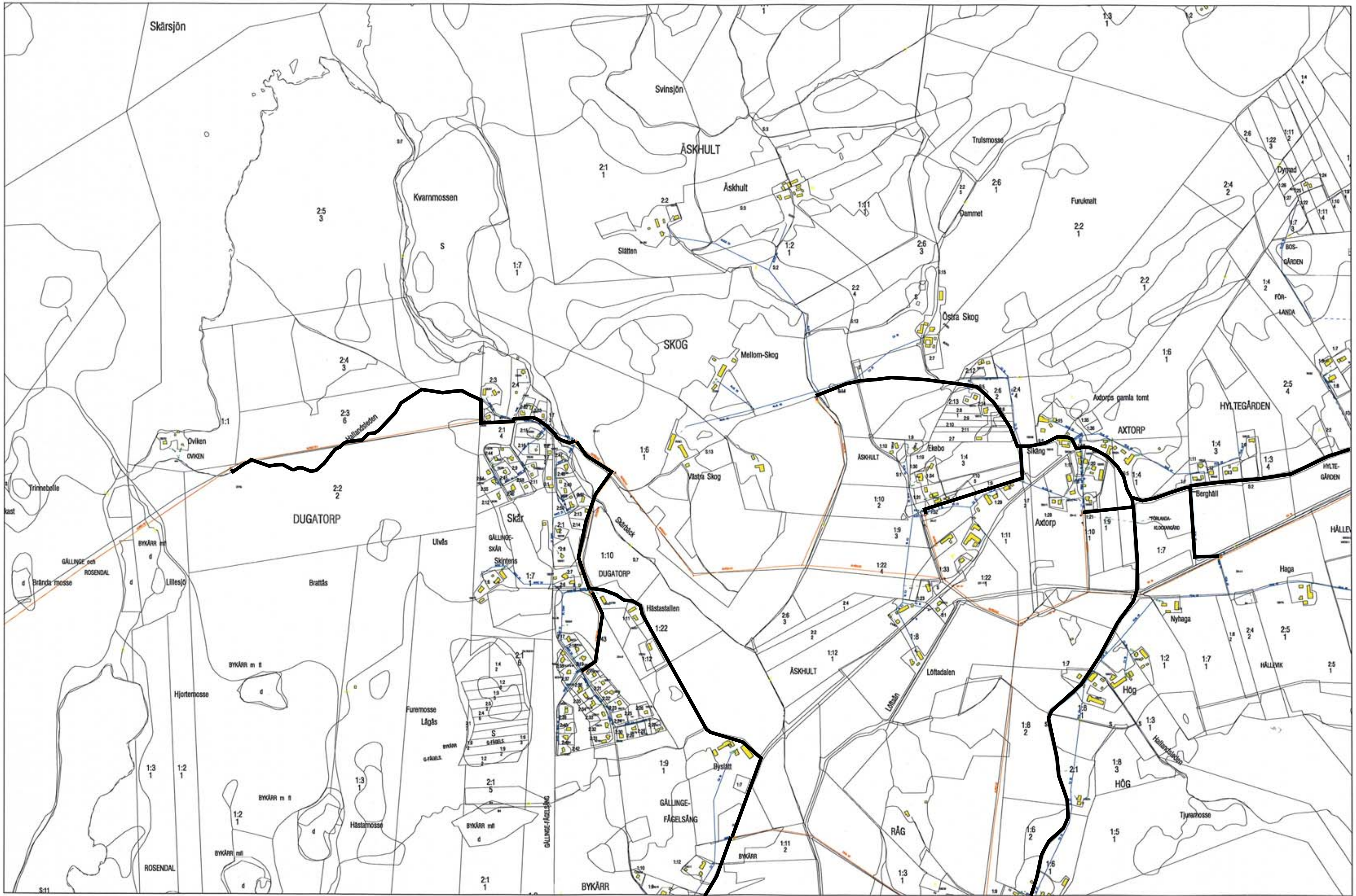
Skala: 1 : 10000

Birka Nät AB



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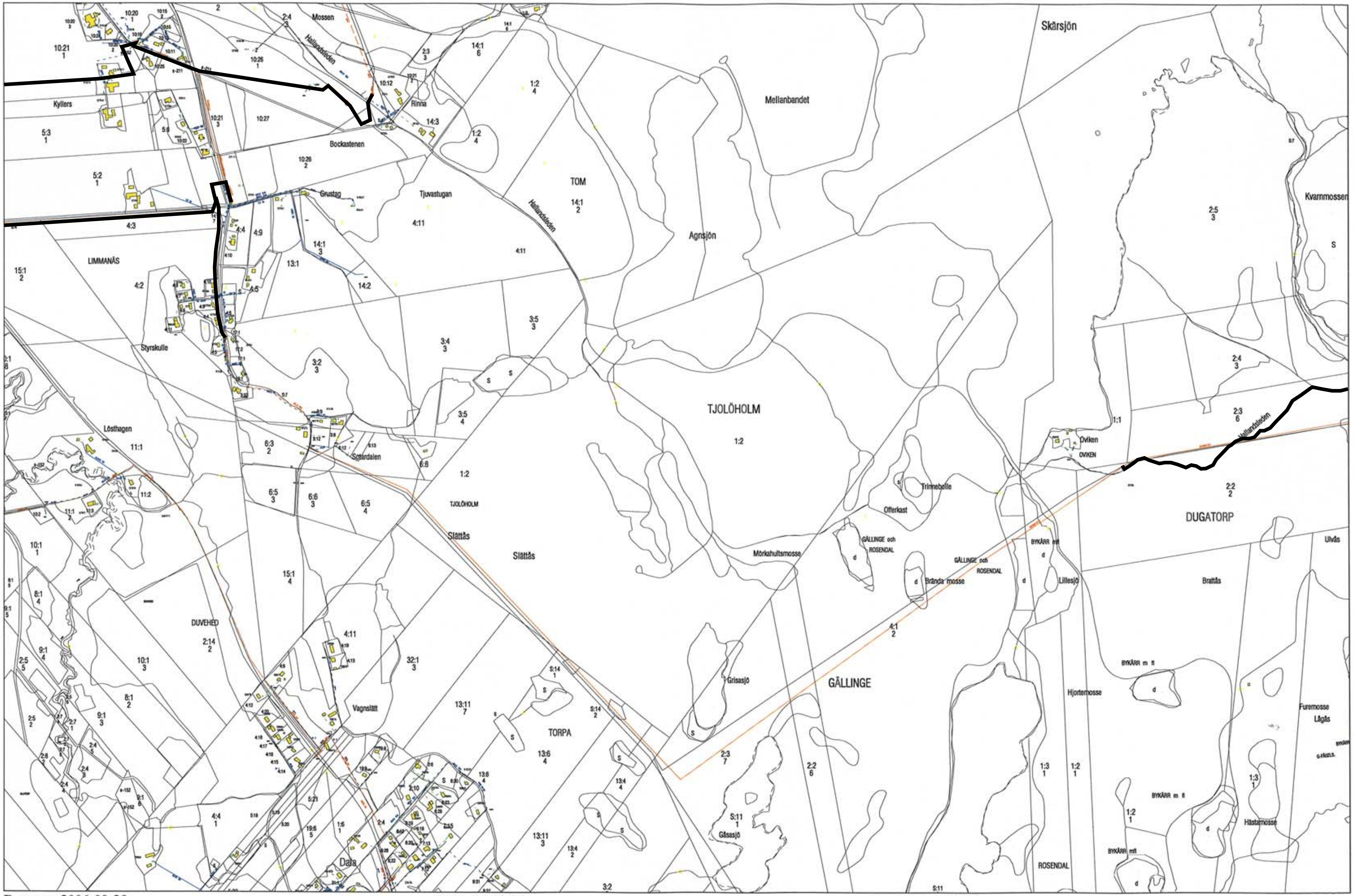
Birka Nät AB



Datum: 2006-09-28
Birka Nät AB

Tid: 14:39:24

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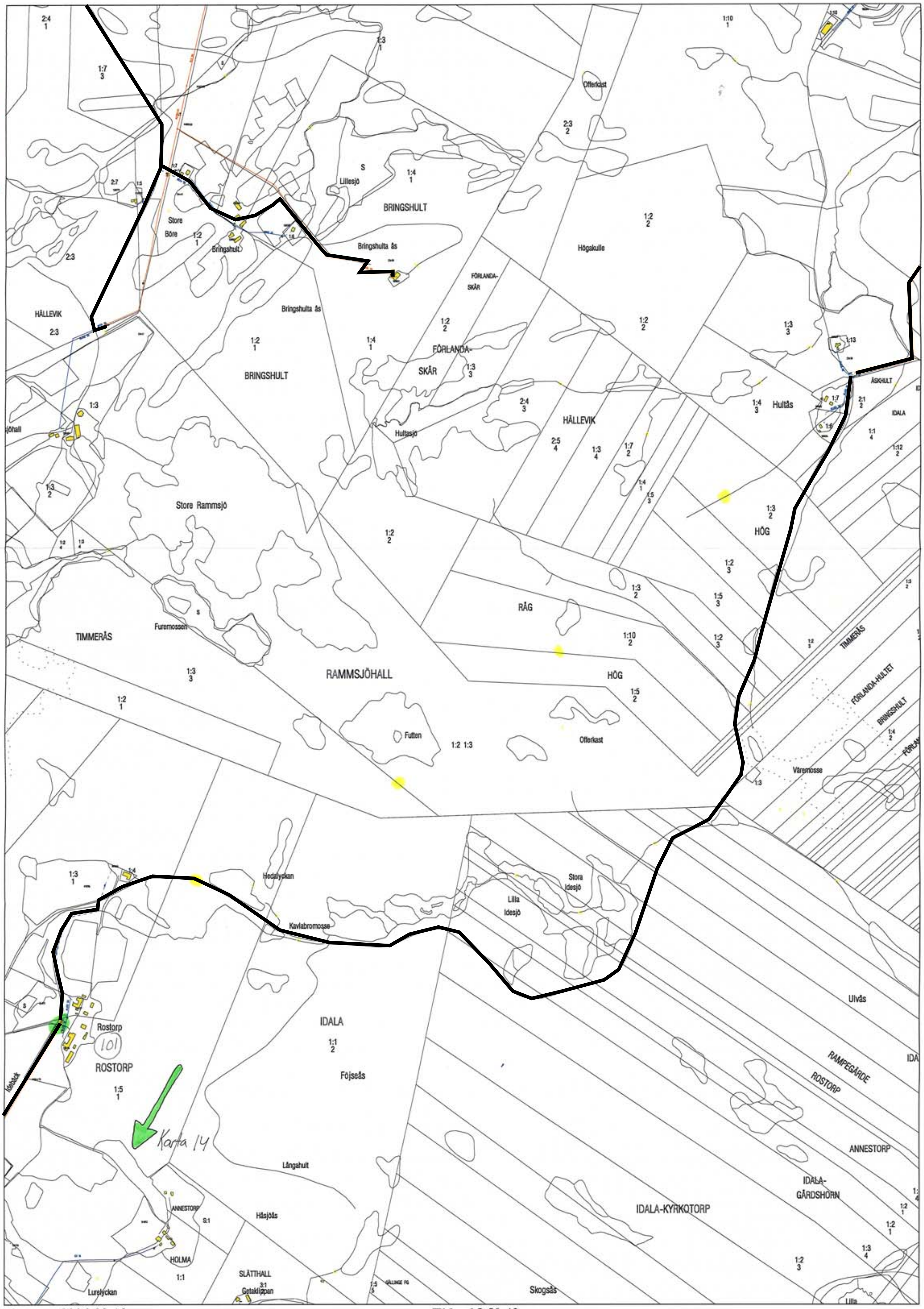
L41 Karta 15



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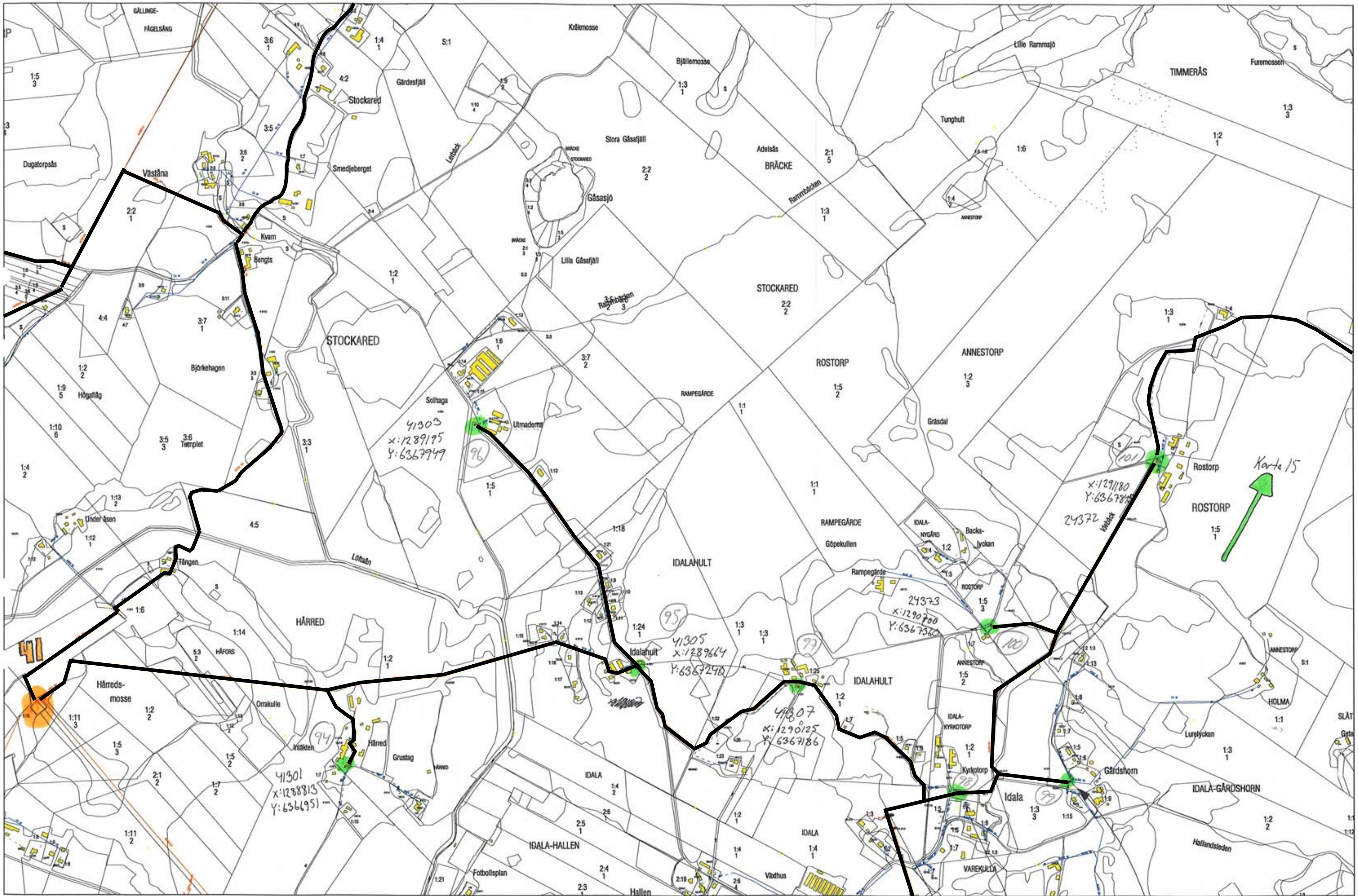
Birka Nät AB

L41 Karta 14



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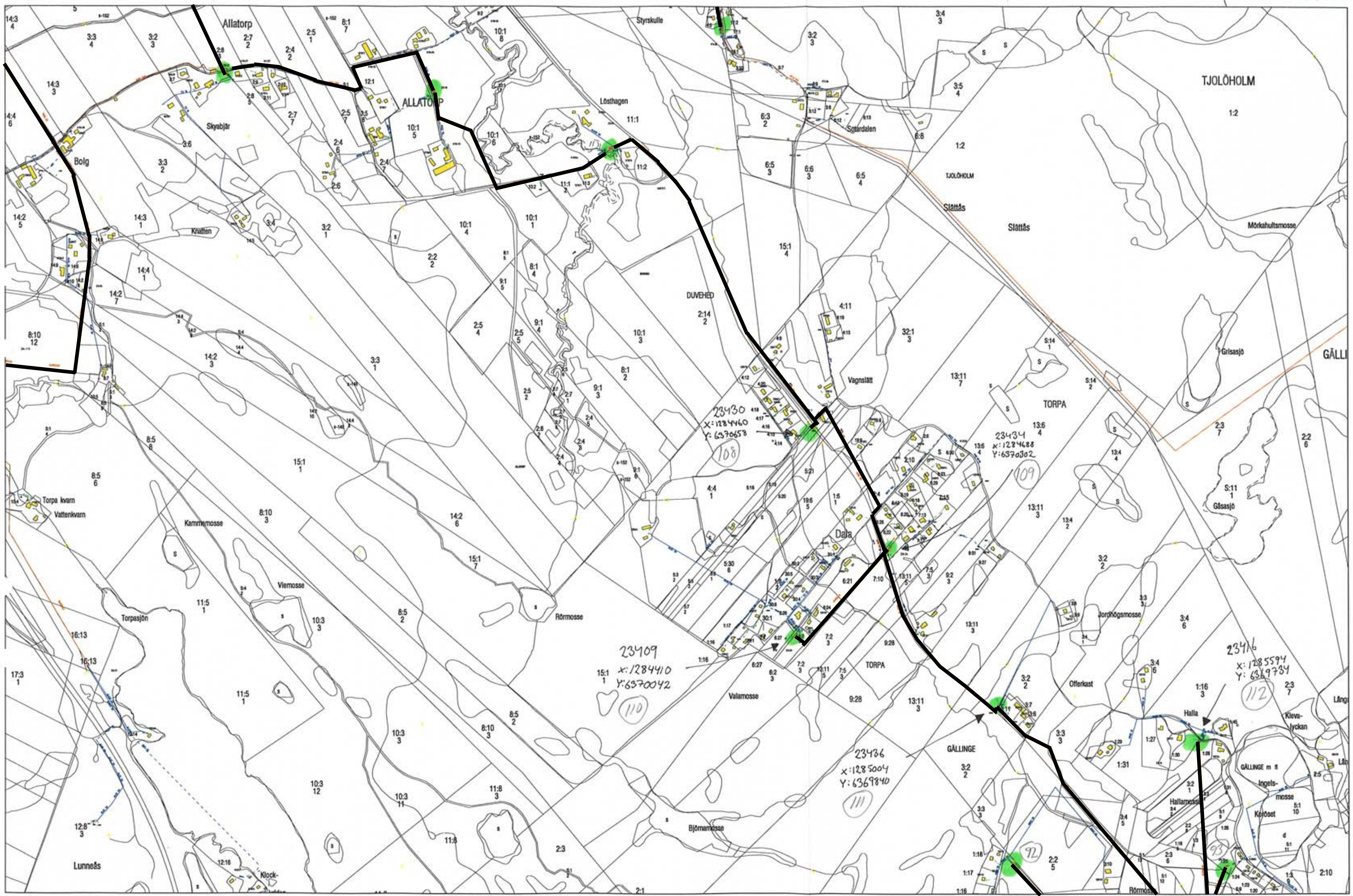
(L41 Karta 13)



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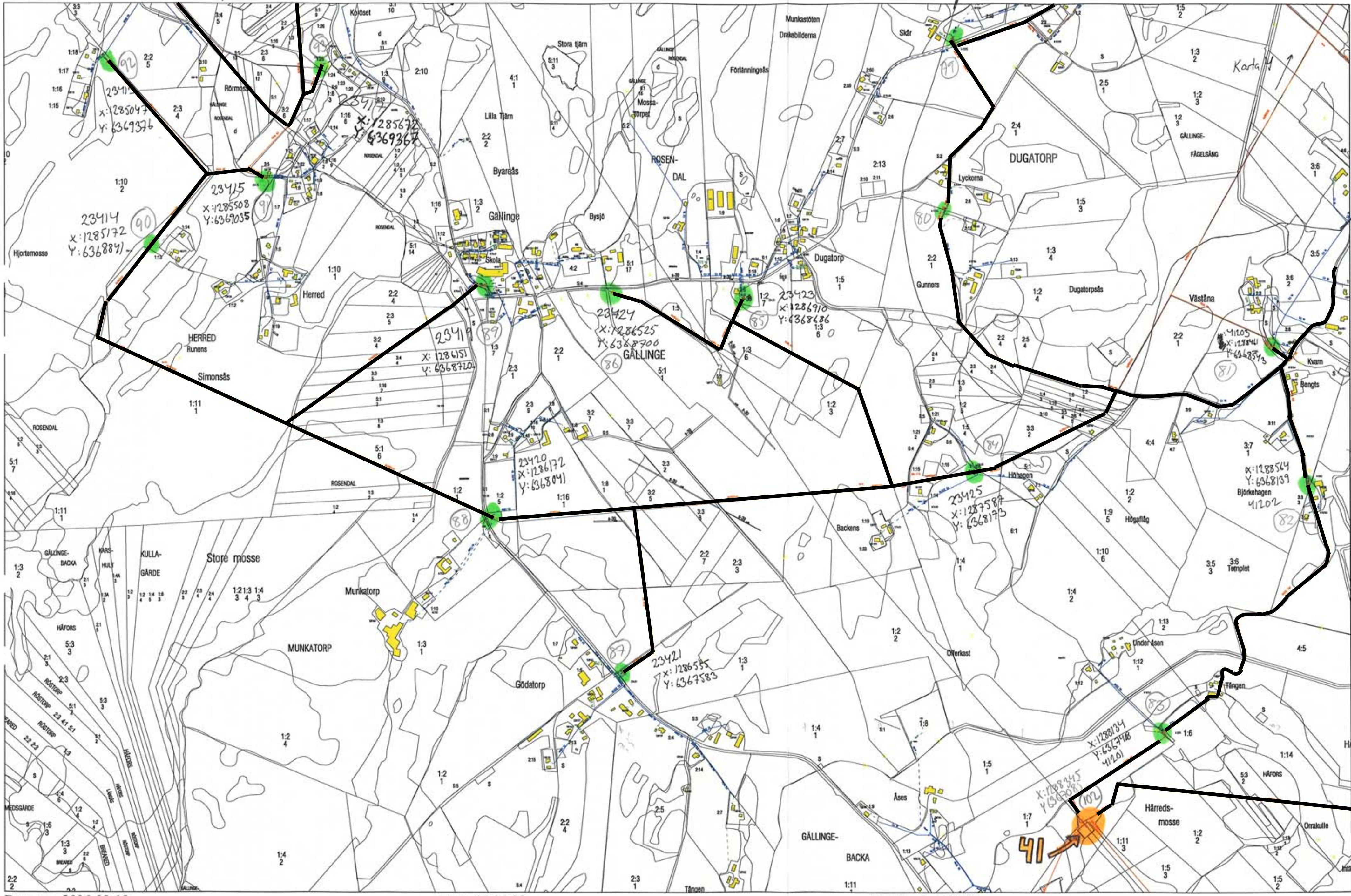
L41 Karta 12



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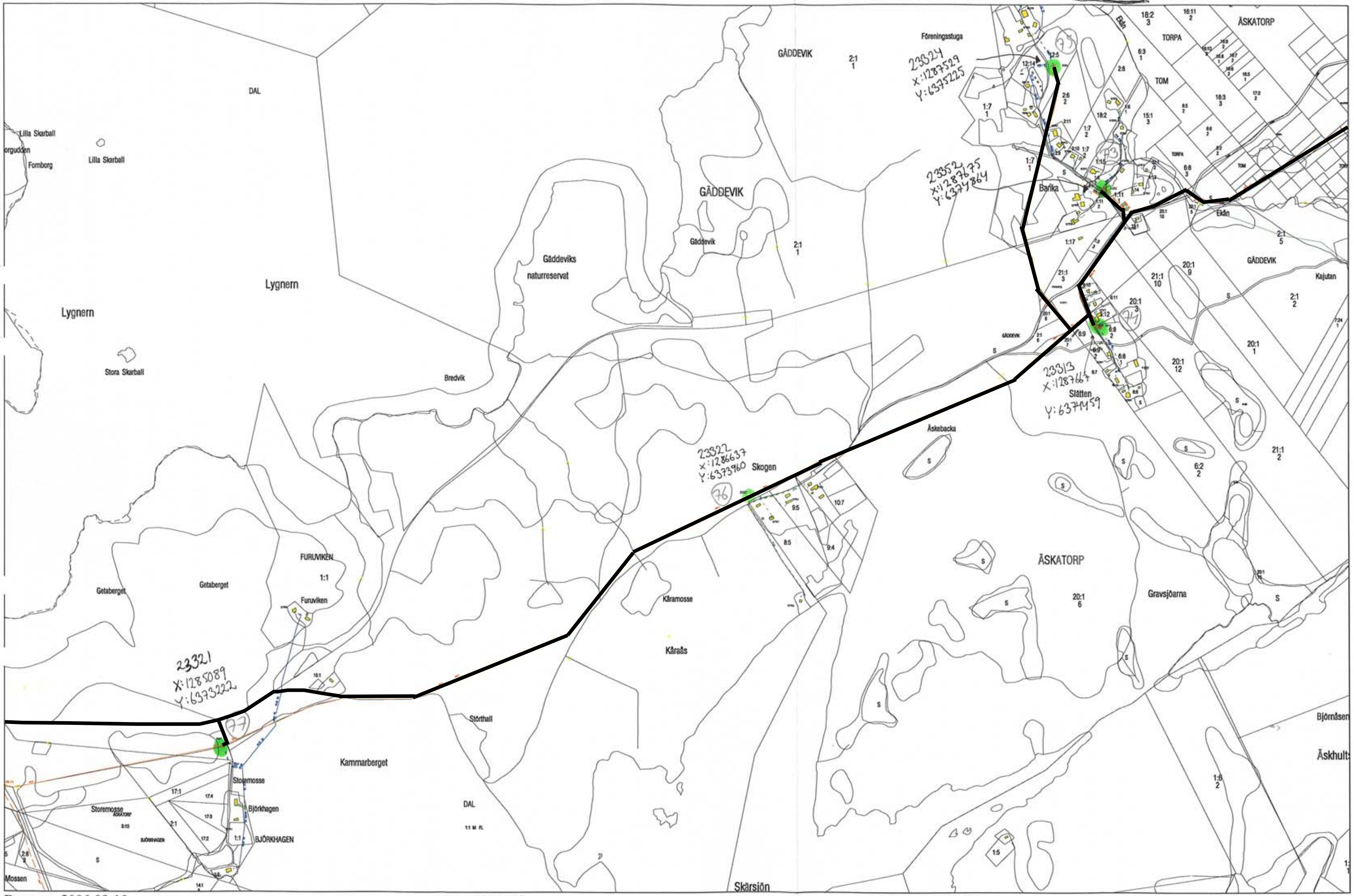
Birka Nät AB

Karta 11



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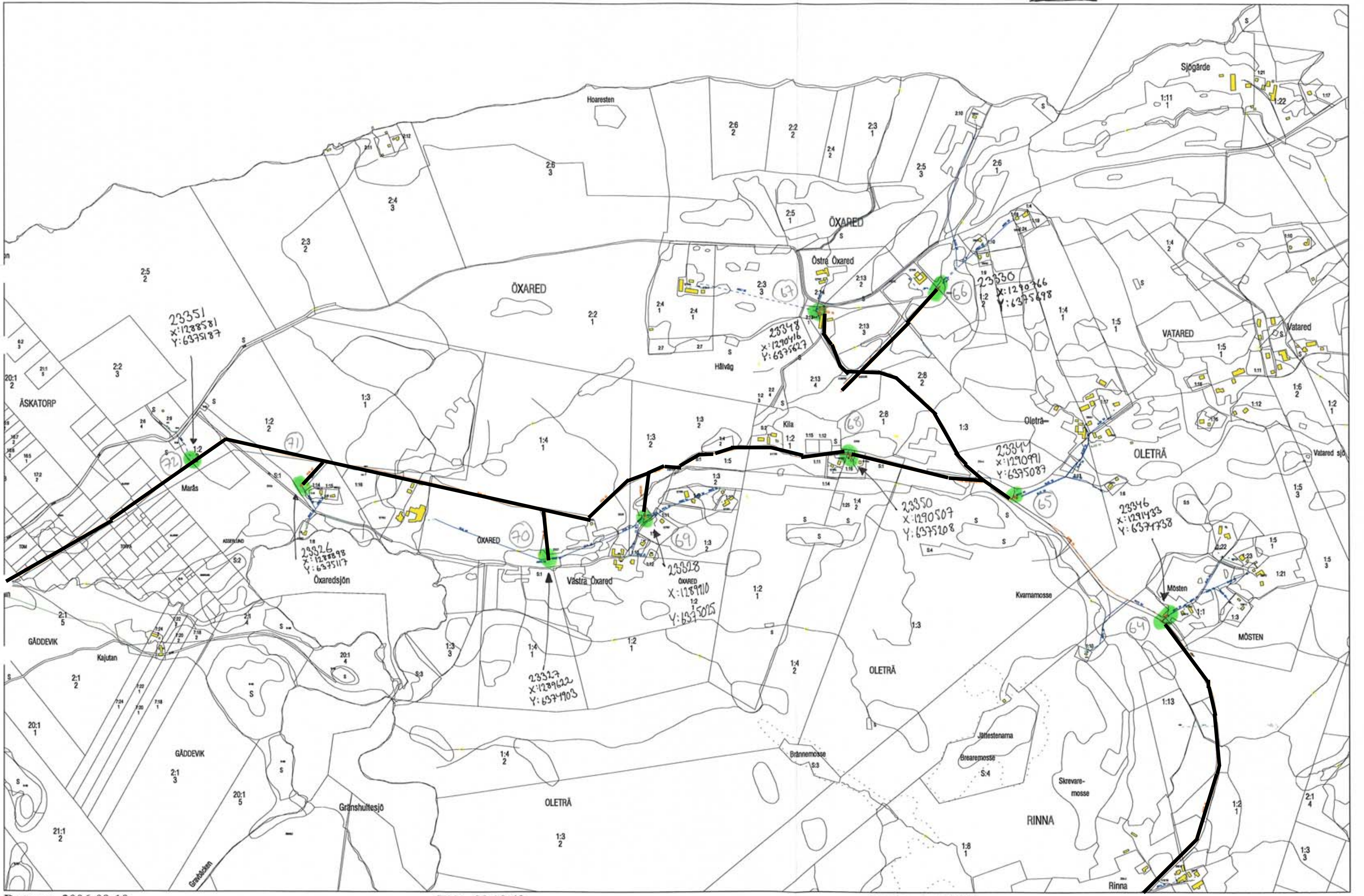
Karta 10



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Birka Nät AB