Abstract

This research studies a probabilistic method to locate the event center of sudden changes in load or generation power. The calculating procedure takes into account the frequency, phase angle deviation influenced by nature and characteristics of the power system dealing with the disturbances. In this way, the angle's error at different places in the power network is found and analyzed to reach the right event location.

A model of 400 kV Nordic grids is set up basing on the data measured in Lulea, Malmo and Goteborg by the phasor measurement unit (PMU). Simulating method is used to perform several tests of generation and consumption trip. The reliability of the event location is confirmed by comparing the results of PMUs recordings and the computed model. Some features of the research are further proposed to be improved in order to get the higher accuracy.

Acknowledgements

I would like to express my great gratitude to my supervisor Dr. Daniel Karlsson and my examiner Prof. Jaap Daalder for their skilled guidance, valuable comments and encouragement.

Special thanks go to Morten Hemmingson who provided me all the necessary data measured from the PMUs. I am grateful to Abram Pernada for helping me with the Nordic 32 buses.

Finally, I wish to thank all the members in Electric Power Engineering Department for their support.

Table of Contents

Introduction

Nowadays, the customers and the power market require a comprehensive view into the facility's electrical system. The utilities also want to get all information of the operating grid so that they can find methods to increase the transmission capacity which closely relates to the power system’s stability limits. Transients as generator trips or load losses need to be detected, measured and analyzed offline.

The development of advantage tools like SCADA, wide area monitoring (WAMs) with phasor measurement unit (PMU) can help to monitor at the electrical nodes or at any critical feeder branch in the network. The abilities for high precision, quick response and time synchronization make these equipments very appropriate for measuring voltage phase angles, frequency and other electrical parameters. This also evaluates the promising future of identifiable techniques and computational requirements for calculating transient stability limits.

The goal of my thesis is to set up a simple model of the Nordic 400 kV grid using the data collected by PMUs in Lulea, Chalmers and Lund. The comprehensive methodology which examines the impact of a power change on the behavior of frequency is studied in this model. Frequency and phase angle deviations have been calculated and then are taken to estimate the event location. This technique offers a sensitive and quick method of detecting the disturbance center in the power system.

The thesis is organized into 3 main parts

- Part 1: Introduction of the PMU and its present applications, especially in Sweden.
- Part 2: Construction of the network model based on the Nordel map.
- Part 3: Tests of locating event centers with several disturbances.

Chapter 1

The phasor measurement unit and its application

The importance of measuring the voltage, current and other parameters of the electrical network have been aware from the early state of the developing power system. One of the old techniques is the Supervisory Control and Data Acquisition (SCADA). SCADA refers to the combination of automatic or manual data acquisition (voltage, current), telemetry (transmission and reception over a wire line system) [1]. The most drawback of SCADA is that it takes time to collect data from many separated places (several seconds). This solution is only focused on the steady state operation; it can give delay when indicating a fault and maybe even miss the short outages which cause the instabilities in the system.

The phasor measurement unit with the support of the Global Position System (GPS) can measure the voltage and current phasors accurately. Moreover, it can get the synchronization data of several readings taken at distant points; therefore directly compare the measurement at the snap shots. By collecting the signal directly, the PMU provides information of power oscillation and out of step conditions, the different angle between one swing node and the others, thus the state estimation can be improved.

In the future, the SCADA and PMUs can be combined to offer the system protection based on the dynamic network view.

1. Structure of the PMU.

PMUs are developed from the invention of the symmetrical component distance relay (SCDR). The PMU calculates the phasor via Discrete Fourier Transform applied on a moving data window whose width can vary from fraction of a cycle to multiple cycles. Equation (1.1) shows how the fundamental frequency component X of the Discrete Fourier transform is calculated from the collection of X_k waveform samples [2].

$$X = \frac{\sqrt{2}}{N}\sum_{i=1}^{N} X_k \varepsilon^{-j2k\pi/N} \tag{1.1}$$

N: number of samplers.

The sampling is collected directly from the analogue signals through the potential transformer and the current transformer. The GPS system which synchronizes the PMU is a system of 36 satellites (of which 24 are used at one time) to produce time signals at the earth's surface [3]. GPS receivers can resolve these signals into $\{x,y,z,t\}$ coordinates. This is accomplished by solving the *distance=(rate)(time)* in three dimensions using satellite signals. The structure of a PMU is as fig 1.1.

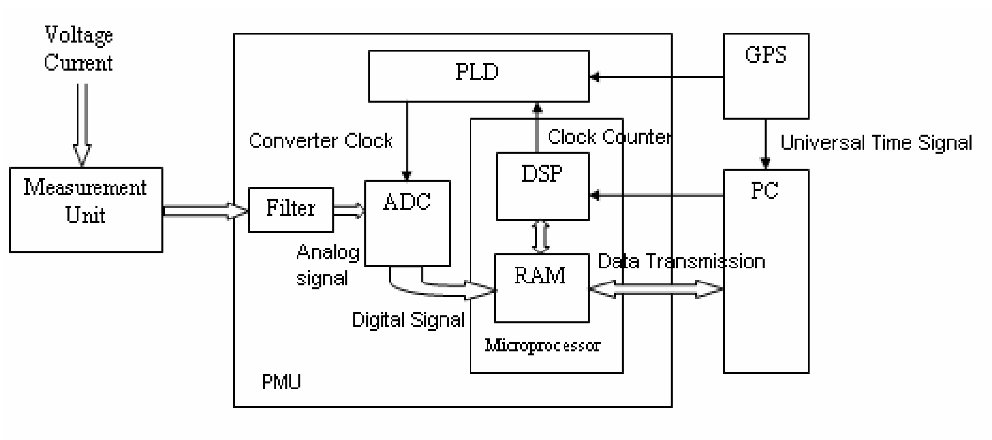

Fig 1.1: Structure of the PMU system

The instantaneous signals after passing through the filter to reduce the harmonic and alias are put into the A/D Converter and then stored in a microprocessor. The collected data such as voltage magnitude, current, phase angle, power are sorted in the system monitor center to give out the instant alarms like high or low frequency, over voltage, overcurrent or to analyze offline.

2. The advantage of using PMU.

The phasor measurement unit (PMU) is considered to be one of the most important measuring devices in the power systems. Using the integral GPS, PMU samples the phasor value synchronously at selected locations in the power system. The benefits of synchronized phasor measurements to power system monitoring, operation and control have been well recognized.

2.1 Indicate the dynamic Performance of a Power System.

Phasor measurement at nodes helps to gain a dynamic view of the power network. The angular velocity can be calculated based on the phase angle as equation (1.2):

$$\omega = \frac{d\theta}{dt} = \omega_{syn} + \frac{d\delta}{dt} \tag{1.2}$$

where ω_{syn} is the synchronous angle velocity.

The difference between the mechanical power supplied by the generator P_m and the electrical power P_e is expressed in relation with the inertia constant.

$$P_a = P_m - P_e = \frac{2*H}{\omega_{syn}}\frac{d^2\delta}{dt^2} \qquad (1.3)$$

where

H: the constant of inertia.

ω_{syn} : the synchronous speed.

δ : the rotor angle

The stability of the energy transfer can be studied from the value for the difference power P_a in the equation (1.3).

Power system monitoring and analysis using PMUs' data are much improved because of the precise snapshots. The system dynamics such as short circuits, auto-reclosure, line switching, or fluctuations due to significant variations in load, generation can be known by the angular displacement. With PMUs, the utilities are able to directly measure voltage angle as compared to the swing bus. The phase angle variations are also obtained behind the machine transient reactance. Besides, much of the uncertain and inherent approximation in the system can be removed, which provides the opportunity for the network operator to analyze the dynamic contingency.

2.2 Detect and record the disturbance.

With the support of GPS, the PMUs can synchronize data with accuracy better than a microsecond. These instant data give enough time for the system to study network's damping and oscillations.

The frequency determines the response of a power system so it is an important indication which helps to improve the efficiency of power system analysis and find real causes of the incident. The equation for frequency and phase angle can be described as:

$$f = f_{syn} + \frac{1}{2*\pi}*\frac{d\delta}{dt} \qquad (1.4)$$

where f_{syn} is the synchronous frequency.

Associating with the special data processing, the PMU can measure the disturbance in each bus and then send signals to the control system or a warning signal to the neighbor buses.

2.3 Predict the voltage instability in the network.

This is the new application field of using the PMU [4]. The collected synchronous data can directly be analyzed to predict the voltage collapse. One common method is the VIP algorithm which uses the difference between load impedance (Z_{load}) and the Thevenin impedance (Z_{The}) to define the condition of load. The main important point in this method is that the Thevenin impedance is not a fixed value, it is measured at each instance and requires being updated in the same time with the change of load.

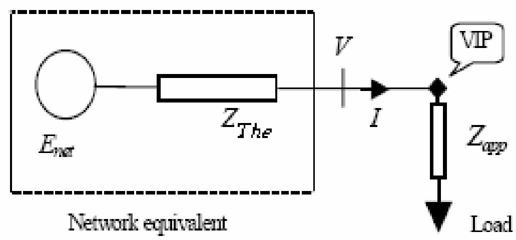

Fig 1.2: Model of the VIP detection

When the voltage instability level is estimated, the setting for the protection system (as setting the trip level for relay or active zone for fuse) can be identified.

3. Structure of PMU system

A system of PMUs must be supported by the communication infrastructure with sufficient speed to match the fast streaming PMU measurements. The deployment of PMUs is a major economic undertaking that depends much on the requirement of grid monitoring and the technical condition in each bus.

3.1 Stand alone.

This scheme of PMU is used mainly on a localized basis. A single PMU has the storage and trigger logic and can therefore be used as a stand-alone device. A limited number of PMUs can be connected together to exchange data. The distance between two PMUs is from 10 to 1000 km.

The extreme time accuracy of PMU and the easy access characteristic enhance the remote control monitoring. By comparing the difference in phase angle, the operator system can deliver the alarm or the instant action like compensating by Static Var Compensator (SVC), Automatic Voltage Regulation (AVR) or switching braking resistors.

3.2 Wide Area Measurement System (WAMS).

WAMS is the most common application based on PMUs. A typical system is set up by 10 to 20 PMUs collecting data at several different locations. The optimal numbers for PMUs in the power system are 1/4 or 1/5 the number of network buses to ensure observation. PMUs can also be installed sparingly in such a way that allows unobserved buses to exist in the system. The phasor data and frequency are collected to the data concentrator which has a mass storage in a FIFO buffer with the capacity for about one week or more (depending on the capacity of the hardware). Relevant power system variable data is transferred through the communication network connecting the terminals together. If the communication is partially or totally lost, actions can still be taken based on local criteria. The sampling speed for sending data to the concentrator is 25/30 or 50/60 samples per channel and second. The numbers of sampled channels are 10 to 20. With access to wide-area measurements, the sensitive system can be made adaptive to cope with the actual system conditions, such as load flow pattern and voltage levels.

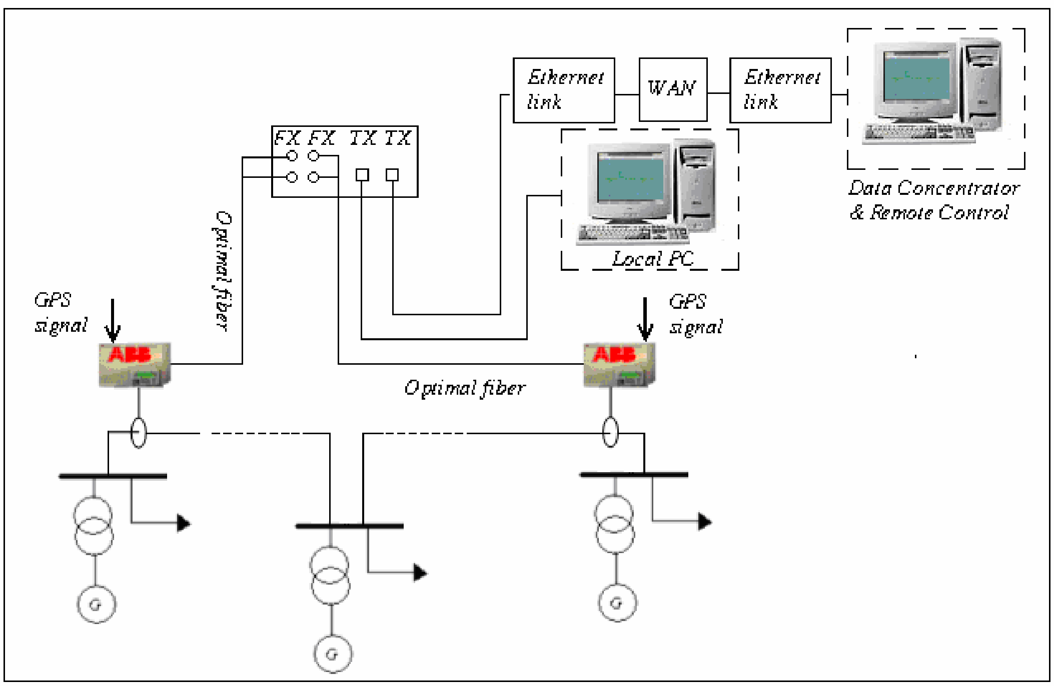

Fig 1.3: The WAMS structure

The most benefit when using the WAMS is the early detection of the power system problems with real time observation, thus preventing propagation of such instabilities, which might lead to wide-spread system outages and ultimately regional blackouts.

The collected satellite-synchronized data give the operator the total view to control the power system reliably while operating the grid closer to its capacity limits.

The WAMS can also provide fast state estimation from which a variety of system stability indexes can be derived. Besides, WAMS data remain retrievable and useful for many years after acquisition.

The WAMS design can be developed by turning a data concentrator into a hub-based local protection center (LPC). In that scheme, the advanced control system and special protection functions are implemented in the data concentrator. They are also possible to combine with the remote feedback and the pre-defined system of the certain assumption to improve the performance, reduce the error.

4. Application of PMUs in the Swedish power grid

The Swedish power system is monitored in 3 places: Lulea, Lund, Chalmers by PMU RES 521 1.0, a product of ABB. As the name given, this equipment provides the AC voltage and current phasor, normally as the real and imaginary parts or the magnitude, frequency and the phase angle.

4.1 Introduction of PMU RES 521 1.0.

The outstanding ability of PMU 521 1.0 is the controlling time signal which follows the Coordinated Universal Time standard with the accuracy better than $\pm 0.5\,\mu s$ [5]. The frequency accuracy is $\pm$5mHz. The reliability of the measured voltage or current can be affected by 3 factors

- The internal calibration due to inaccuracy of terminal measurement transformer.
- External calibration due to inaccuracy of substation instrument transformer and are settable by HMI interface.
- System calibration due to different phase angle in two nodes of the power network.

RES 521 collects data directly from 12 current analog inputs, 6 voltage analog inputs as well as 8 binary inputs. The special module inside the PMU can immediately provide some basic analyzed information of the measured signals: such as the high or low frequency in compare with the setting level, the change of frequency, the overcurrent, etc... Besides, this equipment also supports to calculate of the internal parameters for the power system like the line resistance or impedance. The RES 521 terminal is designed towards the equipment protection. This aims to save the power system from damage and isolate the faulted nodes, minimize the negative impact. The anti-aliasing filters inside help the PMU to filter out the input waveform frequencies above the Nyquist rate.

4.2 The application of RES 521 in monitoring the Swedish power network

Three PMUs RES 521 are installed in Lulea, Malmo, Goteborg (Sweden) after the serious blackout on 23rd, September, 2003. The investigations of this blackout indicate that if the behavior of the Swedish power system is regularly monitored, analyzed, methods to improve its stability can be found. More-ever, the reliable, efficient measuring tools as PMUs can satisfy the need of predicting and preventing the situation leading to the sequent failure events.

The placements of these PMUs are chosen to allow the direct observation in the whole power system. Lulea is an important node, of which the production occupies a large part in the Swedish electrical system. The generators here are hydro power plants and are considered as the main power reserves. The decision for installing the PMU in Lulea is also based on the reason that the signification amount of power transfer over a long distance from the north to the heavy load centers located in the central and south of Sweden should be monitored so that the operators can have bases to regulate the system.

Two biggest nuclear powers plants with capacity of 3530 MW in Ringhals are also the main sources of production in the south of Sweden. From the lesson of the blackout in the end of 2003, it is realized that the outage of these generators at the same time can cause a voltage collapse. This problem is typically associated with the reactive power demands of loads not being met because of limitations on the production (generator, SVC) and transmission of reactive power (reactive power loss on heavily loaded lines, line outages). Therefore, most of changes have a significant effect on reactive power production, consumption and transmission in the south of Sweden need to be collected to find out the countermeasures against voltage collapse. Besides, there are two important connections (1200 MW) between this area of Sweden and Norway. Information of the large amount of power transfer through these lines can be used to estimate the system situation in the south of Sweden.

Malmo is the end ‘point’ of Swedish transmission system. This place and Eastern Denmark are closely interconnected as a single grid region. After the closure of

Barseback nuclear power plant, the production here is limited although the demand from the populated city (21500 GWh) in this area is always high.

Two PMUs locating in Goteborg and Malmo are necessary for the power control and study.

These three PMUs have provided phasor data of the Swedish grid since 2004. Almost all the special behaviors in the south of Sweden and Easter of Denmark can be recognized in the recorded signal of voltage angle and frequency. The main application of these information is for offline analysis rather than towards online operator support due to the limited numbers of PMUs. These researches using the stored data have the overall goal to contribute to understand and improve performance of the power system. The important issue in maintaining power quality is the exchange of knowledge and reports between the member utilities which is encouraged and facilitated by the data from these PMUs.

The most common fault of these equipments is the loss of communication due to the long distance from the substations and that causes the interrupted or “noise” data. Sometimes, this problem gives out the wrong signals of the power state.

In my thesis, these PMUs have been implemented as a source of information to set up 400 kV model and to detect the power change location in the Nordic grid.

Chapter 2

The simulation of Nordic grid

A simulation model of the Nordic power system is set up in this chapter. The purpose of this model is to calculate the power flow and then use the result to estimate places of sudden power change.

1. Power situation in Nordic countries

The Nordic countries' electricity is based on different electrical production methods. This grid also has a high level per capita of consumption. Data of the power system in these places lay a foundation for the simulation model. Therefore, in this section, the current structure of the Nordic electricity will be briefly described.

1.1 Sweden

Sweden has a mixed electrical system comprising hydro power in the north (40%) and nuclear in the south (49%), with conventional thermal power production accounting for only about 5 % [6]. Swedish generators value the flexibility of being able to alter their bids up in the last minute to take account of unforeseen changes in the balance of supply and demand. Oil-fired cold condensing power plants and gas turbines are used primarily as a reserve capacity during dry years and they help to reduce the stress for low hydropower production. Sweden is developing the capacity of generation by the new wind power plants but their contribution to the country's electricity balance is still very small.

Electricity consumption in Sweden which concentrates in the middle and south doubled from 1970 to the mid-1990s because of the higher demand in the household and service sectors, especially in the cold winter. The industrial sector has also contributed to the increase.

The generation capacity of Sweden now is 33 700 MW and the peak load is 26400 MW [7].

Sweden has mainly been a net exporter of electricity. This country has low reservoir storage capacity and runs down its reservoirs during the period of peak winter demand.

1.2 Finland

Power in Finland is mostly generated by thermal and hydropower plants. So far only a very small volume of electricity is produced by wind power, although the relative increase of wind power capacity has recently been quite rapid. Finnish production's capacity is approximately 16 500 MW and the peak load is 14040 MW. The main consumptions are situated in the southern part of the country [8]. In Finland, the total primary energy consumption per capita was about 60 % higher than the European Union average (according to 1996 statistics). This is mainly due to the weather, which demands space heating for most of the time, and the structure of the industry, which is energy intensive processing industry (wood, especially paper, heavy metal and chemical). A third factor is a relatively high transportation requirement per capita caused by the low population density.

1.3 Norway

Norway has a special geography and climate which are suitable for hydropower development. Norwegian electric power generation is almost exclusively hydropower (99%) while thermal generation is only 1% [19]. Norway still has the potential to increase hydro-generated power, through refurbishing existing facilities, as well as constructing new hydropower plants. This country has also looked towards wind power as a way to supplement the hydroelectric capacity.

The generation capacity of Norway is 28000 MW and the peak load is 19984 MW. Norway's peak electricity usage occurs in the winter, for climate control and heating water [9].

The low cost of electric power in Norway and a growing economy led to steadily increasing electric consumption and also generation throughout the 1990s. As a result, Norway is now a net importer of electricity.

1.4 Denmark

Due to a special location, Denmark has two unconnected and largely autonomous grid systems, located west and east of Great Belt, respectively. Most of electrical generation in Denmark comes from thermal power plants: coal, gas and bio-fuelled CHP. Denmark has also become a leading pioneer of using renewable energy in an attempt to reduce its reliance on fossil fuels and imported power. The main part of renewable sources is wind power (about 40% of the world market). This country has also made considerable progress in the development of solar power and bio-fuel technologies.

East of Denmark has generation capacity 5334 MW and peak load is 4000 MW [10].

2. Exchange of power between the Nordic countries

During the 1990s, the Nordic countries as Denmark, Norway, Sweden and Finland regulated and created a framework for a common electric power market based on open competition. In 1993, Nord Pool – the common power market by means of the common power exchange was established and it became the first international commodity exchange for trading electric power.

2.1 Some common features of the Nordic countries' electrical system.

- All the Nordic countries (except Denmark) have reliance on hydropower, which requires imports to meet seasonal shortages, but also opens the possibility of exports during wetter conditions.
- The Nordic countries have the high demand of consumption in the winter. Due to the cold weather in this area, the combination of hydropower and thermal power is a considerable potential for profit in trade of electricity.
- The similar structure of the power transmission 400/220 kV is used in this region. The distribution network has several lower steps: 130, 70, 45, 22, 10 kV.
- Before joining the common market, each country's generation was mainly controlled by the government which caused difficult for the smaller utilities to be competitive because of the high network fee.
- The special location of the Nordic countries which have the same border in Scandinavia so it is an economical solution to make the transmission connection between them.
- These countries have low population density; most of their populations are concentrated in the south so this requires long transmission from the power plants to the customers.
- They all have the increasing demand of consumption from the industrial customers.

The transport sections between the Nordic countries help to increased flexibility in dry and wet years, better capacity between thermal or wind dominated areas and hydro-dominated areas and even give the better balance. These interconnections also contribute to reduce the congestion of each country's network.

2.2 The power exchange situation in the Nordic countries.

The installed capacity in the Nordel system is about 90 GW and the peak (winter) load is 60 GW [11]. The power regulation is based on the principle that each country would build enough generating capacity to be self-sufficient. Trading means to achieve optimal dispatch of a larger system and investment in interconnection do not generally depend on net exports but on expected savings from pooling available generating capacity. The countries exchange information about their marginal cost of production. When there is a difference, trading takes place, at a price that is an average of the two marginal costs.

Finland- Sweden: At the moment, there is 1750 MW transfer capacity from Finland to Sweden and 2150 MW from Sweden to Finland. This equals to approximately 14 % of the Finnish production capacity. This transfer capacity is sufficient to guarantee the Swedish producers to bring competitive pressure to Finland.

Norway – Sweden: The connection to Sweden is by means of 3 transmission 400 kV lines at various points across the border. In the north of Norway, one line connects from Ofoten to Ritsem. The capacity of power exchange between Norway and Sweden is 1350 and 700 MW.

The amount of net import fluctuates from year to year depending on the hydropower situation in Sweden and Norway.

Norway – Finland: there is small power (70 MW) exchange between Norway and Finland in the north of Norway, connecting Varagerbotn and Ivalo.

East Denmark – Sweden: The Zealand grid in eastern Denmark is closely connected to the Swedish grid by a double-circuit 400 kV set of submarine AC cables, capacity up to 1900 MW.

Besides, HVDC links from Sweden (Baltic Cable) and Denmark (Kontek) to Germany, connection between Finland and Russia satisfy the Nordic's remaining energy requirements and therefore reduce the stress for the Nordic market.

3. The simulation model of Nordic grid

In Nordic countries which have the development of economy, there are rapidly growing demands for transmission capacity. Raising the capacity on lines is a present solution for that problem. In the realm of system operations and planning, increased power transfers will heighten the need for more sophisticated analytical tools to precisely measure capabilities and display of the information in real time. Besides, using the full transmission capacity makes the power systems increasingly vulnerable to disturbances that can endanger the reliability.

To get the better view and control of the grid, the propagation of these disturbance events should be performed and analyzed to get some common threads among them, and maybe find methods to prevent or reduce the effects.

Power flow models have been typically used for network studies, as these allow for a quick and approximate analysis of the changes in operating conditions. The aim for the simulation model is to accurately estimate the state of the power system in real time before and after the disturbance (mainly provide bus voltage magnitudes and phase angle). The change in generation and transmission capacity, load in the real cases, is proposed to have the same behavior as in the models. Solving frequency response recorded by the power model will help later in how to deal with the mismatch power and the regulation in the whole system. Moreover, from the fact that the generator connecting to the transmission system should take the responsibility to provide frequency deviation, the simulation can give the ability to identify the event center. New system characteristics motivate transfer limits can be regularly tested.

The model in this paper is intended to simulate the 400 kV grids in the synchronous NORDEL system consisting of Finland, Norway, Sweden and the part of Denmark east of Great Belt. The reason for choosing this level of voltage to research is that the 400 kV is the popular high voltage level mainly used in Nordic network. From a technical point of view, the 400 kV line has many benefits. It has a higher capacity per line which can help to reduce the number of long line. A 400kV line carries about three times as much power as a 275kV line and about 18 times that of a 132kV line. It can avoid unduly restricting generation, reduce the power loss, and extend the age of line because of the lower thermal resistance. At the level of 400 kV, we don't need many towers for transmission although the tower must be higher and needs 5m gap.

In the simulation of Nordic grid, the power system is modeled as a series of inter-connected bus bars with individual loads and generation sources connected to particular buses. The power system is analyzed in the condition of three phase balance so the calculation is made per phase. The equivalent model consists of 13 buses, 13 generators, and 20 lines (Fig 2.1). The position of these buses and lines are distributed as figure 2.1.

3.1 Bus

The model is designed with three types of buses: type 1 is a load bus, type 2 is a generator bus and type 3 is a reference or swing bus or slack bus. The Swedish 400 kV network is divided into 8 buses based on the geographical areas and the location of the main generators. Bus 8 is chosen to be the swing bus because in this place, all the generators are hydro plants and their capacity are flexible. The high reserve of power in this bus is the key factor of power regulation. The voltage and angle of the swing bus are known. Voltage in this bus is 1.02 pu and phase angle is zero degree. After calculating system power flows, the mismatch power of the loads and generation, is injected at the swing bus, this value is equivalent to system losses which can only be determined after network solution. The net real and reactive power inflow to a swing bus are free variables and follow the power flow solution.

For other generator buses in Sweden, 4 buses in Finland and 1 bus in the south of Norway are, as expected, the buses to which a generator or multiple generators are linked. Denmark has two separate high voltage grid networks so in the relation of power exchange with Sweden, only the East of Denmark is described in the model as the part of the south bus 4 of Sweden. Voltage and real power flow are regarded as known quantities (P-U bus), while reactive power and phase angle are unknown and these values are determined after the network solution. The power for the generator buses can be controlled.

For the load buses, real and reactive power flows are known (P_Q bus) but voltage and phase angle must be calculated. The load buses are uncontrollable and totally depend on the customers' demands. In this power simulation, the load bus and the generation bus are combined into one bus with the assumption that the loss of step down transformer is neglected.

Fig 2.1: The location of buses in the simulation model

.

3.2 Load

In power flow simulation, a required condition for solution is that all loads are known; hence loads can be regarded as constants. Because the main aim of the grid simulation is to calculate the power flow in the steady-state, when frequency of normal operation is almost unchanged over an allowable voltage range, the load is represented as the real power consumption P and reactive power consumption Q.

The distribution of load is different in the Nordic countries. In the middle and south of Sweden, there is the high concentration of consumption. The loads in the south of Finland are much larger than those in the north.

The exact amount of consumption for each test later is difficult to get so the estimated load is relied on annual unit consumptions and hourly load curve models of different customer groups. From 8 a.m to 16 p.m every working day, the loads are heavy. During the weekend, the demands tend to lower. The consumptions are also the seasonal dependence. Normally, there is a large amount of electricity in need for the heating in the cold winter.

3.3 Generator

The phase synchronous generators produce the overwhelming majority of electricity in the modern Nordic power systems. They have the same speed and the same frequency. Thus, for steady state studies in this paper, the generator is referred to connect a PV bus and the parameter needed for the generators are fixed active power P. In order to limit the model size, all the units of one generation site are aggregated in one machine at each bus.

The value for the generators outputs is determined from the supplying power capacity and utilization in different period. The generator is assumed to be connected to a bus by a step-up transformer.

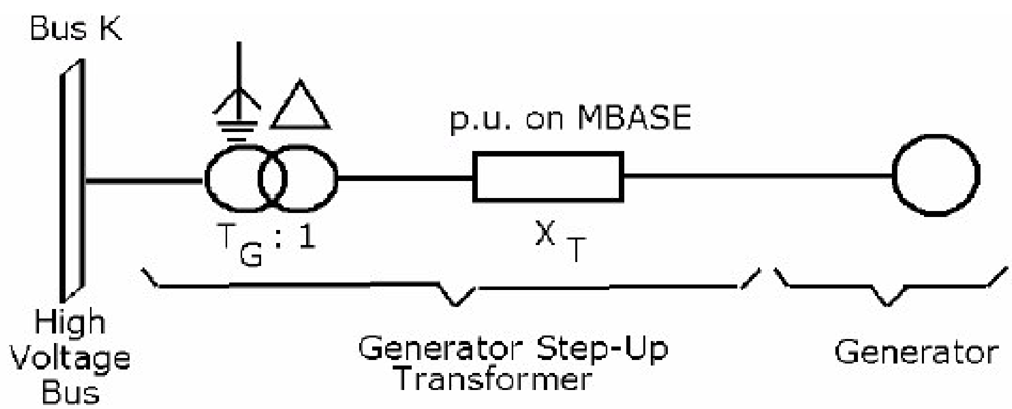

Fig 2.2: The model of generator

In the north of Sweden, the hydro power plants are the main types and they provide the electricity to the local areas and the south. Eight nuclear stations in the centre and the south also contribute to satisfy the high demand and they are divided into 5 buses of the model. In Finland, the mixed types of generation with nuclear and thermal power occupy bus 11, 12, 13 and 14 (fig 2.1); among these buses, the last two buses have the large capacity of production. All the generators in south of Norway are considered to belong to bus 10. The detail parameters for all the power plants can be seen in the appendix.

3.4 Line

The lines connect between buses. The lines' impedances are represented in the simulation by series and shunt (parallel) components. Because most of the 400 kV transmission lines are longer than 200 km, capacitance can not be neglected. A reasonable circuit model is to simply split the total capacitance evenly with each half at each end of the line and the line impedance and admittance are proportional to the length. These are represented as π equivalent scheme.

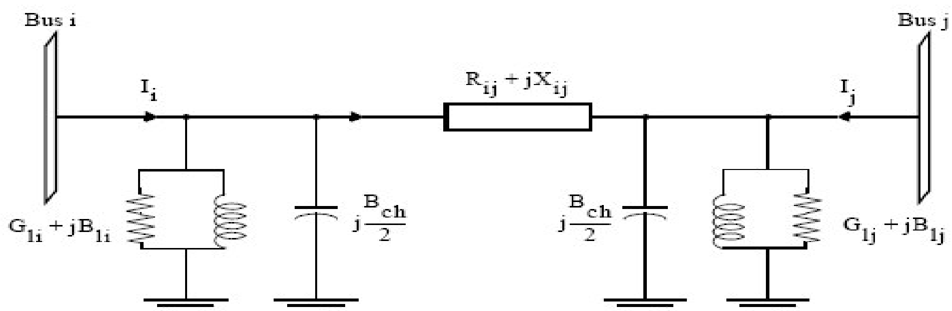

Fig 2.3: The model of transmission line

Total serious impedance for the long line transmission

$$Z' = Z_c \sinh(\gamma l) = Z \frac{\sinh(\gamma l)}{\gamma l} \tag{2.1}$$

γ: the propagation constant

l: length of the line

Z_c: the impedance $Z_c = R_{ij} + jX_{ij}$

Total shunt admittance for the long line transmission

$$\frac{B_{ch}}{2} = \frac{\tanh(\gamma l/2)}{Z_c} = \frac{Y}{2} \frac{\tanh(\gamma l/2)}{\gamma l/2} \tag{2.2}$$

G_{li}, B_{li}: complex admittance of the line shunt.

For some long lines (more than 400 km), there are series compensations up to 70%. These compensations can increase the power transmission capacity without increasing the voltage angle to higher value and it can improve the stability. The capacitor in the serious compensation can cancel part of the line reactance; make 'electrical' length shorter and therefore increasing the active power transmission. Another benefit of the series capacitor is to reduce the power loss; therefore it optimizes the power flow between parallel lines. The reactance of the line with compensation reduces as:

$$X_{ij\_comp} = X_L - X_C = (1-k)\, X_L \tag{2.3}$$

Thus the impedance for the line with serious compensation is

$$Z_c = R_{ij} + jX_{ij\_comp} \tag{2.4}$$

The 400 kV line in Sweden

Today the 400 kV network in Sweden contains eight North-South lines and has a total length of roughly 10,500 km.

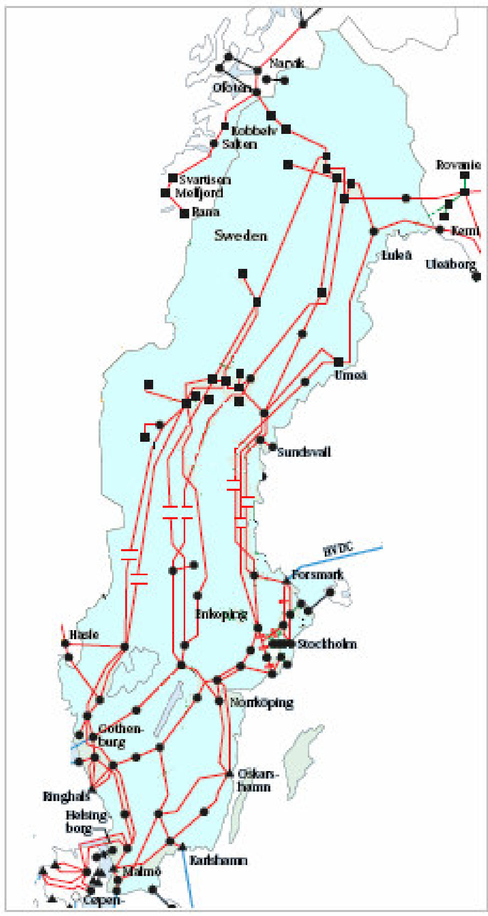

Fig 2.4: The 400 kV grid of Sweden

These 400 kV lines are the backbone in the transmission system, connecting the main source of production in the north to the customers in the south. Some long lines are compensated with the series capacitors up to 70% as in table 2.1 [12].

Substation	Voltage (kV)	Rate power (Mvar)
Isovaara	400	500
Tandö	400	600
Stöde	400	493
Djurmo EK2	400	600
Djurmo I	400	213
Djurmo EK4	400	603
Vittersjö I	400	305
Vittersjö II	400	802
Kättbo	400	216
Haverö I	400	200

Table 2.1: The series compensation in the Swedish 400 kV grid

The Fenno- Skan HVDC is used to import and export power over a long interconnection between the souther part of Sweden and Finland. Because, this DC line tries to maintain scheduled active power transfer in the static state, so it is simulated as the constant load (positive and negative). The capacity of this interconnection at any given time is dependent on system condition.

The 400 kV line in Norway

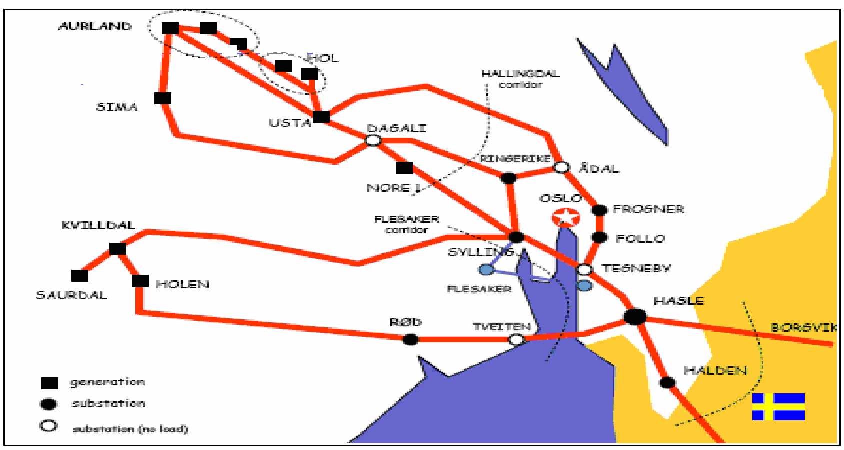

Fig 2.5: The 400 kV grid in the South of Norway

The total length of 400 kV lines in South of Norway is 1200 km. These lines transfer power from the hydro power plants to the customers and export to Sweden.

Two 400 kV lines in the south enable Norway to export 2000 MW to Sweden through Hasle- Borgvik and import 1650 MW from Sweden by the line Halden – Skogsater. These 400 kV interconnections have the total length of 220 km and critically depend on voltage support from an SVC.

400 kV line in Finland

Finland has about 3,900 kilometers of 400 kV lines, consisted of 33 lines with 3,793 km of wires, 34 km of underground land cables and 99 km of submarine cable [18]. The series compensation between northern and southern Finland was enabled an increase of approximate 400 MW in transmission capacity (table 2.2)

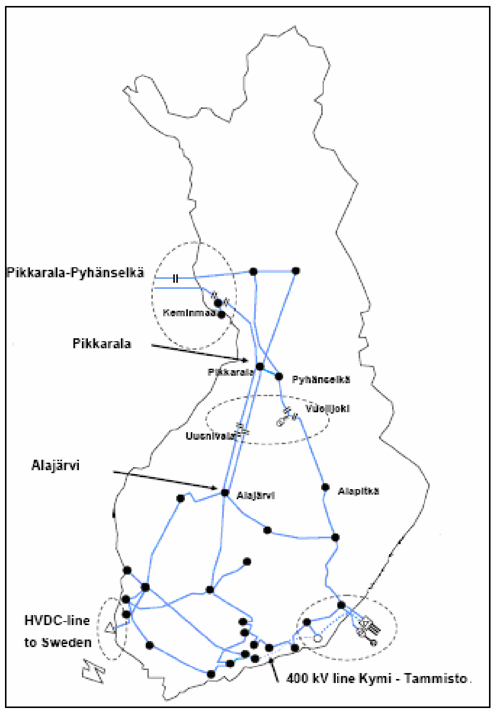

Fig 2.6: The 400 KV grid of Finland

Substation	Voltage (kV)	Rate power (Mvar)
Keminmma	400	301
Uusnivala	400	400
Isovaara	400	515
Vuolijoki	400	300

Table 2.2: The series compensation of Finnish 400 kV grid

Two AC 400 kV connections to Sweden are located in the northern Finland (Letsi-Petajaskoski, Svartbyn-Keminmaa) and the transmission capacity from Sweden towards Finland is about 1800 MW.

The DC interconnection to Sweden, the Fenno-Skan HVDC link – 600 MW, 200 km, is located in south-western Finland (Formark – Rauma). Effectively being parallel to the AC lines around the Bay of Bothnia, it has considerable leverage on electromechanical oscillations between generators in Finland and central Sweden.

4. Power flow analysis

The difficulty in computing the power-flow solutions arises from the fact that the equations are inherently nonlinear arising from the balancing of power quantities.

At each bus, there are six variables P_{Gi}, Q_{Gi}, P_{Li}, Q_{Li}, V_i, and δ_i. In power-flow studies, we usually assume that both these control mechanisms are operating perfectly and so the real power output P_{Gi} and V_i of the generators are maintained at their specified values. The load variables P_{Li} and Q_{Li} are also assumed to be known. The reactive output is considered to be fixed at the limiting value between $Q_{Gi,max}$ and $Q_{Gi,min}$ respectively to keep the bus voltage magnitude at a specified value [14] **.**

The flowchart for solving the power flow is shown in fig 2.7**.**

There are two main methods to calculate the power flow: Gauss Seidel and Newton Raphson. Other methods developing from the basic algorithm are “Fast Decoupled power flow” and “DC power flow”.

Two main methods have the same procedure to come to the final result of the power flow. Both of them aim to solve for the bus voltage magnitudes V_i and the phase angles δ_i when the power generations and loads are specified.

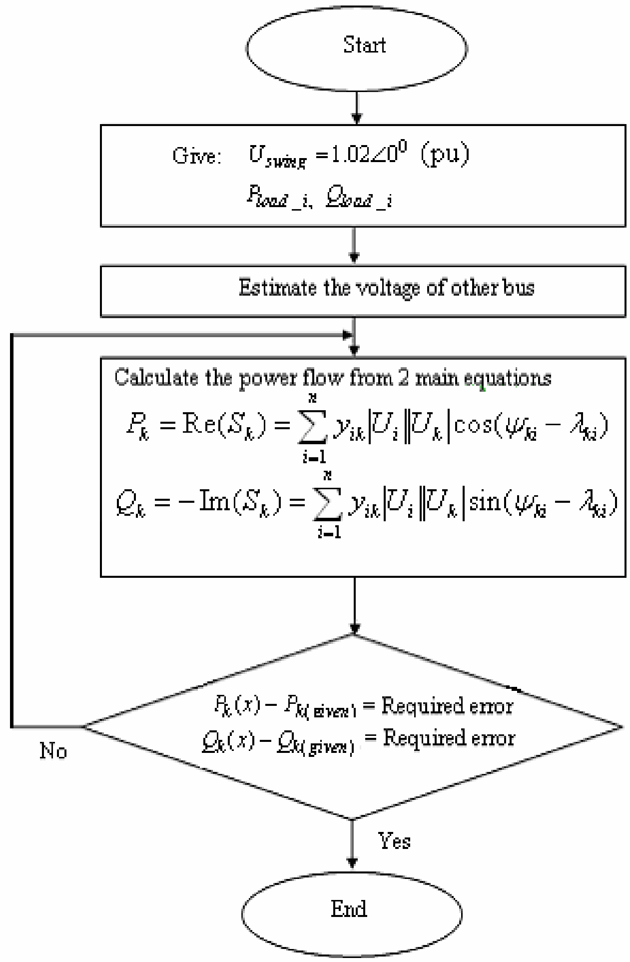

Fig 2.7: The flow of solution for the power

The Gauss-Seidel method can be tolerant of data errors, insoluble conditions in local areas of network but doesn't converge well in situations where real power transfers are close to the limits of the system.

The Newton-Raphson method is generally tolerant of power system situations when there are difficulties in transferring real power, rapid convergence on well-conditioned cases and it has small bus mismatches. It is also suitable for the network containing series capacitors. The disadvantage of the solution is that if there are complicatedness in the allocation of generator reactive power output or if the solution has a particularly bad voltage magnitude profile. The Newton- Raphson is chosen to solve the power flow in the model.

5. Result for the simulation model

The designed model uses the Power System Simulator PSS/E, software of the Siemens as the tool to calculate the power flow in the steady state. The boundary condition for the model is:

- The loads are constant power. The constant power characteristic holds the load power unchanged as long as the bus voltage exceeds the value specified by the solution parameter.
- The generators that regulate their own voltage hold their scheduled voltage as long as their reactive power limits are not violated.
- The voltage and the phase angle of the swing bus is kept constant, the active and reactive power of this bus are free variables and follow the power flow.

The simulation with the heavy load is created to test the limit of transmission level in the system. For this case, the generator at each bus is set up to the power near the maximum capacity. The detailed data for the generation and load can be seen in the first and second column of table 2.3

X-- AREA --X	FROM GENERATION	TO LOAD	SHUNT	TO BUS SHUNT	TO LINE CHARGING	NET INT	FROM LOSSES	TO NET INT DESIRED
1	597.0	2580.0	0.0	0.0	0.0	-1983.0	0.0	0.0
	395.0	520.0	-245.9	0.0	0.0	120.9	0.0	
2	3217.0	4020.0	0.0	0.0	0.0	-816.2	13.2	0.0
	1486.8	890.0	0.0	0.0	26.6	492.2	131.2	
3	3630.0	3850.0	0.0	0.0	0.0	-221.2	1.2	0.0
	1324.6	922.4	0.0	0.0	123.3	513.7	11.8	
4	1050.0	3640.0	0.0	0.0	0.0	-2620.5	30.5	0.0
	960.0	620.0	0.0	0.0	91.5	126.9	304.6	
6	2450.0	2550.0	0.0	0.0	0.0	-173.0	73.0	0.0
	968.7	680.0	0.0	0.0	473.5	212.7	549.5	
7	3950.0	2280.0	0.0	0.0	0.0	1424.2	245.8	0.0
	1317.3	476.0	0.0	0.0	557.7	-338.5	1737.5	
8	5953.8	1820.0	0.0	0.0	0.0	4041.8	92.1	0.0
	1168.0	706.0	0.0	0.0	35.1	-437.1	934.2	
9	2120.0	2030.0	0.0	0.0	0.0	32.6	57.4	0.0
	724.9	660.0	0.0	0.0	406.5	42.6	428.8	
10	4650.0	3050.0	0.0	0.0	0.0	1518.1	81.9	0.0
	469.4	438.0	-50.0	0.0	291.3	-454.5	827.2	
11	950.0	980.0	0.0	0.0	0.0	-116.5	86.5	0.0
	590.0	221.0	0.0	0.0	139.3	-374.0	882.3	
12	1550.0	2210.0	0.0	0.0	0.0	-677.4	17.4	0.0
	847.1	586.0	0.0	0.0	45.7	132.9	173.9	
13	3460.0	2800.0	0.0	0.0	0.0	659.9	0.1	0.0
	834.8	889.0	0.0	0.0	72.5	16.9	1.4	
14	4620.0	5680.0	0.0	0.0	0.0	-1068.7	8.7	0.0
	2013.6	2074.0	0.0	0.0	92.8	-54.5	86.9	

TOTALS	38197.8	37490.0	0.0	0.0	0.0	0.0	707.9	0.0
	13100.1	9682.4	-295.9	0.0	2355.7	0.0	6069.3	

Table 2.3: Buses report of the simulation model

The total load in the whole Nordic model is put to 37490 MW and the generation capacity is 38198 MW. For a system with a large number of generators like the Nordel network, there are many benefits for the interconnection between areas. Different utilities could exchange energy and share generation reserves. Individual system reliability could be enforced because of improved frequency response to the disturbance like loss of load or generation. Frequency changes for a given loss of load or generation are smaller for a large, interconnected system than the single area. The disadvantage of sharing load is frequency instability which can be caused by a large generation/demand mismatch could lead to significant frequency deviation.

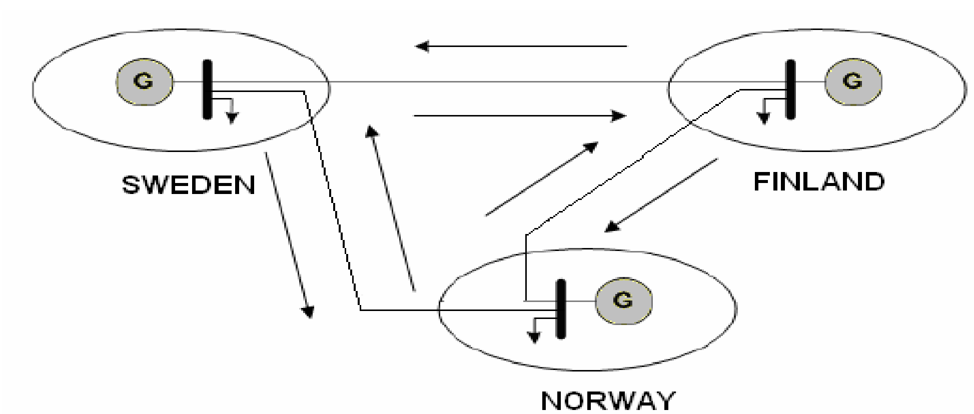

Figure 2.8: The model of power transfer between two areas through single line

The power exchange between the Nordic countries can be explained as below. Due to the consumption in Finland is higher than the production; it needs 1209 MW to fulfill the mismatch of power while Sweden generates 22967 MW and only absorbs 22770 MW. At the same time, Norway has 959 MW more than its demand. The new balance in the whole system can be achieved by equal production and consumption.

$$\sum_{i=1}^{2} P_i = \sum_{i=1}^{2} L_i \qquad (2.5)$$

The power exporting from Sweden to Finland through the connecting line is

$$P_{line\_SweFin} = P_{gen\_Fin} - P_{load\_Fin} = 12260 - 11130 = 1130 \text{ MW}$$

Where P_{gen_Fin} is the generation power of Finland, P_{load_Fin} is the load of Finland, P_{line_SweFin} is the power of the link between Sweden and Finland.

The Swedish imported power from Norway is

$$P_{line\_SweNor} = P_{gen\_Swe} - P_{load\_Swe} - P_{line\_SweFin} = 22967 - 22770 - 1130 = 933 \text{ MW}$$

Country	Generator (MW)	Load (MW)
Sweden	22967	22770
Finland	11130	12260
South of Norway	4650	3050

Table 2.4: The power situation in Sweden, Finland, Norway

The calculated active and reactive power flows into each line and bus from the PSS/E can be seen in the table 2.5, fig 2.9. They show the same result as the previous estimation. The power system delivers power to every node in the grid with the acceptable voltage and frequency. The main principle for power flow is that the total power flowing in each node is equal to the output power.

$$S_i = P_i + jQ_i = S_{generator} - S_{load} - S_{shunt} - \sum S_{branches} \quad (2.6)$$

In the perfect power flow, S_i is equal to zero. The braches losses associated with any transmission line in the simulation depends on the line resistance and the line current magnitude. As the line current values are not known at the beginning of a power-flow computation, the actual values for the line losses in the transmission network is unknown. For that reason, the power for the swing bus 8 is a free variable to satisfy the real power conserve. At the end of the solution, the power for bus 8 is determined as 5953 MW. It is an accepted generation amount because the maximum capacity in this bus is 7000 MW. The power flows from the bus 8, 7, 6 which have the high production and low consumption to the buses in the middle and south. Finland receives 1209 MW from Sweden and accommodates the heavy load in the south. The magnitude of voltage at each bus is in the allowed range.

Phase angles in some buses are quite high (larger than 30 degree) so in the practical performance of this case, there may be a dynamic problem. The voltage and angle result for each bus can be seen in fig 2.9.

This simulating method shows that it is an effective tool for monitoring and diagnostic. It can help to determine the control setting of optimal power transfer capability or achieve an acceptable voltage profile over the transmission grid. The model is also useful for avoiding unplanned outage by, for example, providing early warning of potential impending controller equipment failure and instructions for the corrective actions.

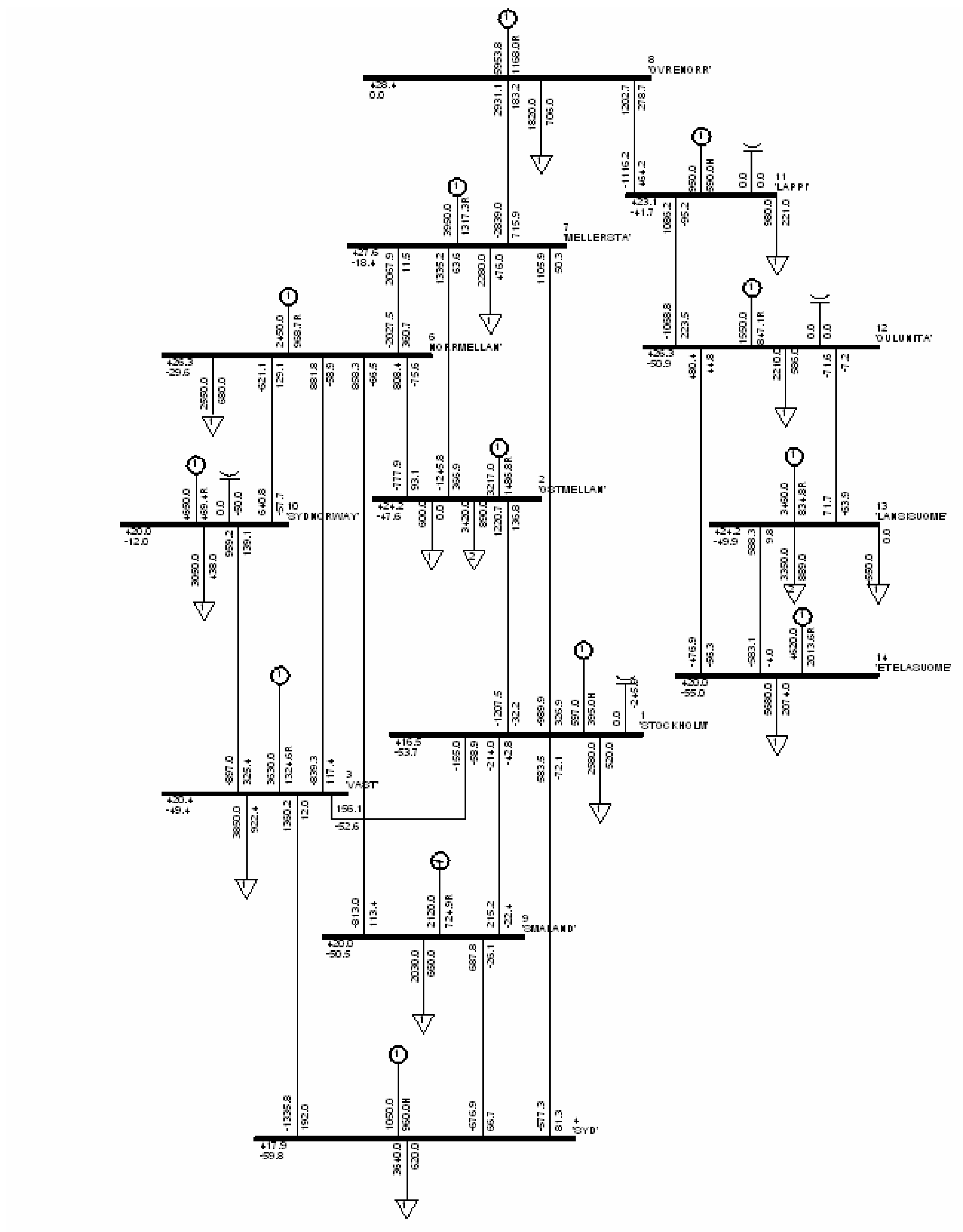

Fig 2.9: The diagram of the power flow in the simulation model

Chapter 3

Event Detection using the phasor data

The stability of the power transmission becomes more critical for the long transmission because of the high impedance in the line. Sudden change of power can lead to several reactions of the frequency, phase angle and voltage. In this chapter, the simple method using the synchronous phasor data to locate the placement of power events is represented.

1. Overview of the stability in the power system

The disturbances like the generator switch off, a line opening or part of load decreases suddenly are common events happening in the power system. The utilities and customers require that the power system must be able to cope with the problem and quickly come back to the normal state. The simple structure of the generation system to analyze the stability is as below

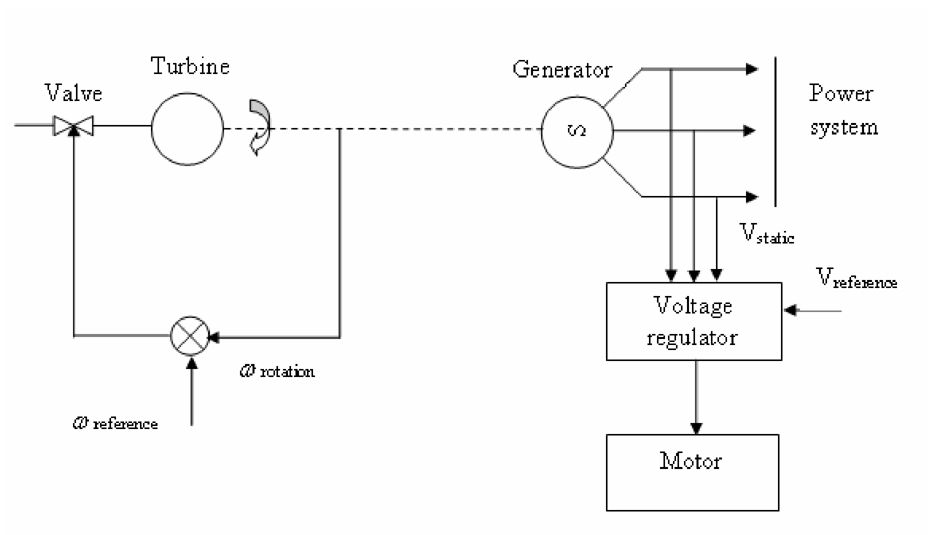

Fig 3.1: The diagram for the generator and a turbine

The output power delivered by the generator can be described in the equation

$$P_G = \mathrm{Re}(V_a I_a^*) = \mathrm{Re}(V_a \left(\frac{E_a - V_a}{Z_g}\right)^*) = \frac{|E_a||V_a|}{Z_g}\sin\delta_m \tag{3.1}$$

$$Q_G = \mathrm{Im}(V_a I_a^*) = \mathrm{Im}(V_a \left(\frac{E_a - V_a}{Z_g}\right)^*) = \frac{|V_a|(|E_a|\cos\delta_m - |V_a|)}{Z_g} \tag{3.2}$$

As seen in equation (3.1), (3.2) the power of the generator has a close relation with the angle so the effective way to monitor the power is following the deviation of phase angle.

The power swing for the generator system is expressed like

$$P_{mech} - P_{gen} = \frac{2 * S_n H}{\omega_0} \frac{d^2\delta}{dt^2} \tag{3.3}$$

δ : rotor angle.

J: The moment of inertia.

S_n: Rated apparent power of the machine

H: The inertia constant; H=$\frac{1}{2} * \frac{J\omega_0^2}{S_n}$; [H]= second

The equation (3.3) reflects the state of the power system. In the balance state, the mechanical power input is equal to the electrical power output; the angle speed w_0 is constant. Therefore, the derivation of the speed is zero.

From the variation of power in the swing equation, the adjustment for mechanical or electrical power can be determined.

2. Principles used in detecting the events.

The stability conditions for the power network are examined by a level of system loading, power transfers across the transmission interfaces, or the capacity of certain power plants. In dealing with this issue, the primary technical method based on the physical apparatus of power transmission studies the frequency response, the control of power flow to detect the placement of the power change. Research focuses on development of a simple method to test this ability by using the simulation created in the precious chapter.

The major execution involves those steps. First, the before - disturbance system is characterized by the data provided by the PMU and the information of production and consumption in the Nordpool website. Then, the frequency change is calculated from the transient behavior of the recorded signal. Because the frequency of a system is brought to stability by the regulating power (e.g. increasing or decreasing the generator's output), we can determine the power change in the system leading to such frequency deviation. This power loss is used to solve the power flow of the new situation. Finally, the phase angle variation is calculated for each bus to detect the disturbance location. Due to the rotor angles of generators have great influence on the shape of the potential energy, they are chosen as the decisive factor for the detection. For the certain amount of power change, the reaction of angle is determined. The failure bus is expected as the bus has smallest error compared with the actually measured angle in the system after the disturbance.

3. Failure models and event location.

In the electric power grid, production and consumption must be matched instantaneously and continuously. Normally, the active control systems attempt to maintain power balance by constantly adjusting kinetic energy of connected synchronous power plants. In operation, it is impossible to avoid the power change. The sudden loss of a generator or transmission line, load can instantaneously create a large imbalance between generation and load. The power system is designed to recover from this type of credible imbalance rapidly but frequency can deviate substantially. Therefore, the simultaneous measurements revealed very complex and interesting frequency excursion patterns. Every measurement point carries the area frequency information with its own local twist. The location of event center is mainly analyzed from the measurement data and is directly dealt with the frequency and phase angle deviation.

3.1 The studied case with the loss of generation.

The example of the sudden change of power in the Nordic system is studied. Frequency instability can be initiated by a large generation/demand mismatch which could lead to significant frequency deviation. The first step makes use of the synchronized real time frequency and area tie line power flow information to predict the generation deficiency.

The rate of frequency in this event is shown as figure 3.2. The factor df/dt is an indicator of power deficiency and can enable incipient recognition of the imbalance.

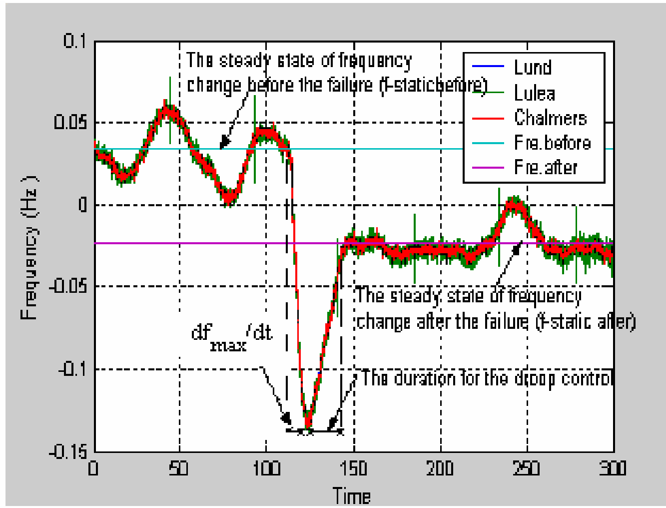

Fig 3.2: The frequency measurement of Lulea, Chalmers, Lund

The bus closest to the incident event center has the greatest change of frequency df/dt while the bus with the further distance has the smaller frequency variation. All buses have their own frequencies (a little difference from each other) and they oscillate around the virtual system inertia center. Therefore, we use area center frequency for the simulation. All the generators in the power system are assumed to run up near the synchronous speed and applied excitation and we can say that they have the uniform system frequency. This condition is only achieved in the steady state after all electromechanical oscillation has died out.

a. Analyze the event frequency.

Because the frequency drops, we predict that there is a trip of generation. A generator trip of sufficiently large capacity causes an immediate imbalance between the generation and the load. The power of the load becomes larger the power generated.

$$P_{mech} - P_{gen} = J\omega \frac{d\omega}{dt} < 0 \Rightarrow \frac{d\omega}{dt} < 0 \tag{3.5}$$

The generator turbine slows down, the rotor decelerates. The magnitude of deceleration depends upon the quantity of the power mismatch, and the inertia of the turbine-generator, the available amount of reserve generation. As a consequence, the difference in power gives the change in the rotational energy and the kinetic energy is loosened. The frequency of all the system is decreased.

As an affect of the disturbance, the grid frequency decreases significantly and very fast. After 9 second, the lowest frequency is 48.32 Hz. The level to which frequency falls prior to recovery depends upon its starting point as well as the system inertia. In this case, the frequency started at high frequency 50.034 Hz so the drop in frequency did not cause any serious subsequent events.

Due to the frequency transmission and reflection on each bus and component, the actual system frequency is the effect of the superposition of all the reflection and transmission at all the buses. The lowest frequency is far outside the tolerance range of ± 0.1Hz and occurred only for a very short time. Generator governors begin to take autonomous action to restore frequency. The frequency is then controlled to increase by the governor. The nominally operating frequency of 49.76 Hz is reached in the end.

b. Calculate of power loss

The first part of the test is based on the magnitude of frequency spectrum. Because sharp changes in grid frequency indicate imbalances between generation and load, the change in frequency is considered to be the sole input signal needed to detect the following major grid events. Instantaneously after generation trip, the lacking power for the load is supplied by all other generations attached to the grid. This is accomplished automatically by the laws of conservation of energy. The frequency decreases to the minimum value.

$$\Delta f_{\max} = f_{staticbefore} - f_{\min} = 0.167 \text{ (Hz)}$$

With speed governors, other generators are able to increase their mechanical power input and match the load. The total change of frequency before and after the disturbance can be seen as

$$\Delta f_{static} = f_{staticbefore} - f_{staticafter} = 0.057 \text{ (Hz)}$$

The deviation of frequency response to the disturbance depends much on the controller. The common method to control the frequency in the Nordic system is “droop control”. This control works in the principles that the synchronous machines’ operation is locked at system frequency (like our assumption). Droop can improve the quality of the grid due to allow less oscillation in frequency and allow load sharing between the generators, prevent one generator from trying to pick up the entire power change. However, one important disadvantage of this method is that the permanent error still exists.

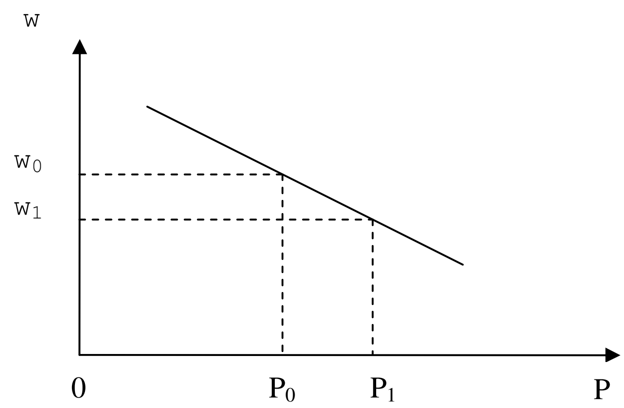

Fig 3.3: The relation between power and speed

When 12 remaining generators detect a frequency deviation, each generator changes the power by its governor control. The frequency of each generator decreases in a manner following the load-generation mismatch. The magnitude and rate change of frequency are depending on the rotor inertia constant R_i and the electrical location of the generations.

$$\Delta P_i = -\frac{\Delta f}{R_i} \tag{3.6}$$

R_i: the gain of each generator's droop regulation.

Δf : the change of the frequency before and after the disturbance $\Delta f = f_0 - f_1$

ΔP : the change of the power before and after the disturbance. $\Delta P = P_0 - P_1$

The system inertia indicates the ability of power system to oppose changes in frequency. Physically, it is loosely defined by the mass of all the synchronous rotating generators and motors connected to the system so in this thesis, R is assumed to proportional to the rate change of frequency. We calculate the frequency control gain R for this case [15].

$$R \cong \frac{\Delta f / \Delta t}{f_0} = \frac{0.057/9}{50} = 0.0001267 \tag{3.7}$$

R: total droop system gain, $\frac{1}{R} = \sum_{i=1}^{N} \frac{1}{R_i}$.

Where f_0 is the synchronous frequency of the power system.

The inertial gain depends much on the types of connected generation and the effect of frequency control system. Due to the regulated power for the Nordic system in the range of 6000 to 14000 MW/Hz, so the estimated regulating characteristic equals to the inverse of R (7892 MW/Hz) can be accepted. [16][20]

The effected power is determined as equation (3.6)

$$\Delta P_{\max} = \frac{\Delta f}{R} = \frac{0.057}{0.0001267} = 450(MW) \tag{3.8}$$

The power mismatch in the system after the failure needs to be compensated by other generators' reserving power.

c. Detect the event location.

The goal of trip production model is to estimate the power loss location that are produced or originated in each zone of a study area. Trip generation is performed by relating frequency and phase angle of trips to the characteristics of the individual bus.

Using all the collected data, we create the power simulation in the same manner with the failure case. The power condition before and after the generator trip is explored to investigate any model changes in the event. The production capacity for each bus is determined from the collected information.

Before the event, in Sweden, the nuclear power Ringhals 2 ramped down its production from 870 to 250 MW. The power plant Kvildal in Norway increased its power output from 1200 to 1900 MW. The station Aveadorevaerket in Denmark reduced 250 MW. There were also some losses of power due to the maintenance in the transmission line such as: Baltic Cable looses 260 MW; Porjus Vietas only transfers 600 in 1100 MW. The exchange power between Denmark and Germany decreases 650 MW. The total production before the disturbance is put to 27171 MW.

The consumption amount is approximately estimated by the normal demand at certain time. The failure was recorded at 7.55 a.m so for this period, there is a high consumption of power. The reason is that it is the beginning of the working day when all industrial factories or offices have the high consumption. However, in this season, the demand for heating is not as high as in the winter. All of them help to figure out that the total load of the simulation is 27170MW.

In the instant of generator trip, the generation deficiency is distributed to other remaining generators based on the electrical location of the generation respect to the bus at which the power mismatch occurs. The principle for adjusting the power generation after the trip is that Sweden and Norway have the prime responsibility for the maintaining the normal frequency when the deviation exceed 0.1 Hz because in these countries, there are a large amount of power reservation due to the high concentration of hydro generators. These generators operating at or near their maximum output capacity don't have to regulate the production. The power flows from the north of Sweden has to increase to compensate for the loss power. The load is considered as unchanged.

The model is created from all the calculated values before and after the disturbance. Because the transmission of electric power in the AC system is dependent on the phase angle separation between nodes so the next step is moving the amount of power loss to each bus in the model and calculate the change of phase angle to identify the event center.

Bus / Angle	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	22,52	21,68	23,25	25,58	21,05	18,47	**23,42**	21,84	15,65	15,65	15,65	15,65	23,76
LTU_CTH	11,04	10,33	13,37	12,39	10,03	7,29	**11,38**	11,37	4,47	4,47	4,47	4,47	10,74
LTH_CTH	11,48	11,35	9,88	13,19	11,02	11,18	**12,04**	10,47	11,18	11,18	11,18	11,18	13,02
$\sum \Delta A^2$	3,999	7,2834	17,04	6,064	11,85	43,27	**1,486**	10,59	108,47	108,5	108,5	108,5	0

Table 3.1: The phase angle between Lulea_Lund, Lulea_Chalmers, Chalmers_Lund

LTU-LTH: Phase angle between Lulea and Lund.

LTU-CTH: Phase angle between Lulea and Chalmers.

LTH-CTH: Phase angle between Lund and Chalmers

Table 3.1 describes the phase angle in each bus after the disturbance. The last row presents the difference between the calculated angle and the measured one.

$$\sum \Delta A^2 = (A^{mea}_{LTU\_LTH} - A^{cal}_{LTU\_LTH})^2 + (A^{mea}_{LTU\_CTH} - A^{cal}_{LTU\_CTH})^2 + (A^{mea}_{LTH\_CTH} - A^{cal}_{LTH\_CTH})^2 \tag{3.9}$$

The amount of phase angle deviation closely relates to the power and the path impedance as seen in equation (3.3)

$$P_G = \frac{|E_a||V_a|}{Z_g}\sin\delta_m$$

From the equation above, it can be realized that with the given power, impedance, and voltage, the phase angle can be determined. Here the E_a is chosen as the voltage of swing bus and is kept constant; V_a is the voltage of the second bus. Normally for the voltage for long line is distributed in the line and depends on the distance.

$$V(x)=\cosh(\gamma x)E_a + Z_c\sinh(\gamma x)I_a \tag{3.10}$$

The impedance is the parameter which is proportional to the line length

$$Z' = Z\frac{\sinh(\gamma l)}{\gamma l} \tag{3.11}$$

For the further place, the impedance of line is normally larger. The action of replacing the power loss in each bus can be understood in simple way that we vary the impedance value and see the reaction of the phase angle. Thus, the relation between phase angle and the distance allows us to identify the place where the power change happens. It is supposed that generator trip location should be the unit where there is a minimum angle mismatch comparing with the real measurement.

From table 3.1, the error angle of the test in bus 9 is the smallest. It means that the generation trip in this bus leads to the similar angle change. We can come to conclusion that bus 9 is the placement of the generator trip. The calculation also shows that those buses 1, 2 near bus 9 also have the smaller angle errors than the farther ones bus 6,7,10. This supports for the suggestion of the event center in this area because the shorter distance to the disturbance place is, the smaller angle error is.

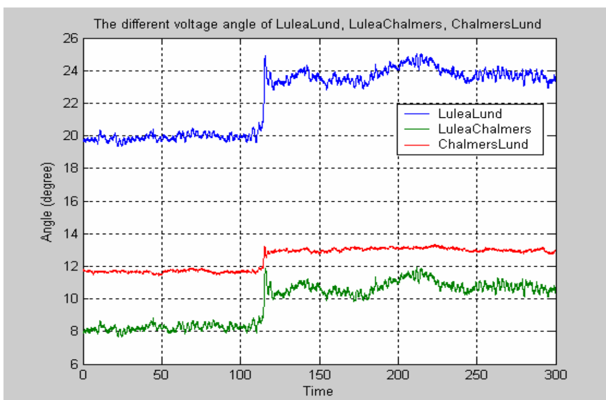

Fig 3.4: The angle measurement in Lulea, Lund, Chalmers

d. Check the reliability of locating result

Compare the result with the information provided by Nordpool, we see that on 27-04-05, at 07.55 am, there was a failure in the Oskarshamn station, the total power affected is 425 MW [17]. So the model is used again to examine the reliability of result.

Replacing the power loss 425 MW reported in Nordpool website in bus 9 of the simulation to check the detection result. We get the power flow before and after the disturbance as in table 3.2.

In this table, ΔP, ΔL, ΔV, ΔA are the differences in the calculated generator power, load power, voltage, angle phase at each bus before and after the failure.

The calculated angles in Lulea_Lund, Lulea_Chalmers of this case only increase to 10.99 and 22.99 degree. In the previous test, when the power loss is larger (450 MW compare with 425 MW), the angle has to increase much more to have a higher power output. The error between the calculated and measured data this time reduces to 1.18. It means that the power flow in the simulation comes nearer to the real value and the prediction of failure source in bus 9 is right. The phase angle change in bus 9 is 5.44^0 because in bus 9, the power transfer increases so much to balance the power. Bus 4, 3, 1 are those buses close to bus 9 so they are the direct sources of generation supply for the load of bus 9. The phase angle in these buses changes visibly.

e. Summarize the event

The power flow of the whole system can be summarized as below. Prior to the generator trip, the load in bus 9 is 1330 MW and the power provided for this bus is 1460 MW. Bus 9 is connected with bus 4, 1, 6 (Fig 3.6). When bus 9 looses 425 MW, the remaining production power at this bus is only 980 MW. Heavy power flows move northward over the ties with bus 9.

The mismatch 350 MW needs to be adjusted by other active generators. The output power from bus 4, 6, 7, 8, 10, 11 increase to compensate the required amount for bus 9. This bus absorbs more power from bus 6 (505.2 MW instead of 135.5 MW as before the disturbance) and provide less power to bus 4 (370 MW compare with 249 MW). In the relation with bus 1, from the situation of exporting power 129 MW, bus 9 changes to import 40 MW. The balance in the whole system is accounted for other remaining buses.

f. Comment of voltage

The voltage of the system is also decreased due to ramp of the power. In the area near the generation loss center, voltage drops immediately (Chalmers, Lund). In the area like Lulea, there is a delay of voltage reduction and the amount of decreased voltage is smaller than the nearby effected area. After the support of control, the voltage tends to come back the previous value.

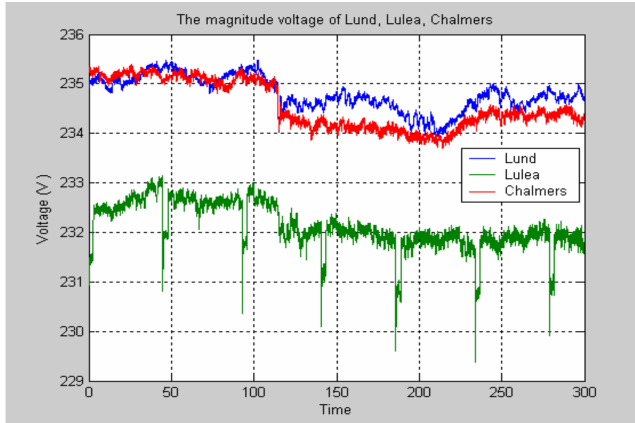

Fig 3.5: The voltage measurement in Lulea, Chalmers, Lund

Sufficient voltage is maintained by supplying the transmission system with reactive power from generating stations and static devices. In this case, when the generation trip happened, the transmission lines became more heavily loaded; they consumed more reactive power to maintain proper transmission voltage. When reactive supply is limited, the heavy loads cause a voltage drop along the line.

Reactive power does not travel over long distances at high line loadings due to significant losses on the wires. Thus, reactive power usually must be procured from suppliers near load center. The result of voltage in Fig 3.5 shows that the voltage decreases in Lund and Chalmers; it means that in these places, there is a lower reactive power compared with the situation before the disturbance. The generation trip also relates to the drop of reactive power. Our suggestion for the event location in bus 9, near Lund, Chalmers is confirmed again.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real}	Before	After	ΔA	ΔA_{real}
'STOCKHOLM'	550	550	0	1950	1950	0	1,0019	0,9999	-0,002		16,22	19,11	2,89	
'OSTMELLAN'	2300	2300	0	2550	2550	0	1,01	1,01	0		13,51	15,62	2,11	
'VAST'	2830	2830	0	2040	2040	0	1,001	1,001	**0**	**-0,003**	8,15	10,99	**2,84**	**2,49**
'SYD'	920	920	0	2460	2460	0	0,9863	0,985	**-0,001**	**-0,004**	19,23	22,99	**3,76**	**3,83**
NORRMELLAN	2050	2140	**90**	2050	2050	0	1,015	1,015	0		5,17	7,08	1,91	
'MELLERSTA'	3050	3130	**80**	1430	1430	0	1,018	1,018	0		0,09	0,68	0,59	
'OVRENORR'	3142	3242	**100**	1780	1780	0	1,02	1,02	**0**	**-0,004**	0,00	0	0,00	**0**
'SMALAND'	1460	1035	***-425***	1330	1330	0	1	1	0		14,28	19,68	5,40	
Sum of Sweden	16302	16147	**-155**	15590	15590	0			0				0,00	
SYDNORWAY	3720	3780	**60**	2720	2720	0	1	1	0		6,37	4,76	-1,61	
Sum of Norway						0			0				0,00	
'LAPPI'	620	660	**40**	920	920	0	1,0055	1,0091	0,0036		32,18	31,38	-0,80	
'OULUNITA'	880	880	0	1550	1550	0	1,015	1,015	0		42,58	41,81	-0,77	
'LANSISUOME	2680	2680	0	2750	2750	0	1,01	1,01	0		46,94	46,31	-0,63	
'ETELASUOME	3850	3850	0	4250	4250	0	1	1	0		49,48	48,8	-0,68	
Sum of Finland	8030	8070	**40**	9470	9470	0								
Total power	28052	27997	**-55**	27780	27780	0								

Table 3.2: The load flow of the failure on 27-04-05

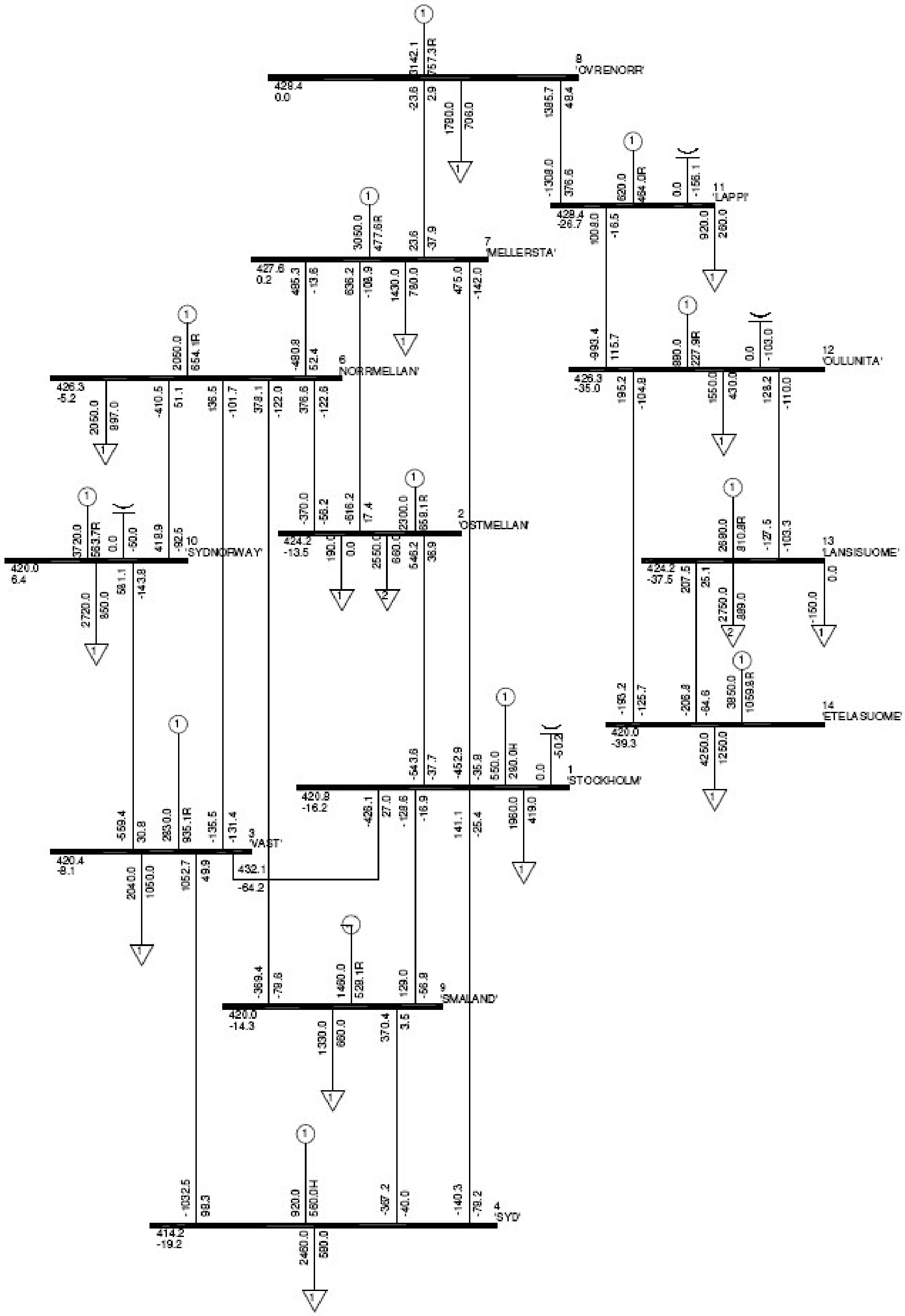

Fig 3.6 : The power flow on 27-04-05, before the generation trip.

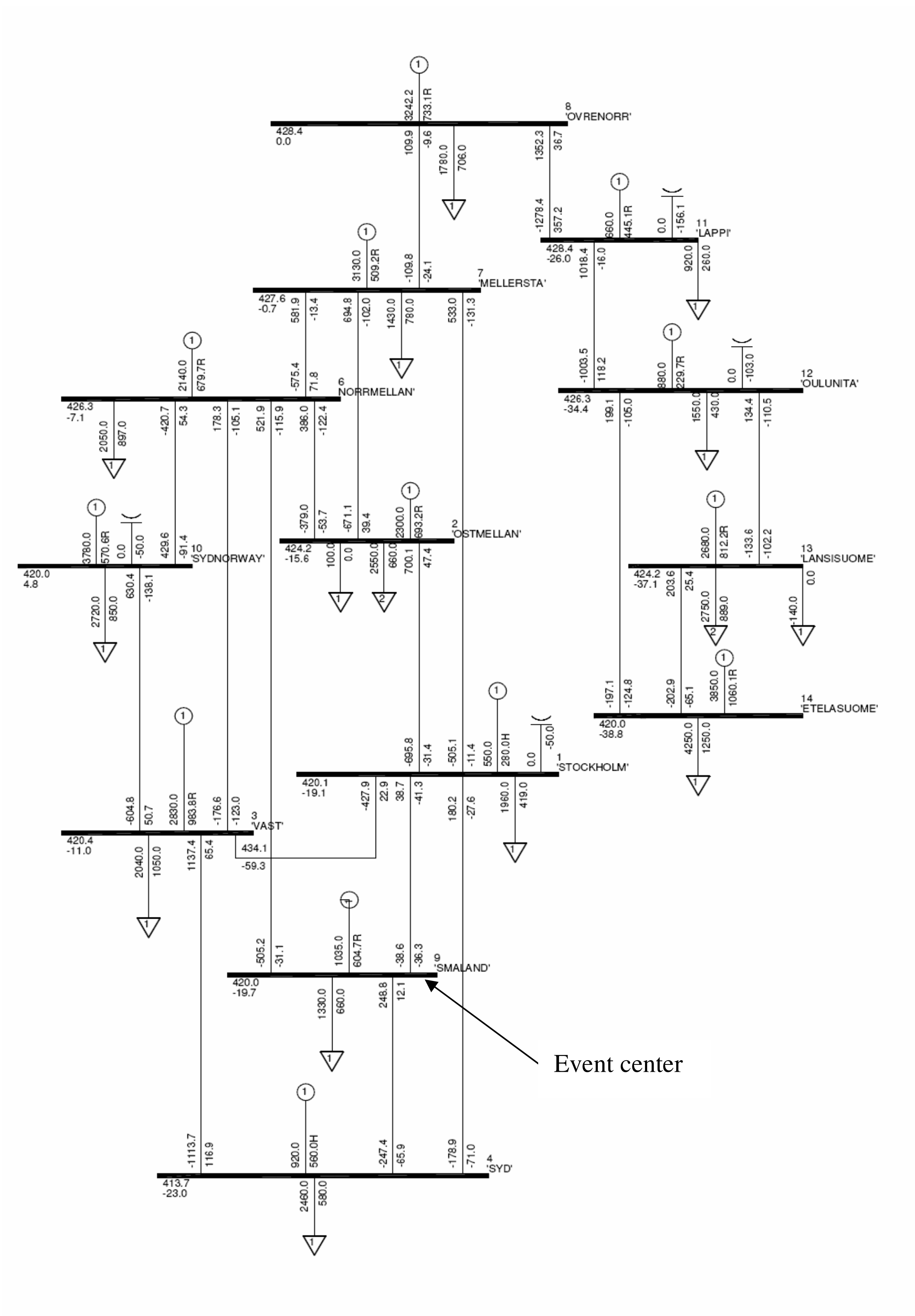

Fig 3.7: The power flow on 27-04-05, after the generator trip

3.2 The studied case with reducing load

Study another case that is recorded by the PMUs. We can see from the collecting data, the frequency increases (Fig 3.8), we predict that there is a reduction of load.

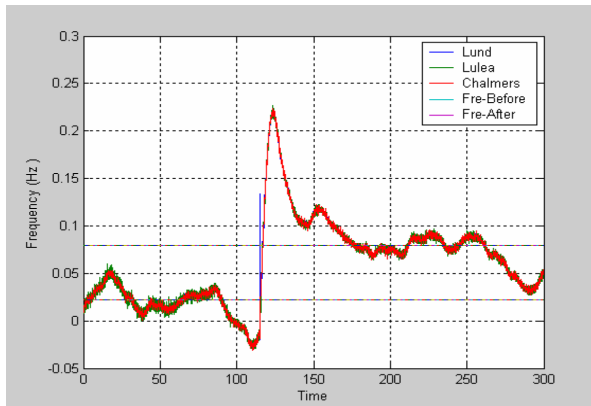

Fig 3.8: The frequency measurement in Lulea, Chalmers, Lund

a. Analyze the event frequency.

The reducing of load causes the unbalance between the mechanical power input and the electrical power output. More mechanical energy is being delivered to a generator than electrical energy removed from the electrical terminals then the excess energy will be stored in the generator's rotation (kinetic energy), resulting in acceleration of the generator. This leads to a brief over-generation, causing the grid frequency to increase. From the normal frequency as 50.021 Hz, the frequency comes quickly to the highest value of 50.24 Hz and it occurs only in a very short time. After few seconds, the frequency then dropped down to 50.082 Hz. It may be supposed that there was a decreasing of load.

b. Calculate of power loss

The same procedure to detect the event center is done as part 3.1. The overview of the power situation before and after the event is analyzed from the deviation of the frequency.

The frequency of each generator increases due to the load-generation mismatch. The rate change of frequency relates closely to the rotor inertia constant R_i and the power regulation. So in order to determine the required amount of power in need for the stability, the same function as (3.8), (3.9) are used.

The inertial gain is

$$R \cong \frac{\Delta f / \Delta t}{f_0} = \frac{0.057/12.5}{50} = 0.0000912$$

The regulation power is determined as the inverse of R which equals to 10965 MW/Hz.

The effected power is

$$\Delta P_{\max} = \frac{\Delta f}{R} = \frac{0.057}{0.0000912} = 625(MW)$$

The result is shown in table 3.3.

$\Delta f_{\max}$	Δf_{static}	$\Delta P_{\max}$	ΔP_{static}
0.22	0.057	625	50

Table 3.3: The deviation of frequency and power

The calculation shows that the large power change can lead to the large variation of frequency. Therefore, the regulation system needs a longer time to control the grid back to the safety operation range.

c. Detect the event location.

The power system's state for the Nordic grid before the disturbance is analyzed to get the necessary data for the simulated model. The production capacity of each bus before the disturbance is estimated by the information in Nordpool website. On 06-09, there was some large reduction of production in Ringhals station – Sweden - 835 MW, Porjus: 220 MW, Aros: 243 MW, Harprongnet: 440 MW. In Norway, the Kvidal station lost 310 MW, Sima reduced 310 MW. In Denmark, the Fynsvearket decreased the output power from 410 to 180 MW. The main reducing power in the south of Finland was in Louvissa 488 MW. Several yearly maintenance and failure in the connection line between area like West Coast Corridor, Kasso- Audorf, SwePol, Oresund existed. All the above data helps to figure out the total generation prior to the event was 27171 MW.

The consumption amount is approximately calculated by the time when the failure happens. It was in the early morning thus, the demands from main customers should be not so large. The total load is set up at 27170 with the detail distribution as table 3.5.

Immediately after the line trip, the flow was automatically and instantaneously redirected over several parallel lines, due to the meshing of the network. Because in this case, the load in one bus reduces its demand so the production amount is larger than the load. Using the theory of power balance, we reduce generation capacity in other buses to get the same situation as the data measured by the PMUs. The rule for controlling the power flow is that the hydro generators take responsibility to the power change. Finland is not necessary to adjust for the conditions tie line between Zealand and Sweden. After the disturbance, the total production in the system reduces 50 MW. The detection of the fault bus is tested in the simulation by moving the loss of load to each bus. The phase angle result is shown in table 3.4.

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	32,59	33,34	31,17	**28,12**	34,34	38,15	31,11	33,28	42,49	42,49	42,49	42,49	42,49
LTU_CTH	22,71	23,31	19,11	**20,52**	23,85	27,88	22,01	22,05	32,2	32,2	32,2	32,2	32,2
LTH_CTH	9,88	10,03	12,06	**7,6**	10,49	10,27	9,1	11,23	10,29	10,29	10,29	10,29	10,29
$\Sigma\Delta A^2$	30,78	41,906	31,39	**0,007**	59,28	164	13,955	42,95	353,29	353,3	353,3	353,3	353,3

Table 3.4: The phase angle for each buses when locating the bus fault

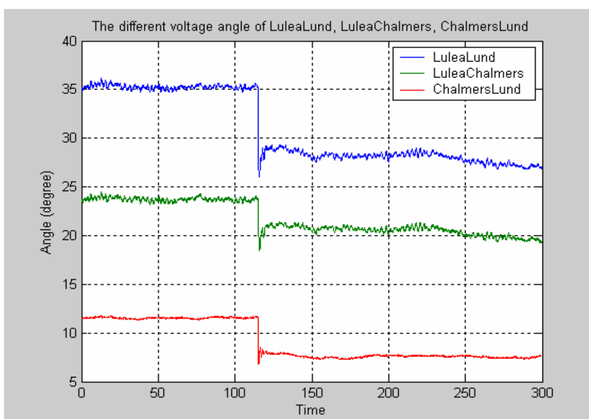

Fig 3.9: The phase angle measurement in Lulea, Chalmers, Lund

The deviation of phase angle in bus 4 is the smallest. In the neighbor buses with bus 4 (bus 9,3), the error of calculated angle change is also much less than the buses in the north of Sweden or in Finland. The phase angle change converges to zero in bus 4 proofs that the failure happened in bus 4. We check the list of failure events provided by the Nordpool to have the detail information. On 06-09-05, at 06.09 am, there was a failure in the Kontek line leading to the loss of load in the bus 4.

d. Check the reliability of locating result

Model simulation would likely be used to test the event location by the load deficit of 600 MW which is actually lost. The result from the simulation (table 3.5) shows that the angle in Lulea_Lund and Lulea Chalmers are 28.67 and 20.97 degree. The phase angle change in bus 4 comes closely to the real measurement so the confirmed event location is in Kontek (bus 4).

e. Summarize the event.

To get the better view of this case, the situation for power flow change can be analyzed as below. The load in bus 4 before the failure is 2520 MW and the power provided for this bus is 780 MW. The production in this bus is not enough for its demand so other buses which have the connection with bus 4 provide the generation for this bus. Bus 3 exports 980 MW to bus 4, the transfer generations from bus 9 and 1 are 548 and 211 (Fig 3.7). When the Kontek line is disconnected, the load center is separated with the whole Nordic grid. The load reduction of 600 MW in bus 4 leads to a regional surplus, the remaining consumption here is only 1920 MW. Therefore, its own generation capacity can provide half of the demand. The mismatch now is only 1140 MW which needs to be regulated by other active generators. Bus 4 after the disturbance receives from bus 3, 9, 1 the smaller amount of power 727 MW, 370 MW, 43 MW. The reduction of power is controlled in bus 6, 7, 8 and 10 (table 3.5). The load flow analysis showed that this reduction could keep the Nordic grid in an admissible operative condition.

From the result of the simulation, the phase angle change can be realized. The angle in bus 4 decreases dramatically to 6.92 degree. In this case, the event happens sharply in the observation of the PMU in Malmo. This supports for the truth that with the right location of the PMU, the analysis of the event is much easier. The angles in bus 1, 3, 9 which have the direct relation with bus 4 also decrease.

f. Comment of voltage

The voltage in Lund and Chalmers increased due to the trip of line. After the disturbance, the lower load consumes less reactive power so the voltage system increases. In Lulea, the voltages recorded after the tripping of the interconnected lines Kontex returned closely to their initial values because of the far distance. Lund is in the same place with the event source so the visible change can be seen in the voltage signals. The voltage in Lund increases to 235.7 KV. Following the initial grid disturbances, voltages change due to the fact that reactive power flows fluctuate.

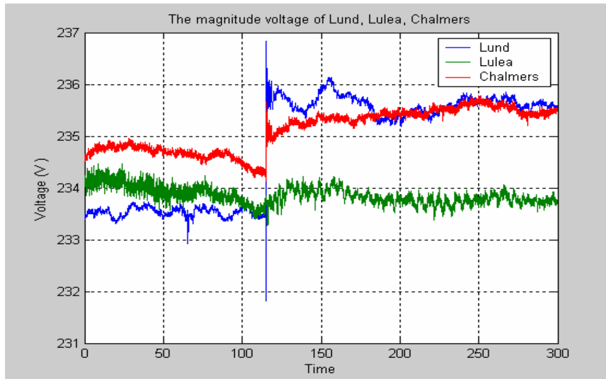

Fig 3.10: The voltage measurement in Lulea, Chalmers, Lund

In this case, the voltage increasing is not so high so it doesn't cause any damage to the whole power system. Generally, in order to limit the post-contingency voltage rise at the line trip, facilities can install an automatic reinsertion to control the reactive power.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real}	Before	After	ΔA	ΔA_{real}
'STOCKHOLM'	520	520	0	1940	1940	0	0,9996	1,0026	0,003		30,49	27,72	-2,77	0
'OSTMELLAN'	2130	2130	0	2720	2720	0	1,01	1,01	0		27,93	26,37	-1,56	0
'VAST'	2510	2510	0	2100	2100	0	1,001	1,001	**0**	**0.0038**	24,63	20,97	-3,66	**-3,28**
'SYD'	780	780	0	2520	1920	**-600**	0,9937	1,0049	**0,0112**	**0.0082**	35,11	28,67	-6,44	**-6,92**
NORRMELLAN	1950	1860	**-90**	1890	1890	0	1,015	1,015	0		17,39	15,96	-1,43	
'MELLERSTA'	2820	2680	**-140**	1390	1390	0	1,018	1,018	0		7,47	7,04	-0,43	
'OVRENORR'	3601	3432	**-169**	1490	1490	0	1,02	1,02	0	**0.0002**	0	0	**0**	**0**
'SMALAND'	1550	1550	**0**	1220	1220	0	1	1	0		27,66	23,66	-4	
Sum of Sweden	15861	15462	**-399**	15480	15480	0			0				0	
SYDNORWAY	3540	3380	**-160**	2650	2650	0	1	1	0		9,52	9,01	-0,51	
Sum of Norway						0			0				0	
'LAPPI'	620	620	0	820	820	0	1,02	1,02	0		19,31	17,38	-1,93	
'OULUNITA'	860	860	0	1450	1450	0	1,015	1,015	0		25,69	23	-2,69	
'LANSISUOME	2580	2580	0	2520	2520	0	1,01	1,01	0		25,92	22,12	-3,8	
'ETELASUOME	3710	3710	0	4250	4250	0	1	1	0		29,21	25,72	-3,49	
Sum of Finland	8450			9570	9570	0								
Total power	27171	26612	**-559**	27170	27170	**-600**								

Table 3.5: The load flow of the failure on 06-09-05

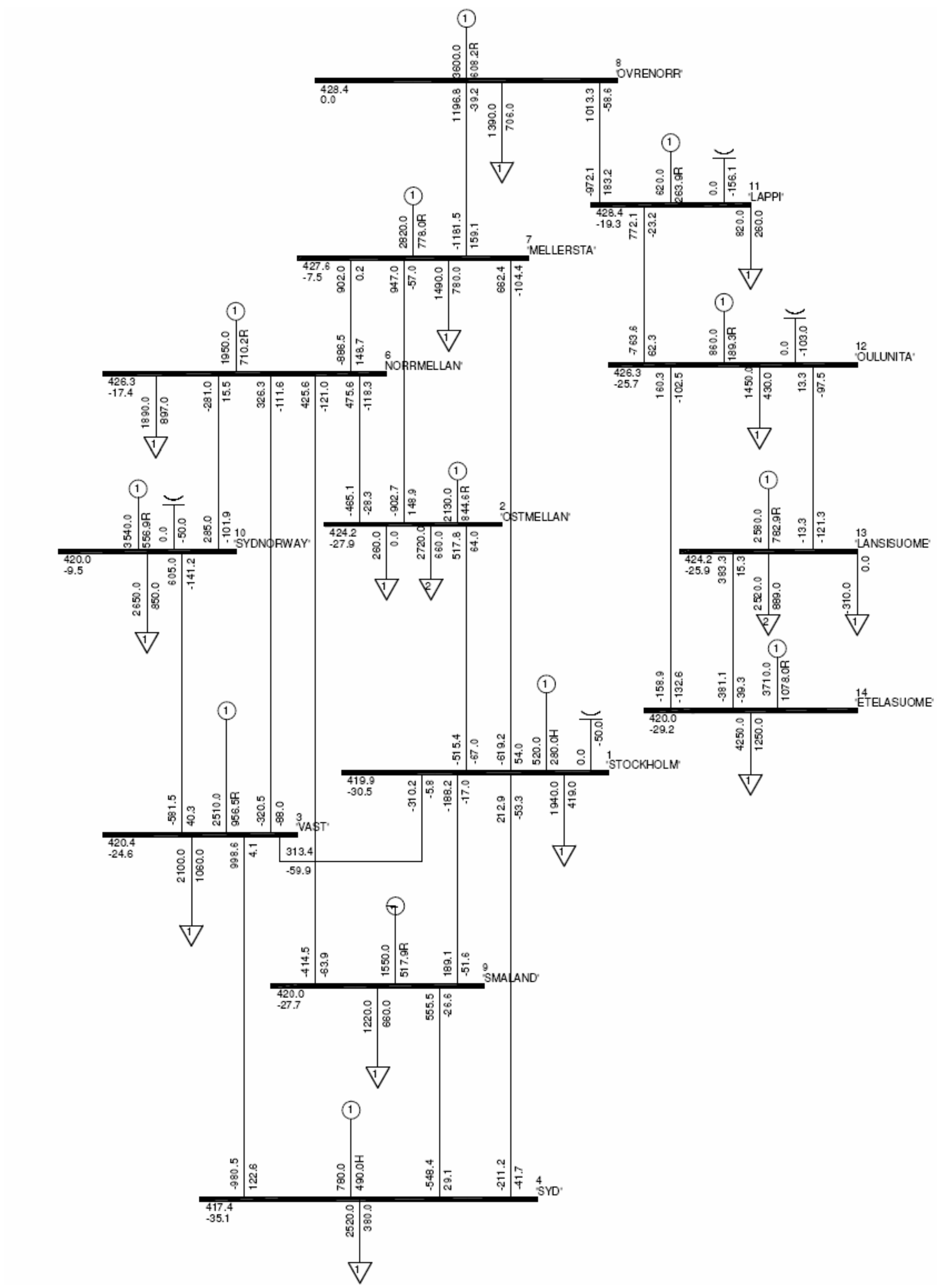

Fig3.11: The power flow on 06-09-05, before the loss of load

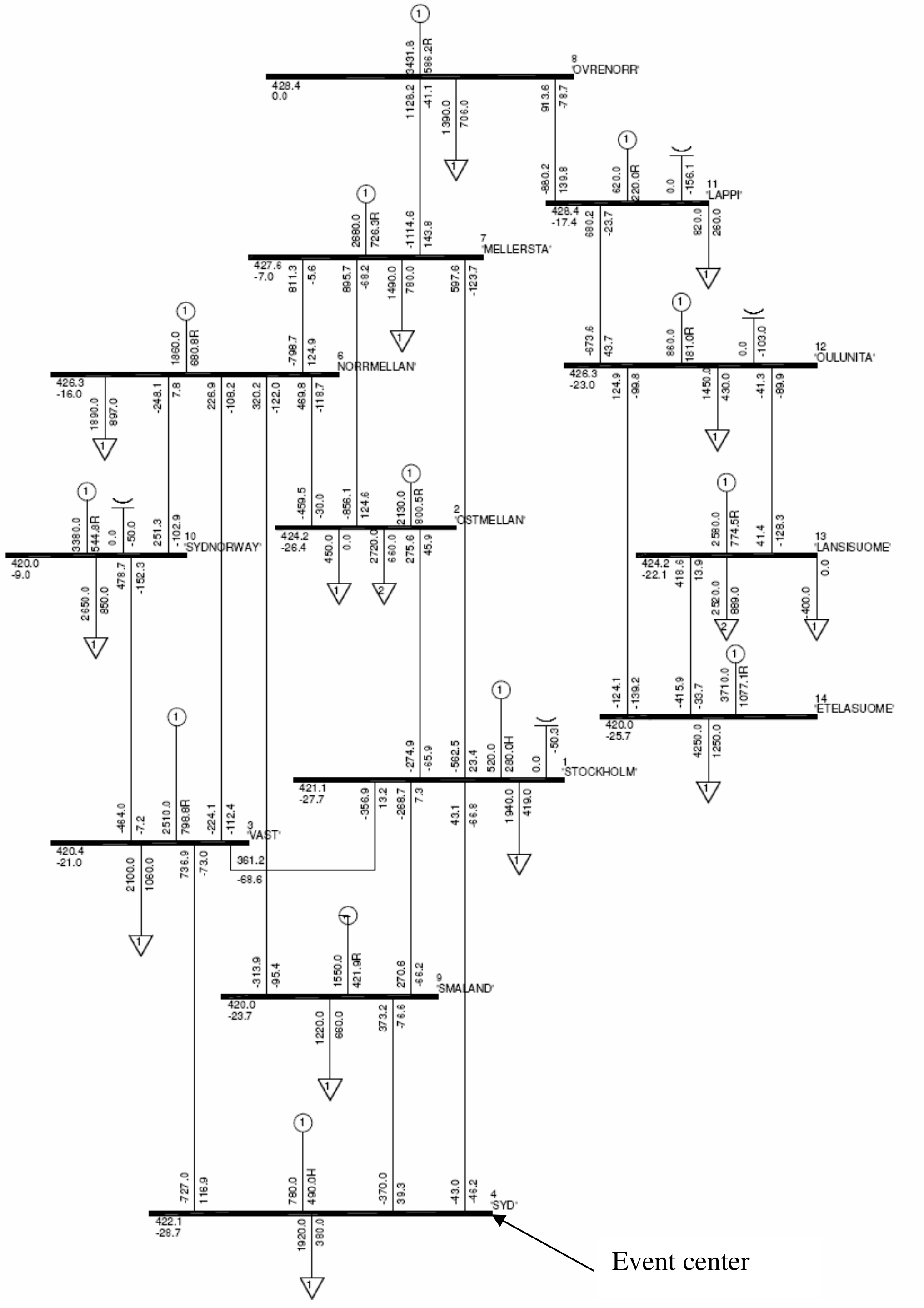

Fig3.12: The power flow on 06-09-05, after the loss of load

4. Other tested cases

The methodology is to calculate many other cases with different fault location. The result for these simulations is shown in the next pages.

4.1 Failure on 29-09-05

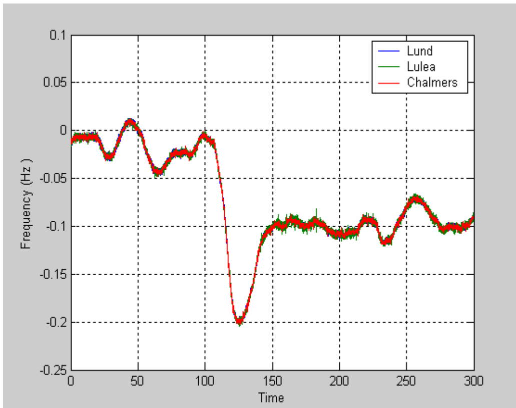

Fig 3.13: The measured frequency

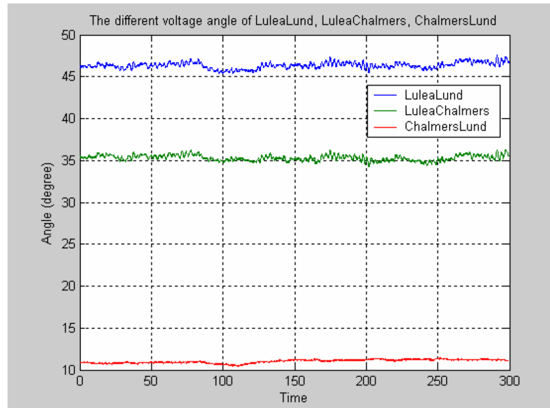

Fig 3.14: The measured angle

In this case the maximum frequency deviation is 0.1866 and the static frequency change is 0.0825. The frequency variation for this disturbance is quite large. The calculated power loss is 1200 MW. Due to this amount of power loss is larger than the capacity in bus 1, 4 so we can skip the tests in two buses. The locating procedure shows that the event center is in bus 2.

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH		**46,02**	51,63		43,82	36,4	51,56	47,1	28,83	42,49	42,49	42,49	45,2
LTU_CTH		**36,08**	45,61		34,8	26,97	39,68	39,55	19,41	32,2	32,2	32,2	35,85
LTH_CTH		**9,94**	6,02		9,02	9,43	11,88	7,55	9,42	10,29	10,29	10,29	9,35
$\Sigma\Delta A^2$		**1,0734**	147,7		3,116	156,3	61,519	20,54	538,26	21,55	21,55	21,55	3E-30

Table 3.6 The calculated phase angle in Lulea, Chalmers, Lund on 29-09

The result is checked against the information provided by Nordpool and it is reported that on 29-09-05, at 15.25, there was a failure in Formarks with the affected power 1185 MW. This is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real}	Before	After	ΔA	ΔA_{real}
'STOCKHOLM'	500	580	**80**	1950	1950	0	0,9916	0,981	-0,0106		34,44	36,61	2,17	0
'OSTMELLAN'	2520	1335	**-1185**	1780	1780	0	1,01	0,9868	-0,0232		27,79	32,02	4,23	0
'VAST'	2640	2640	0	3050	3050	0	1,001	1,001	**0**	**0.0022**	35,77	35,85	**0,08**	**0,1**
'SYD'	805	890	**85**	2980	2980	0	0,983	0,9867	**0,0037**	**0.0032**	45,45	45,79	**0,34**	**-0,3**
NORRMELLAN	2020	2430	**410**	1890	1890	0	1,015	1,015	0		21,46	20,15	-1,31	
'MELLERSTA'	3180	3500	**320**	1320	1320	0	1,018	1,018	0		7,27	6,56	-0,71	
'OVRENORR'	3320	3390	**70**	1750	1750	0	1,02	1,02	**0**	**0.0036**	0	0	**0**	**0**
'SMALAND'	1610	1610	0	1350	1350	0	1	1	0		34,66	35,35	0,69	
Sum of Sweden	16595	16375	**-220**	16070	16070	0			0				0	
SYDNORWAY	3510	3630	**120**	2750	2750	0	1	1	0		18,97	16,81	-2,16	
Sum of Norway			0			0			0				0	
'LAPPI'	620	620	0	1020	1020	0	1,02	1,02	0		15,67	19,47	3,8	
'OULUNITA'	910	910	0	1450	1450	0	1,015	1,015	0		19,77	25,08	5,31	
'LANSISUOME	2740	2790	**50**	2650	2650	0	1,01	1,01	0		17,43	24,34	6,91	
'ETELASUOME	3950	3950	0	4050	4050	0	1	1	0		21,28	27,64	6,36	
Sum of Finland	8750			9170	9170	0								
Total power	28325	28275	**-50**	27990	27990	0								

Table 3.7: The load flow of the failure on 29-09-05

4.2 Failure on 28-05-05

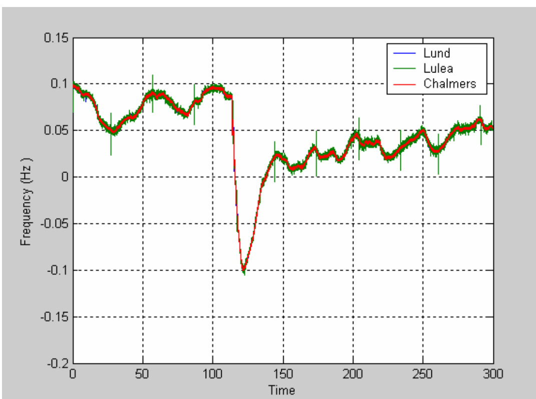

Fig 3.15: The measured frequency

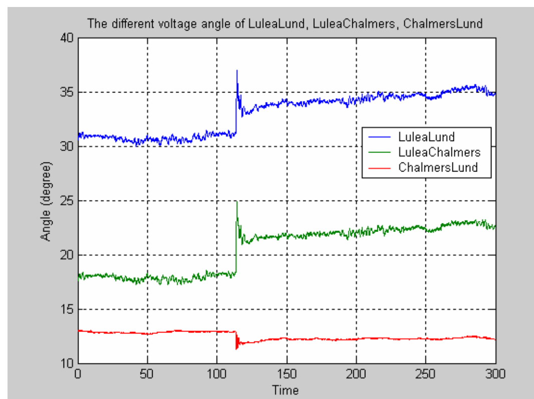

Fig 3.16: The measured angle

In this case the maximum frequency deviation is 0.178 and the static frequency change is 0.071. The calculated power loss is 775 MW. Due to this amount of power is larger than the capacity in bus 1 so we can skip the test in bus 1. The locating procedure shows that the event center is in bus 3.

Bus / Angle	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH		29,31	**31,99**	36,38	28,02	23,7	32,34	29,47	18,44	18,44	18,44	18,44	34,78
LTU_CTH		16,84	**21,93**	20,27	16,13	11,5	18,61	18,5	6,79	6,79	6,79	6,79	22,5
LTH_CTH		11,75	**10,06**	16,11	11,89	12,2	13,73	10,97	11,65	11,65	11,65	11,65	12,28
$\Sigma\Delta A^2$		62,237	**13,04**	22,2	86,43	244,9	23,188	45,91	514,2	514,2	514,2	514,2	3E-30

Table 3.8: The calculated phase angle in Lulea, Chalmers, Lund on 28-05

The result is checked against the information provided by Nordpool and it is reported that on 28-05-05, at 20.52, there was a failure in Ringhals with the affected power 840 MW. This is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real} d)	Before	After	ΔA	ΔA_{real} d)
'STOCKHOLM'	540	540	0	2080	2080	0	0,9979	0,9955	-0,0024		26,09	27,88	1,79	0
'OSTMELLAN'	2320	2320	0	2820	2820	0	1,01	1,01	0		22,99	23,73	0,74	0
'VAST'	3020	2180	**-840**	2290	2290	0	1,001	0,994	**-0,007**	**-0,002**	18,63	23,79	**5,16**	**4,7**
'SYD'	880	920	**40**	2620	2620	0	0,9833	0,9816	**-0,002**	**-0,002**	30,44	33,61	**3,17**	**3,62**
NORRMELLAN	2010	2350	**340**	1880	1880	0	1,015	1,015	0		12,63	12,41	-0,22	
'MELLERSTA'	3110	3220	**110**	1240	1240	0	1,018	1,018	0		3,36	3,21	-0,15	
'OVRENORR'	3208,3	3217	**8,7**	1520	1520	0	1,02	1,02	**0**	**0.0006**	0	0	0	**0**
'SMALAND'	1210	1210	0	1120	1120	0	1	1	0		24,61	26,33	1,72	
Sum of Sweden	16298	15957	**-341**	15570	15570				0				0	
SYDNORWAY	3580	3870	**290**	2770	2770	0	1	1	0		5,15	3,89	-1,26	
Sum of Norway						0			0				0	
'LAPPI'	750	750	0	720	720	0	1,02	1,02	0		22,74	23,43	0,69	
'OULUNITA'	920	920	0	1740	1740	0	1,015	1,015	0		32,35	33,3	0,95	
'LANSISUOME	2020	2020	0	2360	2360	0	1,01	1,01	0		35,82	37,14	1,32	
'ETELASUOME	4060	4060	**0**	4290	4290	0	1	1	0		35,61	36,83	1,22	
Sum of Finland	7750	7750		9110	9110	0								
Total power	27628	27577	**-51,3**	27450	27450	**0**								

Table 3.9: The load flow of the failure on 28-05-05

4.3 Failure on 25-03-05

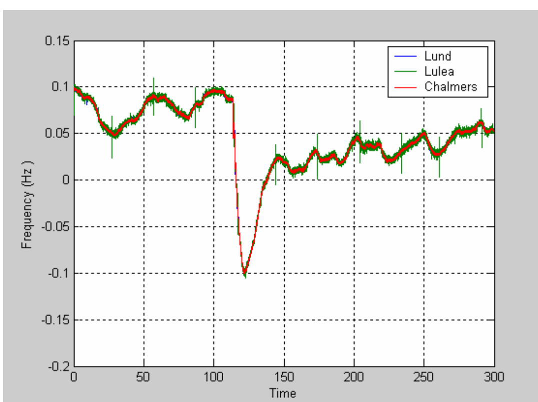

Fig 3.17: The measured frequency

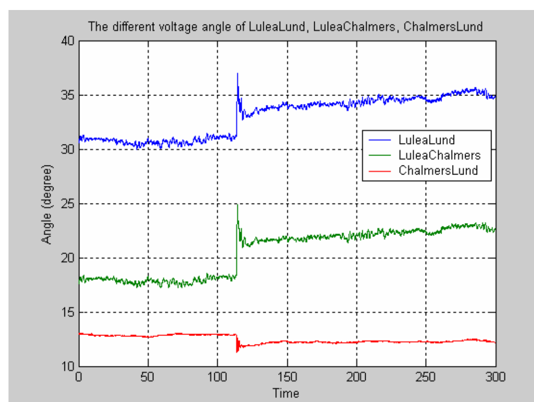

Fig 3.18: The measured angle

In this case the maximum frequency deviation is 0.107 and the static frequency change is 0.031. The calculated power loss is 350 MW. The locating procedure shows that the event center is in bus 4.

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	29,22	23,76	29,87	**31,54**	28,08	26	29,9	28,81	23,76	18,44	18,44	18,44	30,82
LTU_CTH	22,29	17,05	24,16	**23,31**	21,5	19,3	22,53	22,65	17,05	6,79	6,79	6,79	22,58
LTH_CTH	6,93	6,71	5,71	**8,23**	6,58	6,71	7,37	6,16	6,71	11,65	11,65	11,65	8,24
$\Sigma\Delta A^2$	4,36	82,765	9,8	**1,051**	11,43	36,72	1,6058	8,371	82,765	414,2	414,2	414,2	3E-30

Table 3.10: The calculated phase angle in Lulea, Chalmers, Lund on 25-03

The result is checked against the information provided by Nordpool and it shows that on 25-03-05, at 14.48, there was a failure in Anavaerket with the affected power 300 MW. This location is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real}	Before	After	ΔA	ΔA_{real}
'STOCKHOLM'	520	520	0	2080	2080	0	1,0007	0,9979	-0,0028		23,82	26,24	2,42	0
'OSTMELLAN'	2250	2250	0	2210	2210	0	1,01	1,01	0		20,15	21,97	1,82	0
'VAST'	2580	2580	0	2420	2420	0	1,001	1,001	**0**	**-0,002**	19,46	22,41	**2,95**	**2,82**
'SYD'	940	640	**-300**	2020	2020	0	0,9922	0,9805	**-0,012**	**-0,005**	26,11	30,42	**4,31**	**4,14**
NORRMELLAN	1950	1980	**30**	2150	2150	0	1,015	1,015	0		13,65	15,39	1,74	
'MELLERSTA'	3040	3090	**50**	1430	1430	0	1,018	1,018	0		3,86	4,66	0,8	
'OVRENORR'	3515	3654	**139**	1640	1640	0	1,02	1,02	0	**2E-04**	0	0	0	**0**
'SMALAND'	1520	1520	0	1330	1330	0	1	1	0		21,44	24,49	3,05	
Sum of Sweden	16489	16411	**-81**	15540	15540	0			0				0	
	3420	3470	**50**	2750	2750	0	1	1	0		7,9	9,62	1,72	
Sum of Norway						0			0				0	
'LAPPI'	620	620	0	920	920	0	1,02	1,0163	-0,0035		24,09	24,32	0,23	
'OULUNITA'	860	860	0	1550	1550	0	1,015	1,015	0		31,47	31,78	0,31	
'LANSISUOME	2640	2640	0	2750	2750	0	1,01	1,01	0		32,51	32,85	0,34	
'ETELASUOME	3950	3950	0	4320	4320	0	1	1	0		34,5	34,9	0,4	
Sum of Finland	8370			9670	9670	0								
Total power	27979	27951	**-31**	27830	27830	**0**								

Table 3.11: The load flow of the failure on 25-03-05

4.4 Failure on 31-05-05

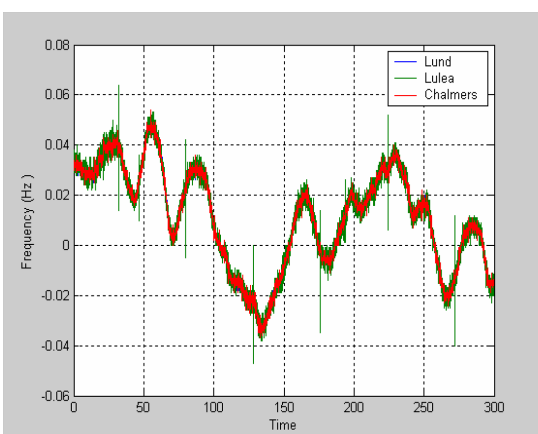

Fig 3.19: The measured frequency

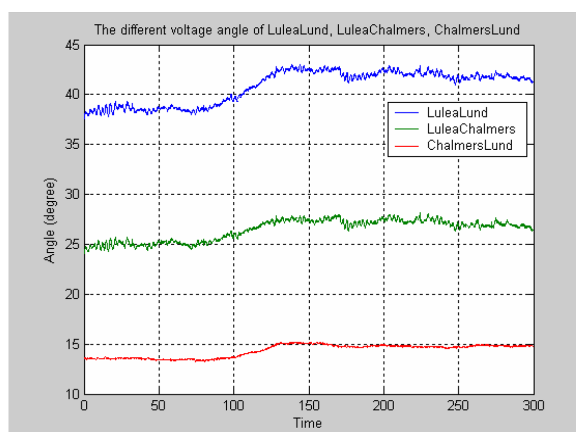

Fig 3.20: The measured angle

In this case the maximum frequency deviation is 0.698 and the static frequency change is 0.042. The calculated power loss is 500 MW. The locating procedure shows that the event center is in bus 4.

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	37,62	36,51	38,51	**41,5**	35,41	32,5	38,63	36,27	29,38	18,44	18,44	18,44	41,99
LTU_CTH	24,95	24,07	27,66	**26,57**	23,54	20,3	25,33	25,01	17,2	6,79	6,79	6,79	27,18
LTH_CTH	11,75	11,75	10,85	**14,93**	11,87	12,2	13,3	11,26	12,18	11,65	11,65	11,65	14,81
$\Sigma\Delta A^2$	33,43	49,066	28,02	**0,627**	65,19	143,4	16,992	50,03	265,53	980,3	980,3	980,3	3E-30

Table 3.12: The calculated phase angle in Lulea, Chalmers, Lund on 31-05

The result is checked against the information provided by Nordpool and it shows that on 31-05-05, at 07.16, there was a failure in Avedorevaerket with the affected power 540 MW. This location is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real}	Before	After	ΔA	ΔA_{real}
'STOCKHOLM'	540	540	0	2180	2180	0	0,9917	0,9818	-0,0099		31,44	32,33	0,89	0
'OSTMELLAN'	2320	2320	0	2790	2790	0	1,01	1,01			27,38	26,91	-0,47	0
'VAST'	2250	2250	0	2090	2090	0	0,9874	0,9629	-0,0245	**-0,004**	25,65	27,35	**1,7**	**2,2**
'SYD'	850	310	**-540**	2810	2810	0	0,9745	0,9461	-0,0284	**-0,004**	37,76	42,51	**4,75**	**3,72**
NORRMELLAN	2110	2290	**180**	1880	1880	0	1,015	1,015	0		15,28	14,72	-0,56	
'MELLERSTA'	3460	3610	**150**	1270	1270	0	1,018	1,018	0		4,18	3,55	-0,63	
'OVRENORR'	3599,3	3662,4	**63,1**	1820	1820	0	1,02	1,02	0	**-1E-04**	0	0	0	**0**
'SMALAND'	1310	1310	0	1210	1210	0	1	1	0		29,94	31,9	1,96	
Sum of Sweden	16439	16292,4	**-147**	15540	15540	0			0				0	
SYDNORWAY	4050	4150	**100**	2770	2770	0	1	1	0		3,82	2,84	-0,98	
Sum of Norway						0			0				0	
'LAPPI'	750	750	0	720	720	0	1,02	1,0108	-0,0092		21,19	29,26	8,07	
'OULUNITA'	920	920	0	1640	1640	0	1,015	1,015	0		30,2	41,37	11,17	
'LANSISUOME	2020	2020	0	2480	2480	0	1,01	1,01	0		34,15	47,91	13,76	
'ETELASUOME	4110	4110	0	4210	4210	0	1	1	0		33,61	47,18	13,57	
Sum of Finland	7800			9050	9050	0								
Total power	28289	28242,4	**-46,9**	27360	27360	**0**								

Table 3.13: The load flow of the failure on 31-05-05

4.5 Failure on 02-03-05

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	35,29	34,31	36,56	**39,3**	32,82	30,1	36,51	34,53	26,22	26,22	26,22	26,22	38,57
LTU_CTH	27,54	26,71	30,74	**29,46**	25,59	22,7	28,07	27,97	19,22	19,22	19,22	19,22	29,65
LTH_CTH	11,75	11,75	5,82	**9,84**	7,23	7,39	8,44	6,56	7	7	7	7	8,92
$\Sigma\Delta A^2$	23,22	34,8	14,84	**1,415**	52,4	123,2	6,9704	24,71	264,99	265	265	265	3E-30

Table 3.14: The calculated phase angle in Lulea, Chalmers, Lund on 02-03

In this case the maximum frequency deviation is 0.764 and the static frequency is 0.062. The calculated power loss is 550 MW. The locating procedure shows that the event center is in bus 4.

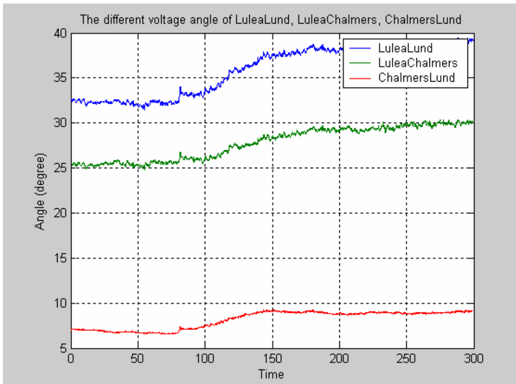

Fig 3.22: The measured angle

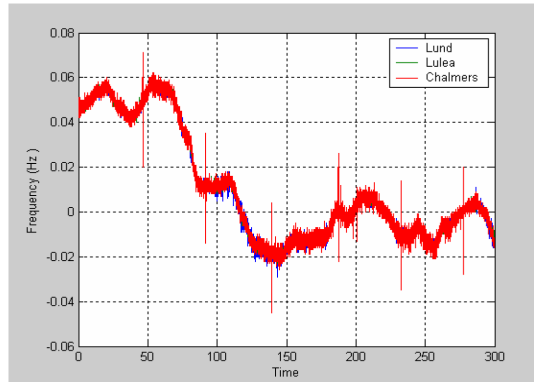

Fig 3.21: The measured frequency

The result is checked against the information provided by Nordpool and it shows that on 02-03-05, at 20.52, there was a failure in Avedoraeverket with the affected power 540 MW. This location is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{real}	Before	After	ΔA	ΔA_{real}
'STOCKHOLM'	540	540	0	2180	2180	0	0,996	0,9912	-0,0048		27,43	30,6	3,17	0
'OSTMELLAN'	2530	2530	0	2600	2600	0	1,01	1,01			22,57	24,85	2,28	0
'VAST'	2120	2120	0	2480	2480	0	1,001	1,001	0	**-0,004**	25,36	29,26	3,9	**4,13**
'SYD'	900	360	**-540**	2360	2360	0	0,9849	0,9729	-0,012	**-0,003**	32,59	39,06	6,47	**6,23**
NORRMELLAN	1950	2250	**300**	2150	2150	0	1,015	1,015	0		15,23	16,17	0,94	
'MELLERSTA'	3720	3880	**160**	1480	1480	0	1,018	1,018	0		3	3,35	0,35	
'OVRENORR'	3926	3934	**8**	1940	1940	0	1,02	1,02	0	**-2E-04**	0	0	0	**0**
'SMALAND'	1620	1620	0	1320	1320	0	1	1	0		25,18	29,21	4,03	
Sum of Sweden	17306	17234	**-72**	15540	15540	0			0				0	
SYDNORWAY	4040	4090	**50**	2970	2970	0	1	1	0		6,5	8,32	1,82	
Sum of Norway						0			0				0	
'LAPPI'	620	620	0	920	920	0	0,9873	0,9873	0		35,65	28,21	-7,44	
'OULUNITA'	860	860	0	1550	1550	0	1,015	1,015	0		47,28	37,14	-10,14	
'LANSISUOME	2640	2640	0	2650	2650	0	1,01	1,01	0		52,77	39,85	-12,92	
'ETELASUOME	3950	3950	0	4450	4450	0	1	1	0		55	42,2	-12,8	
Sum of Finland	8070			9570	9570	0								
Total power	29416	29394	**-22**	28080	28080	**0**								

Table 3.15: The load flow of the failure on 02-03-05

4.6 Failure on 08-01-05

In this case the maximum frequency deviation is 0.233 and the static frequency is 0.059. The calculated power loss is 800 MW. The locating procedure shows that the event center is in bus 3.

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH		42,17	**46,07**	41,29		36,55	45,9	42,88	31,65	31,65	31,65	31,65	48,58
LTU_CTH		32,12	**37,95**	31,32		26,33	34,2	33,82	21,43	21,43	21,43	21,43	40,28
LTH_CTH		11,75	**8,12**	9,97		10,22	11,7	9,06	10,22	10,22	10,22	10,22	8,3
$\Sigma\Delta A^2$		119,58	**11,76**	136,2		343	55,709	74,8	645,63	645,6	645,6	645,6	1E-29

Table 3.16: The calculated phase angle in Lulea, Chalmers, Lund on 08-01

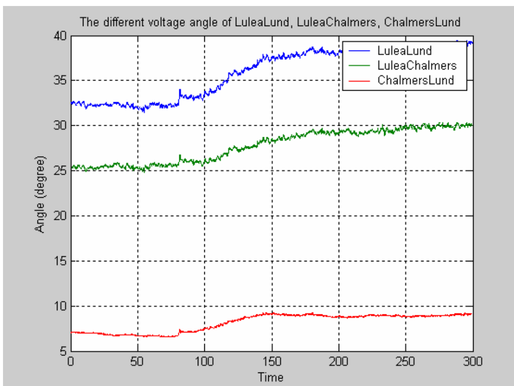

Fig 3.23: The measured frequency

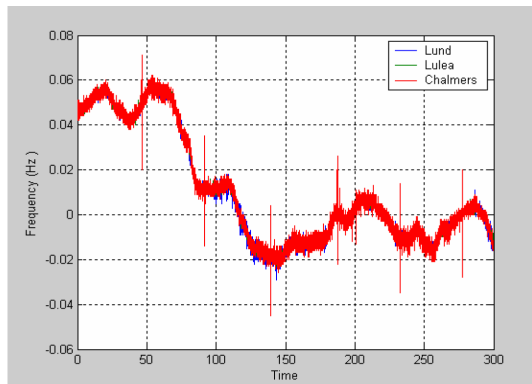

Fig 3.24: The measured angle

The result is checked against the information provided by Nordpool and it shows that on 08-01-05, at 19.41, there was a failure in Ringhals with the affected power 870 MW. This location is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{mea}	Before	After	ΔA	ΔA_{mea}
'STOCKHOLM'	500	500	0	2050	2050	0	0,9941	0,9892	-0,0049		33,73	37,94	4,21	0
'OSTMELLAN'	2650	2650	0	2620	2620	0	1,01	1,01	0		28,53	31,64	3,11	0
'VAST'	2420	1550	**-870**	2660	2660	0	0,9894	0,9866	-0,0028	**-0,001**	31,94	40,06	8,12	**7,62**
'SYD'	600	600	0	2580	2580	0	0,9975	0,9949	-0,0026	**-0,001**	41,89	47,94	6,05	**5,84**
NORRMELLAN	1970	2380	**410**	1850	1850	0	1,015	1,015	0			21,03	21,03	
'MELLERSTA'	3200	3410	**210**	1320	1320	0	1,018	1,018	0		6,7	7,26	0,56	
'OVRENORR'	3888	3910	**33**	1850	1850	0	1,02	1,02	0	**-1E-04**	0	0	0	**0**
'SMALAND'	1420	1420	0	1140	1140	0	1	1	0		32,41	36,82	4,41	
Sum of Sweden	16648	16420	**-228**	15540	15540	0			0				0	
SYDNORWAY	3960	4170	**210**	2950	2950	0	1	1	0		12,69	14,79	2,1	
Sum of Norway						0			0				0	
'LAPPI'	720	720	0	820	820	0	1,02	1,02	0		44,28	41,75	-2,53	
'OULUNITA'	960	960	0	1740	1740	0	1,015	1,015	0		62,41	58,91	-3,5	
'LANSISUOME	2820	2820	0	2860	2860	0	1,01	1,01	0		71,54	67,26	-4,28	
'ETELASUOME	4080	4080	0	4690	4690	0	1	1	0		76,38	72,27	-4,11	
Sum of Finland	8580	8580	0	10110	10110	0								
Total power	29188	29170	**-18**	28600	28600	**0**								

Table 3.17: The load flow of the failure on 02-03-05

4.7 Failure on 15-09-05

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	31,1	30,52	31,58	33,17	29,99	28,23	**31,68**	30,45	26,34	26,34	26,34	26,34	31,17
LTU_CTH	18,09	18,09	20,14	19,51	17,79	15,92	**18,79**	18,6	14,03	14,03	14,03	14,03	18,19
LTH_CTH	11,75	12,43	11,44	13,66	12,2	12,31	**12,89**	11,85	12,31	12,31	12,31	12,31	12,98
$\Sigma\Delta A^2$	1,784	0,855	6,66	6,079	2,327	14,39	**0,6562**	2,199	41,227	41,23	41,23	41,23	0,01

Table 3.18: The calculated phase angle in Lulea, Chalmers, Lund on 15-09

In this case the maximum frequency deviation is 0.2061 and the static frequency is 0.0832. The calculated power loss is 300 MW. The locating procedure shows that the event center is in bus 9.

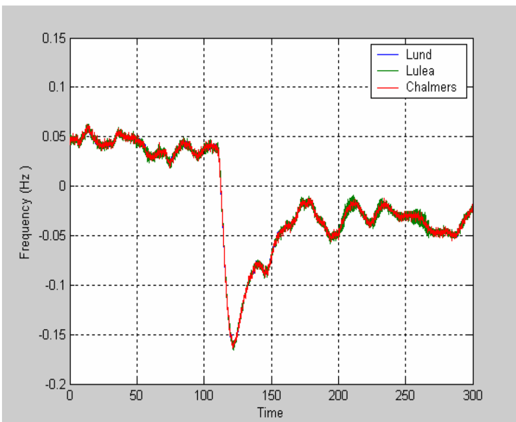

Fig 3.25: The measured frequency

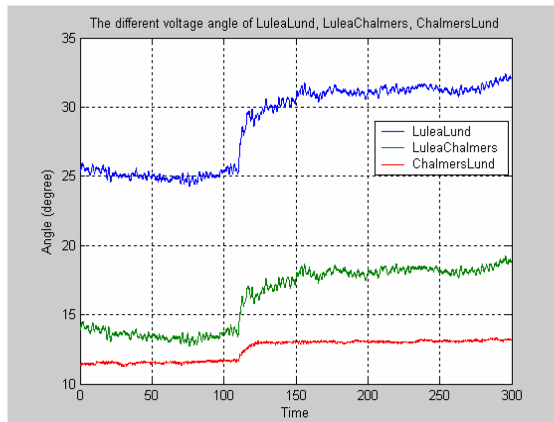

Fig 3.26: The measured angle

The result is checked against the information provided by Nordpool and it shows that on 15-09-05, at 15.41, there was a failure in Oskarhamn with the affected power 245 MW. This location is the same as the calculated event place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{mea}	Before	After	ΔA	ΔA_{mea}
'STOCKHOLM'	580	580	0	2150	2150	0	0,9992	0,9979	-0,0013		20,9	25,81	4,91	0
'OSTMELLAN'	2610	2610	0	2810	2810	0	1,01	1,01	0		17,51	22,39	4,88	0
'VAST'	2490	2490	0	2020	2020	0	1,001	1,001	0	**-0,006**	13,26	17,91	4,65	**4,34**
'SYD'	890	890	**0**	2730	2730	0	0,9907	0,9923	0,0016	**-0,002**	25,46	30,69	5,23	**5,82**
NORRMELLAN	2080	2190	**110**	1890	1890	0	1,015	1,015	0		6,67	10,19	3,52	
'MELLERSTA'	3580	3630	**50**	1700	1700	0	1,018	1,018	0		0,43	2,38	1,95	
'OVRENORR'	3121	3173	**52**	1750	1750	0	1,02	1,02	0		0	0	0	0
'SMALAND'	1510	1265	***-245***	1350	1350	0	1	1	0		18,74	24,87	6,13	
Sum of Sweden	16861	16828	**-33**	15540	15540	0			0				0	
SYDNORWAY	4210	4210	0	2820	2820	0	1	1	0		-8,13	-4,01	4,12	
Sum of Norway						0			0				0	
'LAPPI'	620	620	0	1020	1020	0	1,016	1,016	0		25,04	19,87	-5,17	
'OULUNITA'	960	960	0	1350	1350	0	1,015	1,015	0		31,94	24,81	-7,13	
'LANSISUOME	2720	2720	0	2950	2950	0	1,01	1,01	0		35,42	24,45	-10,97	
'ETELASUOME	4020	4020	**0**	4550	4550	0	1	1	0		37,75	28,56	-9,19	
Sum of Finland	8320			9870	9870	0								
Total power	29391	29358	**-33**	28230	28230	**0**								

Table 3.19: The load flow of the failure on 15-09-05

4.8 Failure on 29-04-05

In this case the maximum frequency deviation is 0.148 and the static frequency is 0.052. The calculated power loss is 350 MW. The locating procedure shows that the event center is in bus 6.

Angle \ Bus	1	2	3	4	6	7	9	10	11	12	13	14	A_mea
LTU_LTH	30,27	29,61	30,72	32,61	**29,05**	26,93	30,94	***29,73***	24,72	24,72	24,72	24,72	27,27
LTU_CTH	17,47	16,91	19,19	18,46	**16,63**	14,38	17,7	***17,74***	12,17	12,17	12,17	12,17	17,06
LTH_CTH	11,75	12,7	11,53	14,15	**12,42**	12,55	13,24	***11,99***	12,55	12,55	12,55	12,55	10,21
$\sum \Delta A^2$	11,6	11,798	18,24	46,16	**8,326**	12,87	23,181	***9,754***	35,984	35,98	35,98	35,98	4E-04

Table 3.20: The calculated phase angle in Lulea, Chalmers, Lund on 29-04

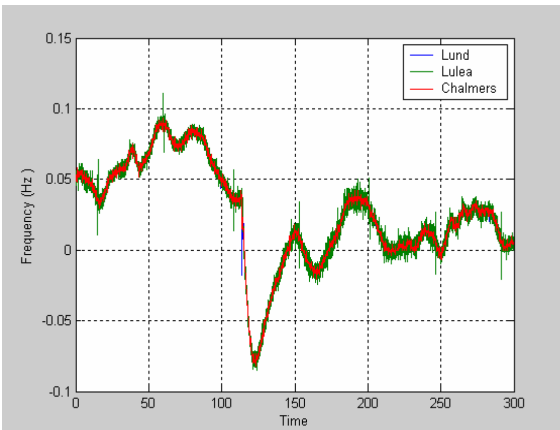

Fig 3.27: The measured frequency

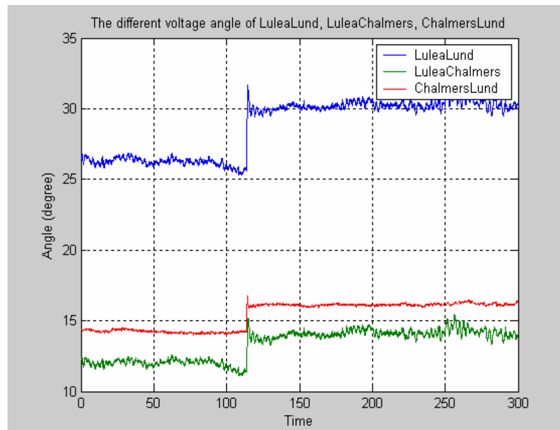

Fig 3.28: The measured angle

The result is checked against the information provided by Nordpool and it shows that on 29-04-05, at 15.41, there was a failure in Sima with the affected power 250 MW. The event center is 2 buses away from the calculating location. The error is due to the reason that the power loss used in the locating test is much larger than the real amount. This leads to the error in angle and then the wrong place.

Bus	Generation (MW)			Load (MW)			Voltage (kV)				Angle (degree)			
	Before	After	ΔP	Before	After	ΔL	Before	After	ΔV	ΔV_{mea}	Before	After	ΔA	ΔA_{mea}
'STOCKHOLM'	480	480	0	2450	2450	0	0,9979	0,9985	0,0006		24,68	27,09	2,41	0
'OSTMELLAN'	2210	2210	0	2620	2620	0	1,01	1,01	0		21,52	23,94	2,42	0
'VAST'	3380	3380	0	2000	2000	0	1,001	1,001	**0**	**0,016**	13,04	16,13	3,09	**3,81**
'SYD'	870	870	0	2310	2310	0	0,9726	0,9818	**0,0092**	**0,004**	25,39	28,28	2,89	**2,11**
NORRMELLAN	1920	1920	0	2150	2150	0	1,015	1,015	0		12,17	14,69	2,52	
'MELLERSTA'	3060	3140	**80**	1290	1290	0	1,018	1,018	0		3,21	4,29	1,08	
'OVRENORR'	3199,7	3339,56	**139,9**	1640	1640	0	1,02	1,02	0		0	0	0	
'SMALAND'	1320	1320	0	1260	1260	0	1	1	0		21,88	24,62	2,74	
Sum of Sweden	16440	16659,6	**219,9**	15920		0			0				0	
SYDNORWAY	3420	3170	**-250**	2750	2750	0	1	1	0		3,83	8,6	4,77	
Sum of Norway						0			0				0	
'LAPPI'	780	780	0	920	920	0	1,02	1,02	0		19,93	19,28	-0,65	
'OULUNITA'	860	860	0	1550	1550	0	1,015	1,015	0		27,05	26,13	-0,92	
'LANSISUOME	2520	2520	0	2750	2750	0	1,01	1,01	0		28,5	27,22	-1,28	
'ETELASUOME	4050	4050	0	4190	4190	0	1	1	0		28,91	27,73	-1,18	
Sum of Finland	8410			9670	9670	0								

Table 3.21: The load flow of the failure on 29-04-05

5. Summarize of result

In this thesis, 10 disturbance cases which are different in event location, time, and power loss amount are identified separately. These models are validated by the recordings collected from PMUs in Lulea, Lund, and Chalmers. From the result showing in table 3.22, 9 simulating cases detected the right event location, 1 case missed 2 buses from the event center. The successful tests normally have the event centers near the PMUs place and large power changes. For the wrong located case, we can see that the calculated power is much larger than the real one which causes the error in determining phase angle. The event center of this case is in Sima which is not in direct observation of any PMU. More ever, the power loss is not so large, that makes frequency deviation not clear.

Case	Date	Time	Power loss (MW)		Event location	
			Calculated	Reported	Calculated	Reported
1	4/27/2005	07.55	450	425	Bus 9	Bus 9 - Oskarhamn G1
2	6/9/2005	06.41	625	600	Bus 4	Bus 4 - Kontek
3	9/29/2005	15.41	1200	1185	Bus 2	Bus 2 - Formark B2
4	5/28/2005	21.52	775	840	Bus 3	Bus 3 - Ringhals B2
5	3/25/2005	13.49	350	300	Bus 4	Bus 4 - Anavaerket B5
6	5/31/2005	08.08	500	540	Bus 4	Bus 4 - Avedoraeverket B2
7	2/3/2005	09.29	550	540	Bus 4	Bus 4 - Avedoraeverket B2
8	8/1/2005	19.02	800	870	Bus 3	Bus 3 - Ringhals B2
9	9/15/2005	12.00	300	245	Bus 9	Bus 9 - Oskarhamn G2
10	4/29/2005	10.55	350	250	Bus 6	Bus 10 - Sima

Table 3.22: Result of the locating cases

It is supposed that with judicious PMU placement or increasing number of PMUs, the phase angle measurement is equally a reliable indicator of event location. By using enough PMUs, the power system can improve the monitoring and control of the system through same time, provide accurate system state information. Meanwhile, if the number of buses in the simulated model increase, the smaller power transfer can be analyzed and thus, the accuracy of this method can be improved.

The result indicates that model analysis is a powerful tool to investigate interconnection area behavior in large power systems as it analyzes the dynamic properties of the whole system by one single simulation per load flow scenario. It also enhances to identify which generator or load plays a significant role in the power change.

Conclusion

In this thesis, we conducted a simple method to detect the power change place in Nordic grid based on frequency and angle reaction. From the observed performance of several tested cases, it can be seen that the model works well in the perfect condition: large disturbance, unchanged load. The calculation result agrees with the recorded data.

It's also demonstrated that the reliability of this method relies much on analyzing the trend of the system behavior before and after the disturbance which is affected by the reaction of the regulating systems and by the tripping of various generating units or loads at the different locations. Thus, the determination of the exact frequency fluctuation or in other hand, the problem of finding the starting time for the regulation control has to be solved properly. Another feature affects the located execution is the calculation of the inertial gain. In some cases, the experienced equation chosen causes the large error in the simulation. It is clearly that if the gain can be measured, the problem turns out to be much simpler.

With the tests for small power change, the accuracy of this method reduces because of the fragile response of frequency.

The model is proposed to exam with the more update failures and special properties of the control governor. The structure of the model is considered to improve by adding the modern compensators or setting the real HVDC line. Future work can also be carried out to develop the grid simulation in the dynamic state and from that point; the operators can get the better inside view into the power flow of the system.

References

[1]. Axel Daneels, Wayne Salter -"What is Scada", the 7th International Conference on Accelerator and Large Experimental Physics Control Systems, Italy, Oct. 1999.

[2]. Joachim Bertsch, Cerdric Carnal, Daniel Karlsson, John Mcd Aniel, Khoi Vu – "Wide-Area Protection and Power System Utilization", IEEE, Vol. 93, No. 5, MAY 2005.

[3]. W. Lewandowski, J. Asoubib, W. J. Klepczynski, "GPS: primary tool for time transfer.", IEEE, Volume 87, No. 1, Jan. 1999.

[4]. Khoi Vu - "Voltage Instability Predictor (VIP) and its application", PSCC 99, June 1999.

[5]. ABB - "Technical reference manual RES 521 * 1.0", 2004.

[6]. Swedish energy report –" The electricity in 2004", May, 2005 .

[7]. Statistic Centre of Sweden- "Annual report 2003", August,2004.

[8]. Finnish Electrical Company -"Annual report 2003", June, 2004.

[9]. Statnett report -"The power situation in Norway", May, 2005.

[10]. Elkraft – "The transmission grid in Eastern Denmark", Nov, 2005.

[11]. K . Ahlgren, D.Holmberg, P. Halversson, L. Angquist, "Thyristor controlled serious capacitor used as a mean to reduce torsion interaction subsynchornous reasonance", Svenska Kraftnat, ABB Power System AB, August, 1999.

[12]. ABB report " ABB Series Capacitor projects Worldwide", Apr, 2005.

[13]. Nordel – "Information of failure", Urgent messeges, 2004-2005.

[14]. Arthur R.Bergen – "Power System Analysis"- Second Edition, Prentice Hall, 2000.

[15]. Thesis of University of Wales, Bangor " Power System Dynamics", 2004.

[16]. Sture Lindahl – "Frequency control in the synchronous Nordel system", Sydkraf, 1984.

[17]. B. J. Kirby, J. Dyer, C. Martinez, Dr. Rahmat A. Shoureshi, R. Guttromson, J. Dagle – " Frequency control concerns in the north American Electric Power System", ORNL, 2003.

[18]. ICF Consulting report –"Unit Costs of constructing new transmission assets at 380kV within the European Union, Norway and Switzerland, Brussel, Oct, 2003.

[19]. Nordpool organization, "The common Nordic power market ", June, 2002.

[20]. Morten Hemmingsson, ” Produktions- och Belastningsbortkoppling 2004-10-25 to 2005-10-14”, October, 2005.

Appendix

1. Data for the line

From bus	From bus Name	To bus	To bus name	Line R (pu)	Line X(pu)	Charging (pu)
1	'STOCKHOLM'	2	'OSTMELLAN'	0.00089	0.00885	0.26550
1	'STOCKHOLM'	3	'VAST'	0.00325	0.03250	0.97500
1	'STOCKHOLM'	4	'SYD'	0.00376	0.03760	1.12800
1	'STOCKHOLM'	7	'MELLERSTA'	0.01015	0.06090	3.04500
1	'STOCKHOLM'	9	'SMALAND'	0.00257	0.02598	0.77940
2	'OSTMELLAN'	6	NORRMELLAN'	0.00480	0.03940	2.27360
2	'OSTMELLAN'	7	'MELLERSTA'	0.00510	0.03830	2.34480
3	'VAST'	4	'SYD'	0.00182	0.01817	0.54600
3	'VAST'	6	NORRMELLAN'	0.00560	0.03940	2.36600
3	'VAST'	10	'SYDNORWAY'	0.00642	0.04301	2.58084
4	'SYD'	9	'SMALAND'	0.00230	0.02323	0.69690
6	NORRMELLAN'	7	'MELLERSTA'	0.00198	0.01975	0.05940
6	NORRMELLAN'	9	'SMALAND'	0.00630	0.04265	2.56000
6	NORRMELLAN'	10	'SYDNORWAY'	0.00480	0.04814	1.24420
7	'MELLERSTA'	8	'OVRENORR'	0.00111	0.01126	0.33780
8	'OVRENORR'	11	'LAPPI'	0.00416	0.03415	2.04880
11	'LAPPI'	12	'OULUNITA'	0.00149	0.01489	0.44670
12	'OULUNITA'	13	'LANSISUOME'	0.00474	0.03560	2.13600
12	'OULUNITA'	14	'ETELASUOME'	0.00528	0.03960	2.41560
13	'LANSISUOME'	14	'ETELASUOME'	0.00153	0.01527	0.45810

2. The power flow calculated in the test cases

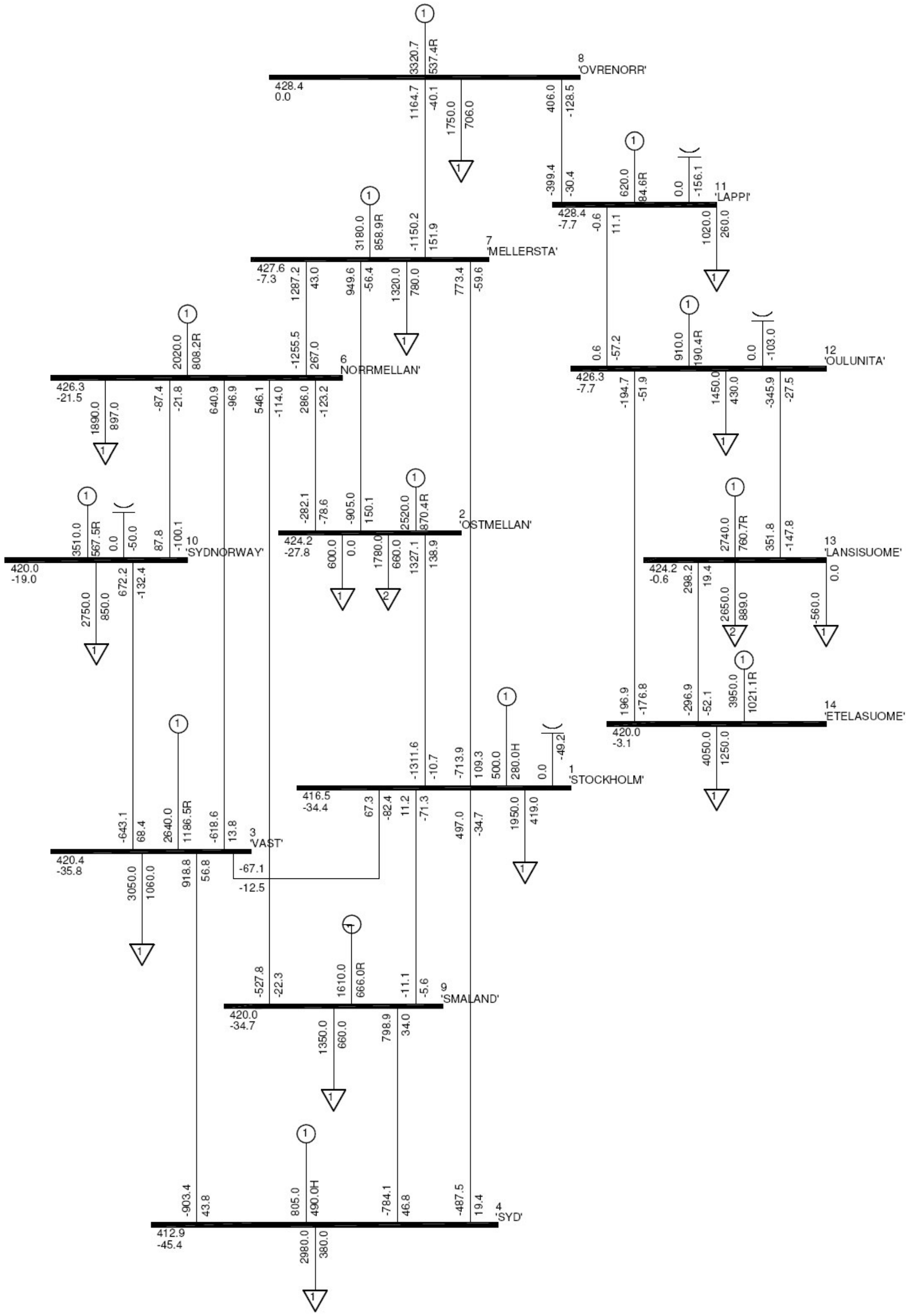

Fig1. Power flow before the failure on 29-09-05

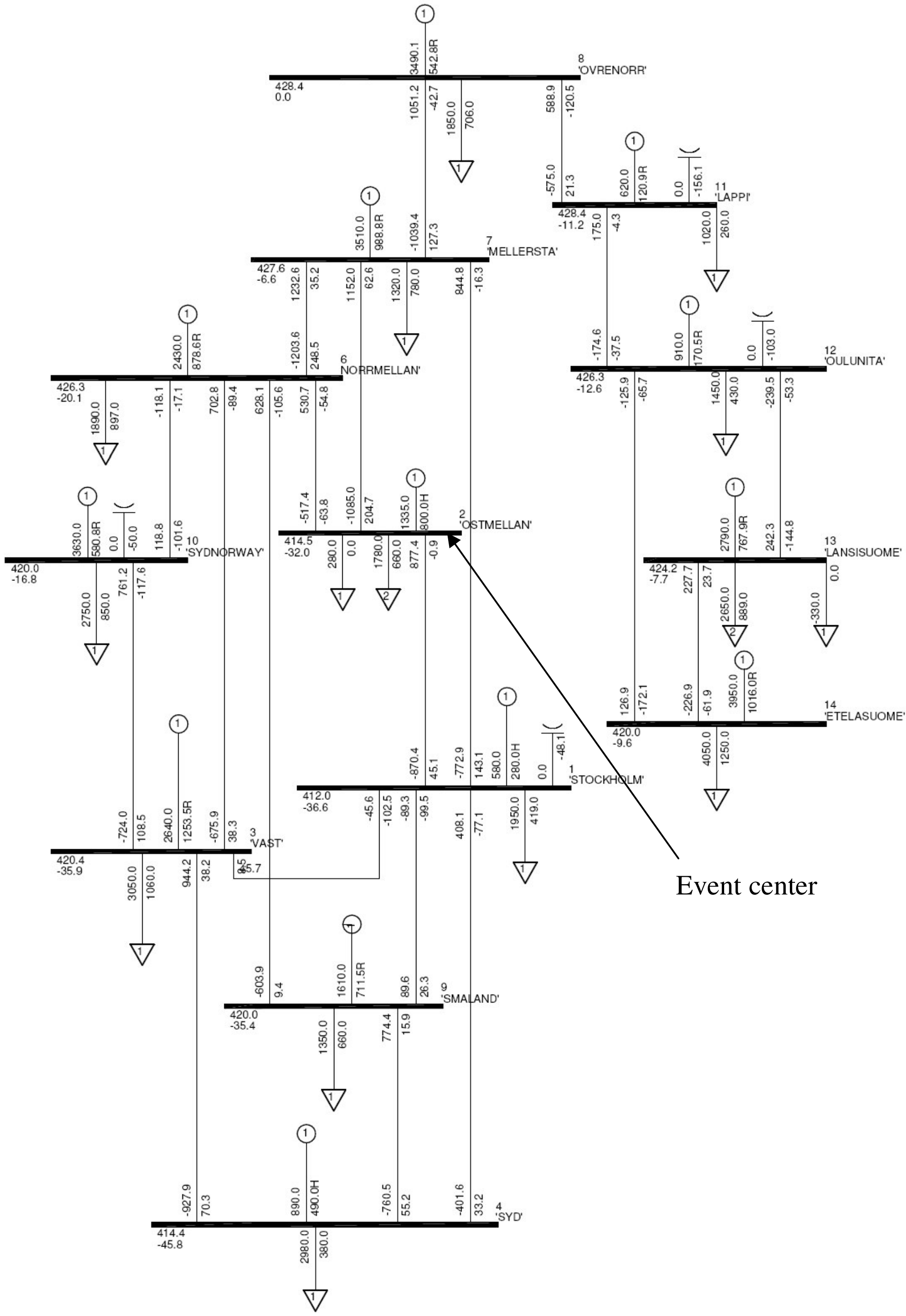

Fig2: Power flow after the failure on 29-09-05

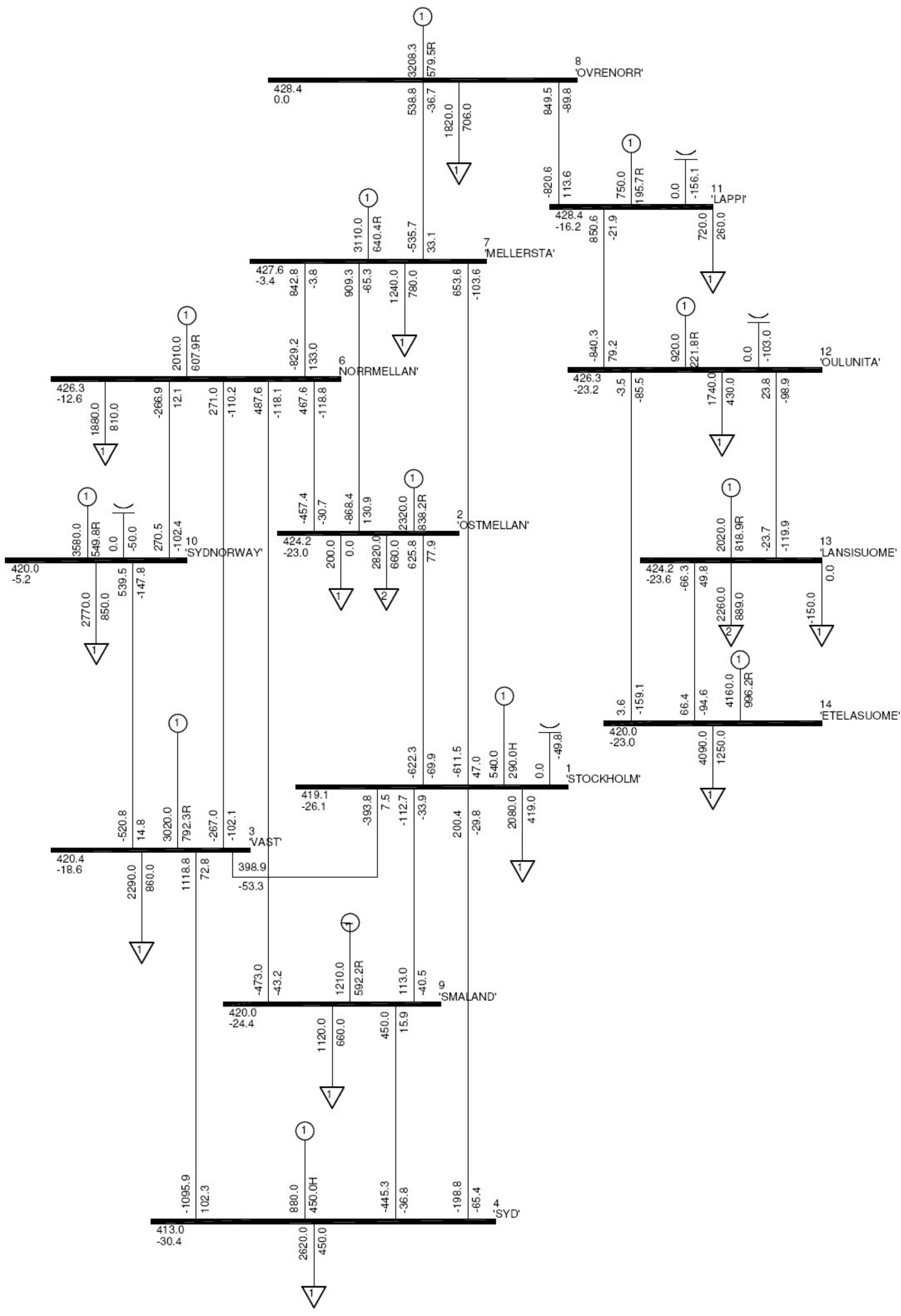

Fig3: Power flow before the failure on 28-05-05

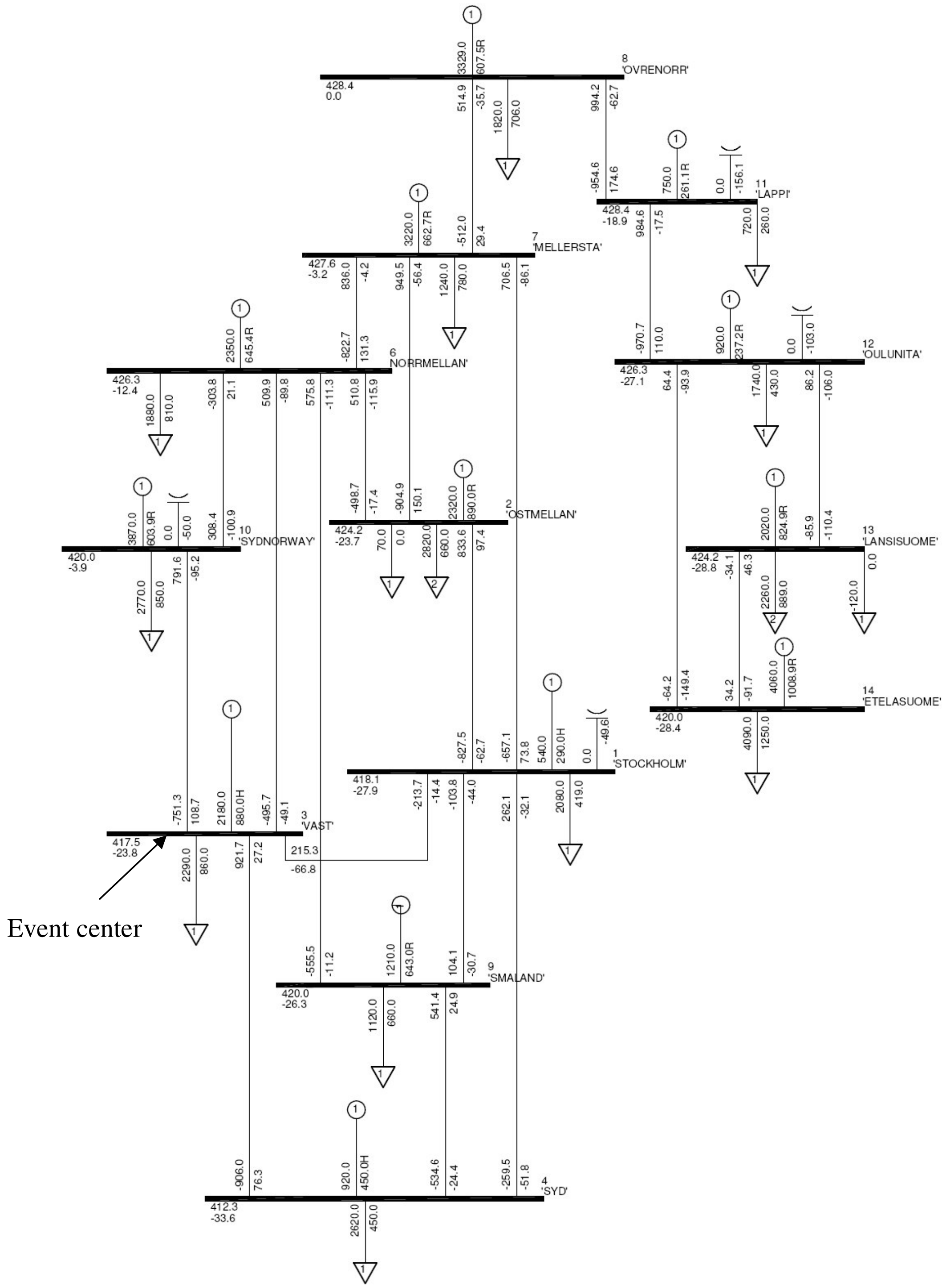

Fig 4: Power flow after the failure on 28-05-05

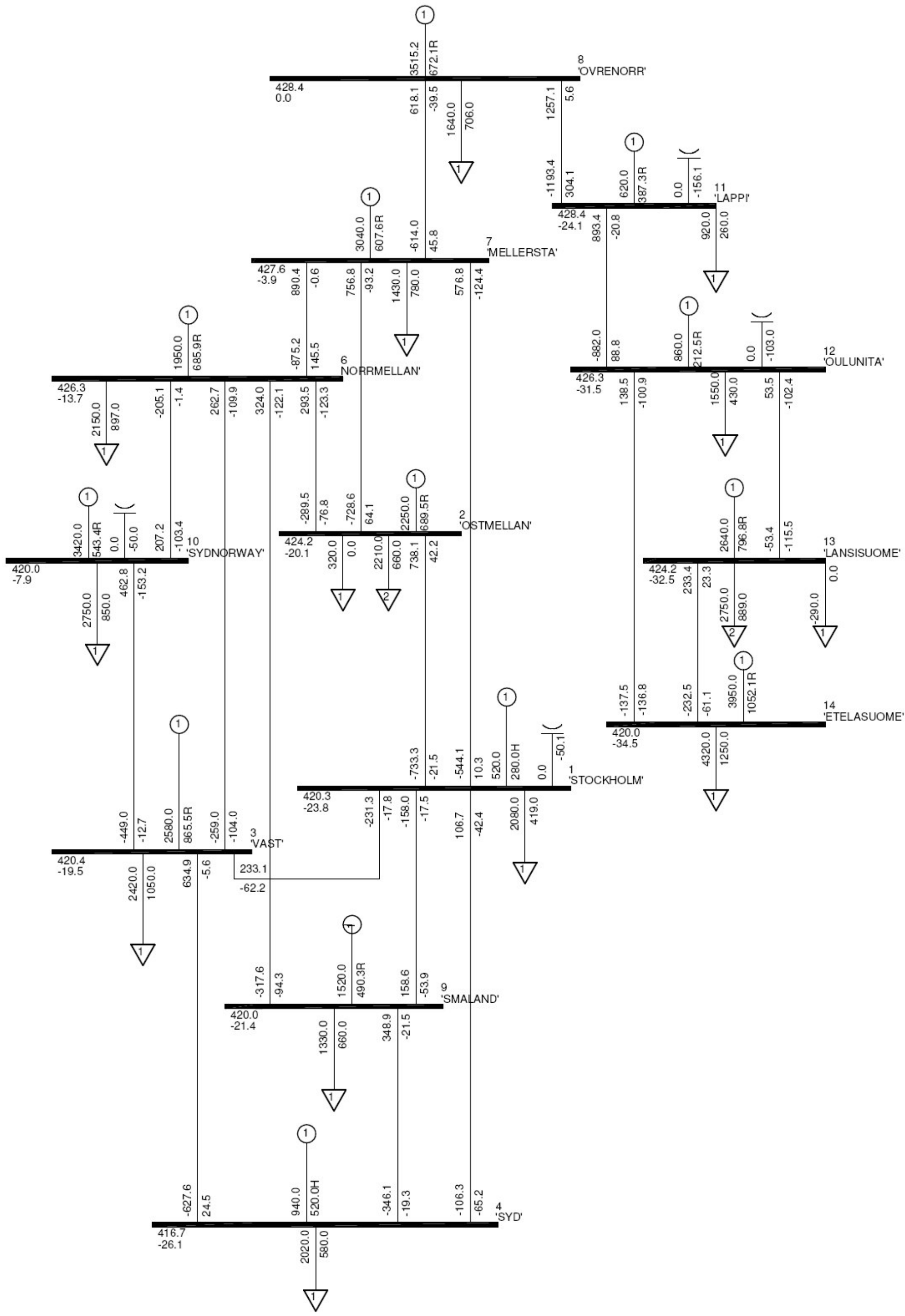

Fig 5: Power flow before the failure on 25-03-05

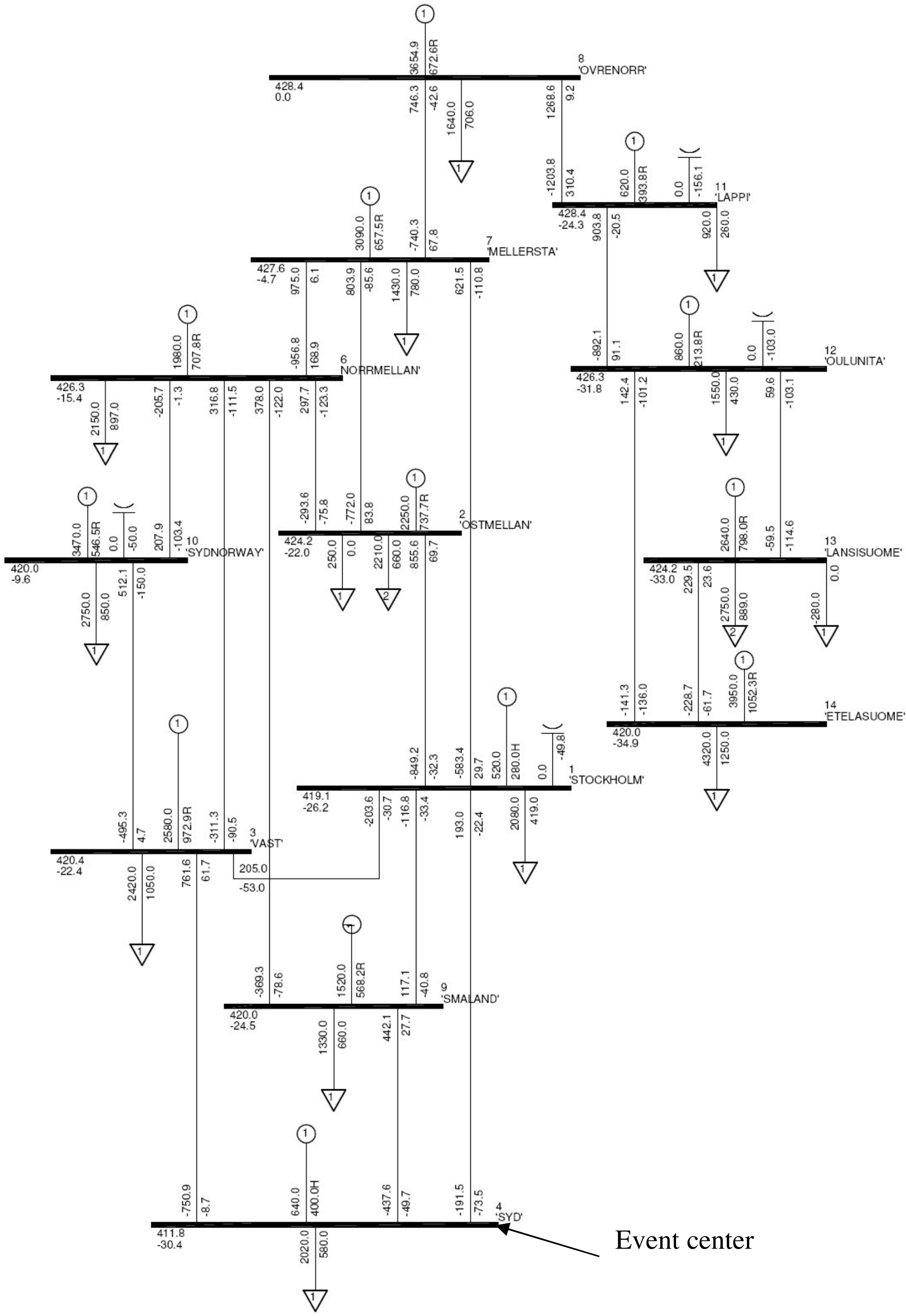

Fig 6: Power flow after the failure on 25-03-05

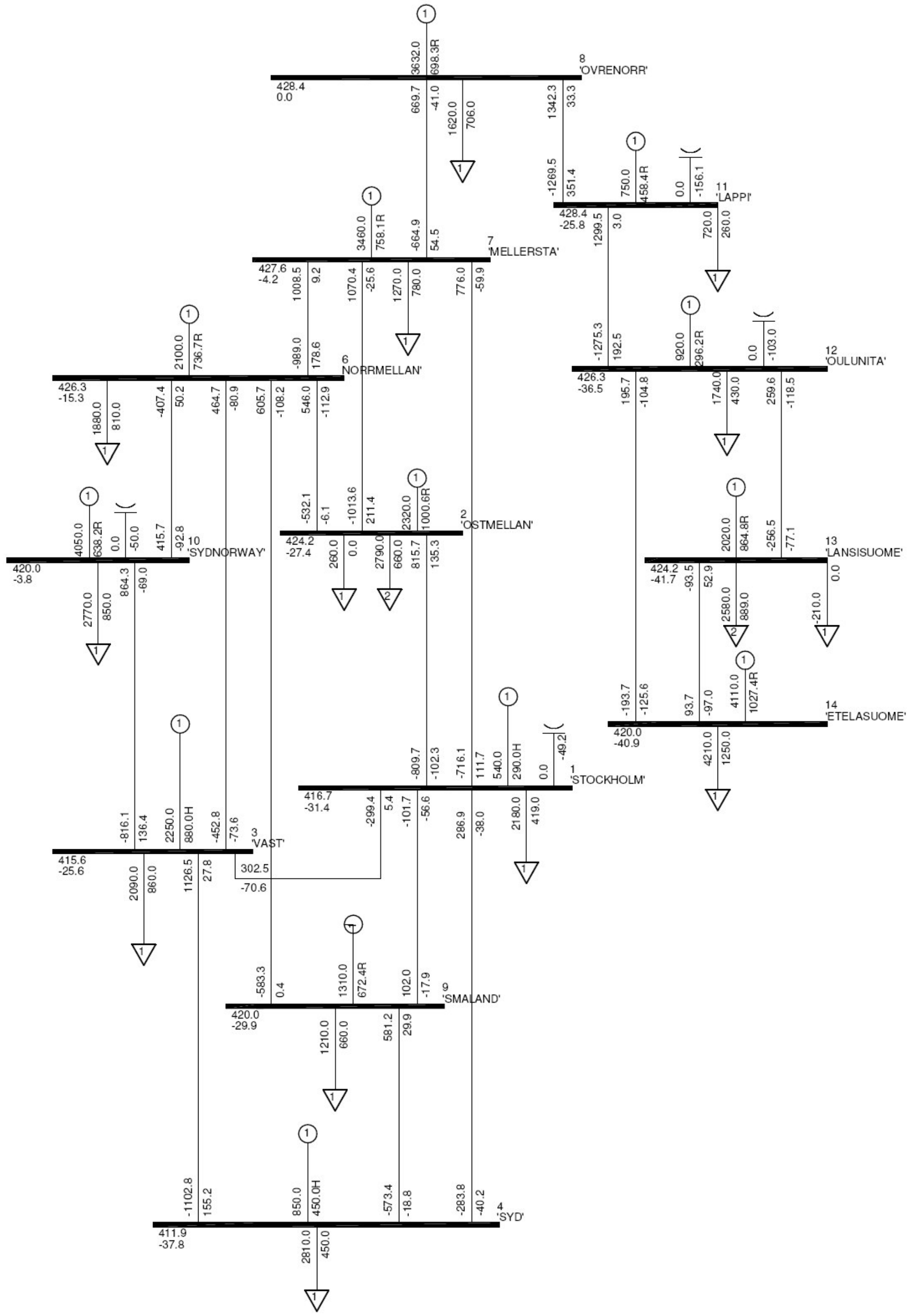

Fig 7: Power flow before the failure on 31-05-05

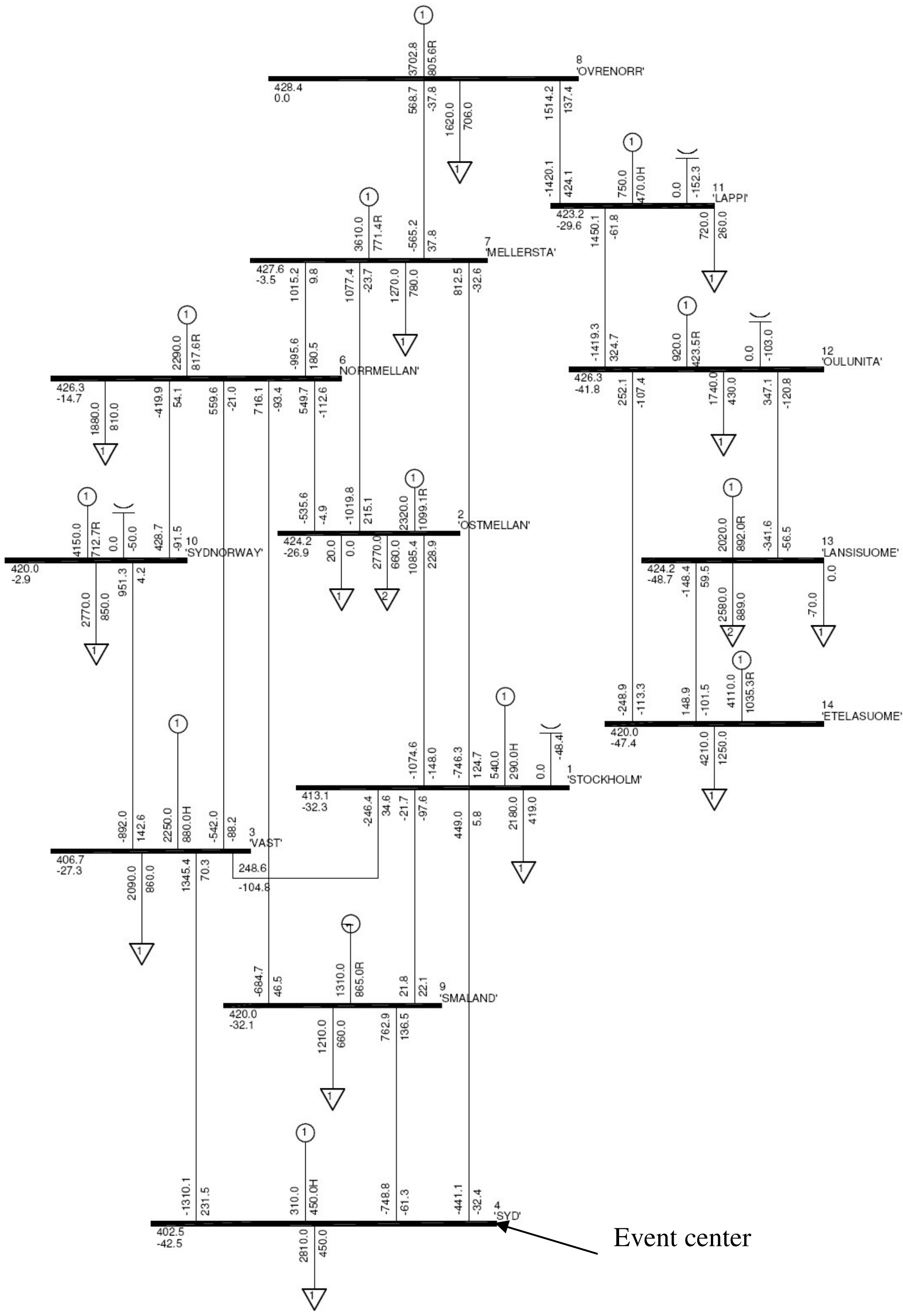

Fig 8: Power flow after the failure on 31-05-05

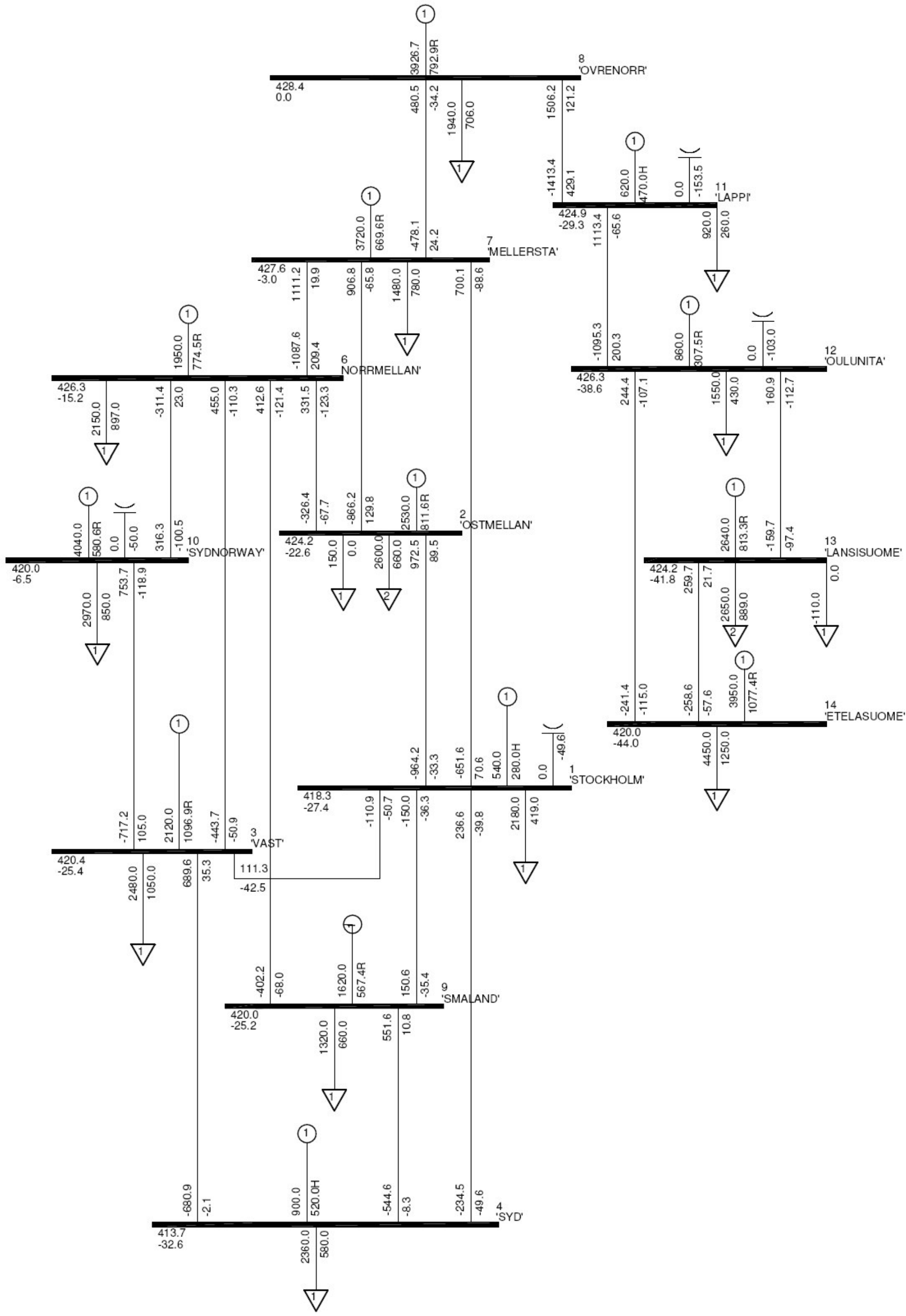

Fig 9: Power flow before the failure on 02-03-05

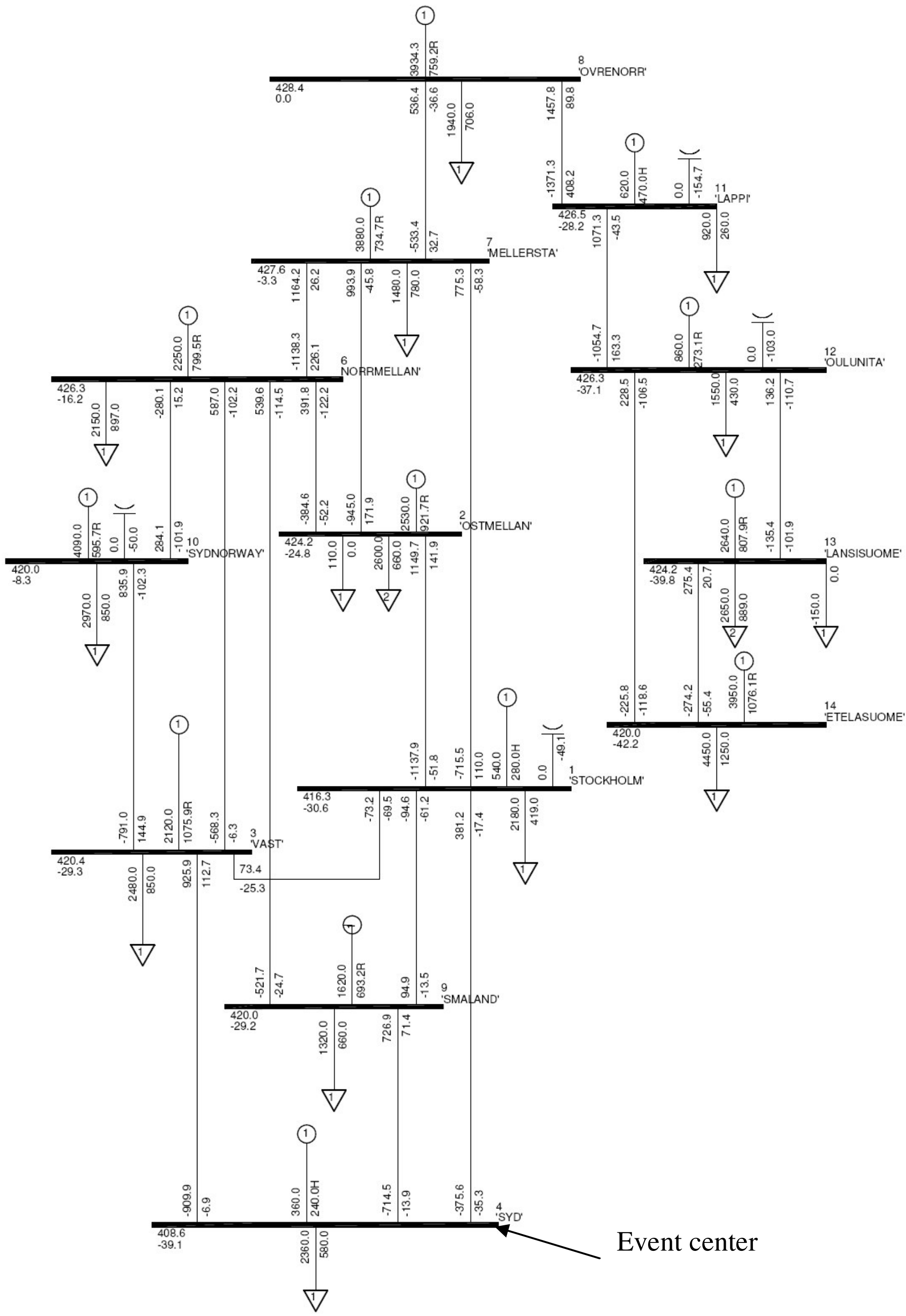

Fig 10: Power flow after the failure on 02-03-05

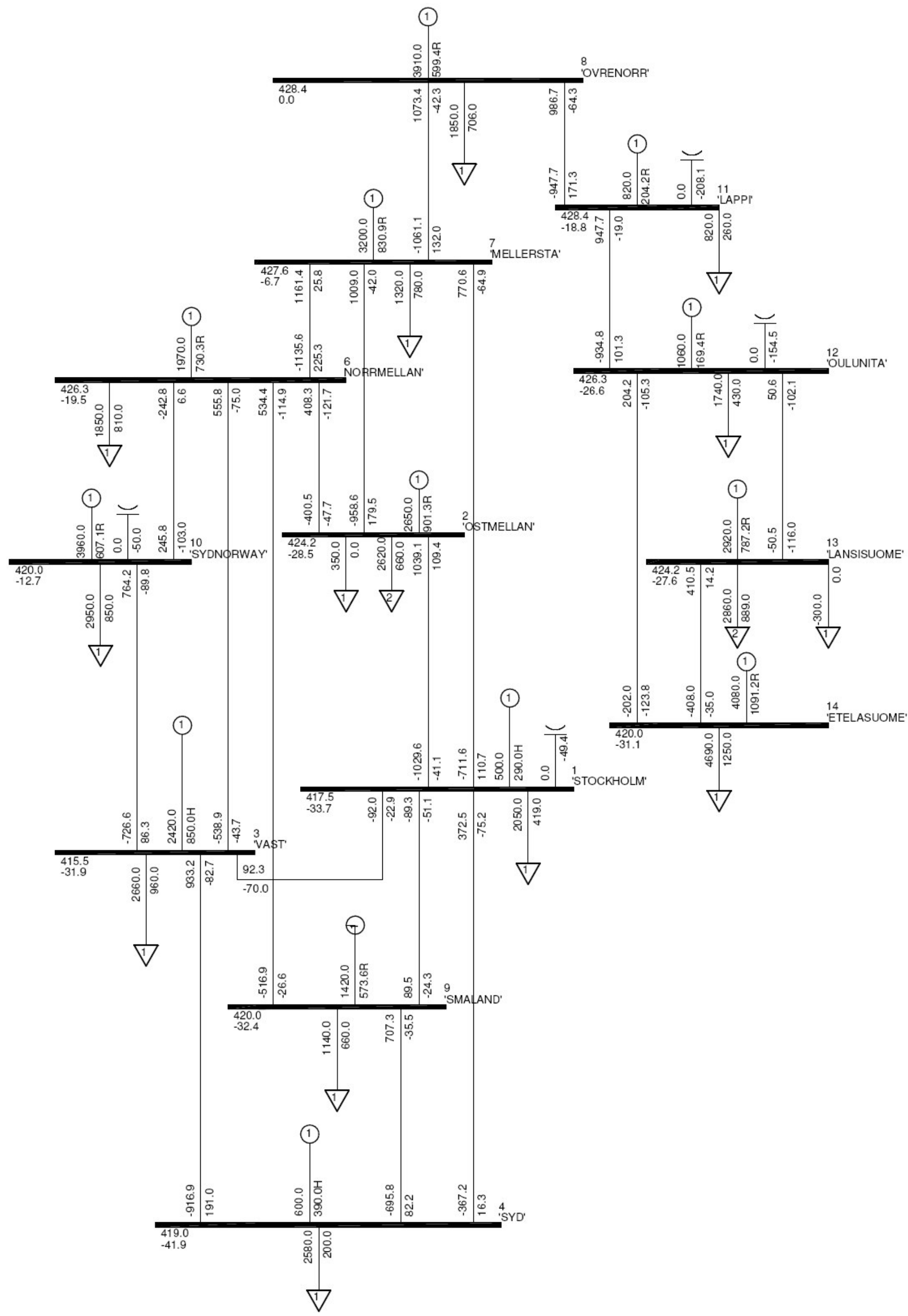

Fig 11: Power flow before the failure on 08-01-05

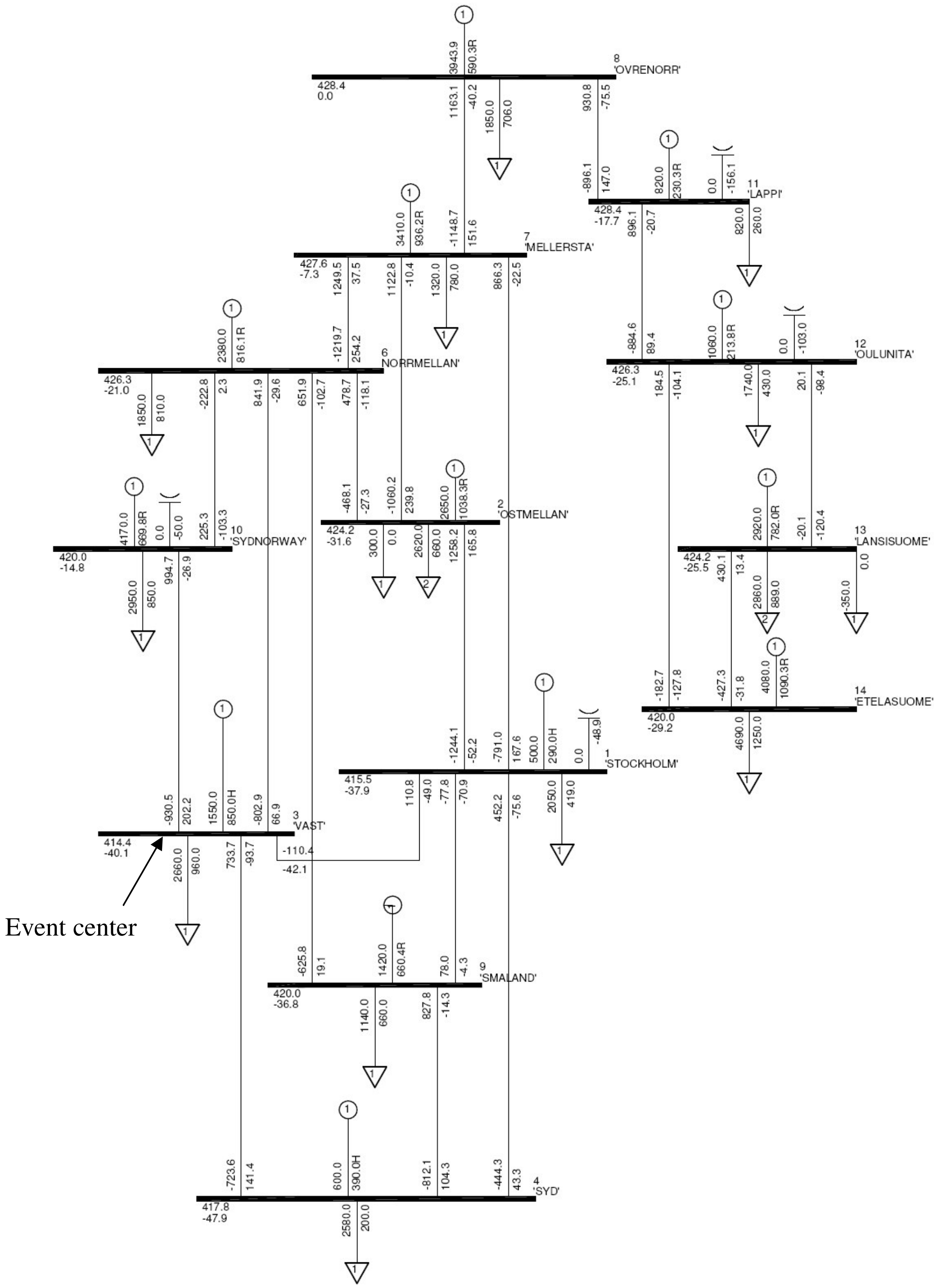

Fig 12: Power flow after the failure on 08-01-05

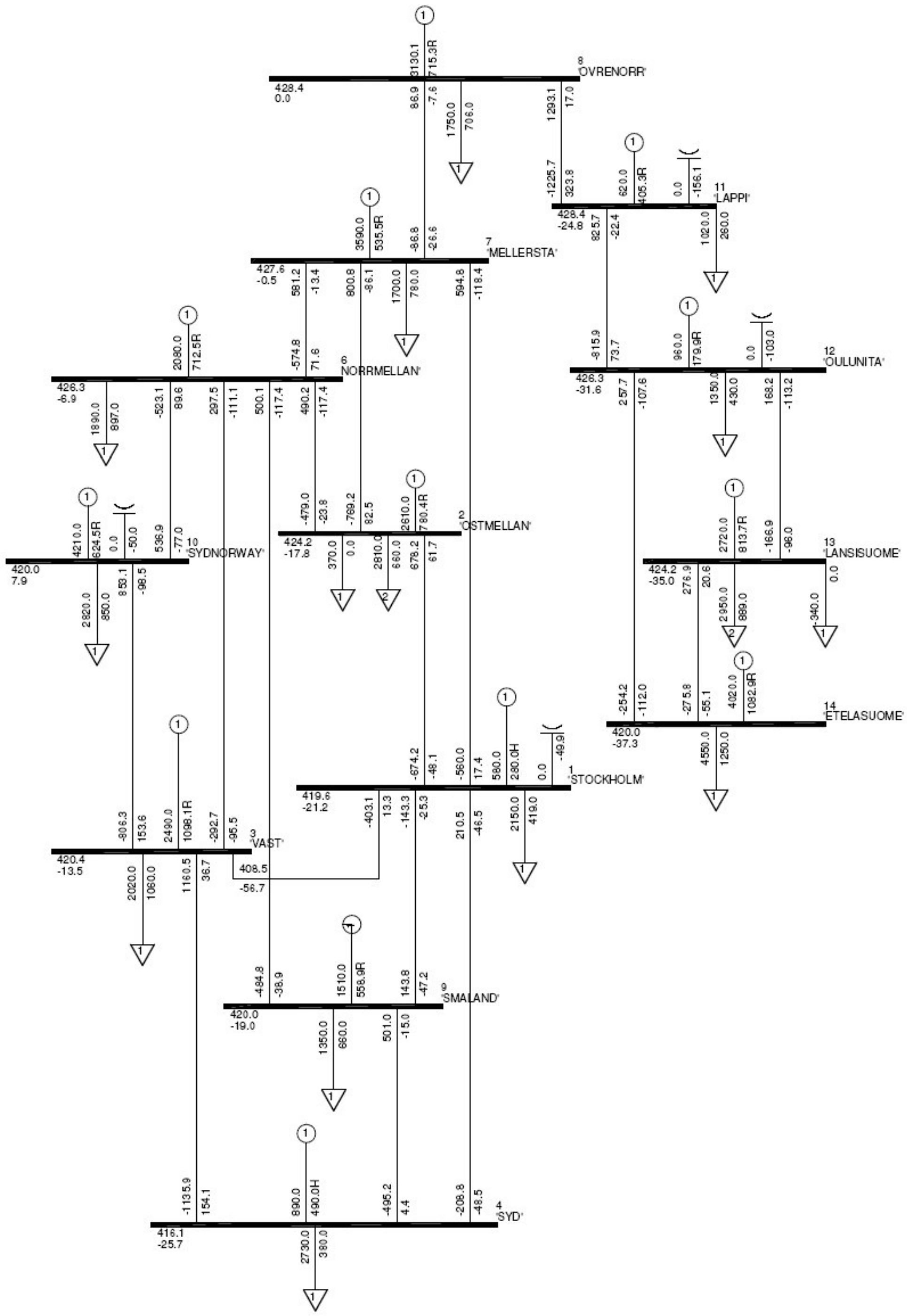

Fig 13: Power flow before the failure on 15-09-05

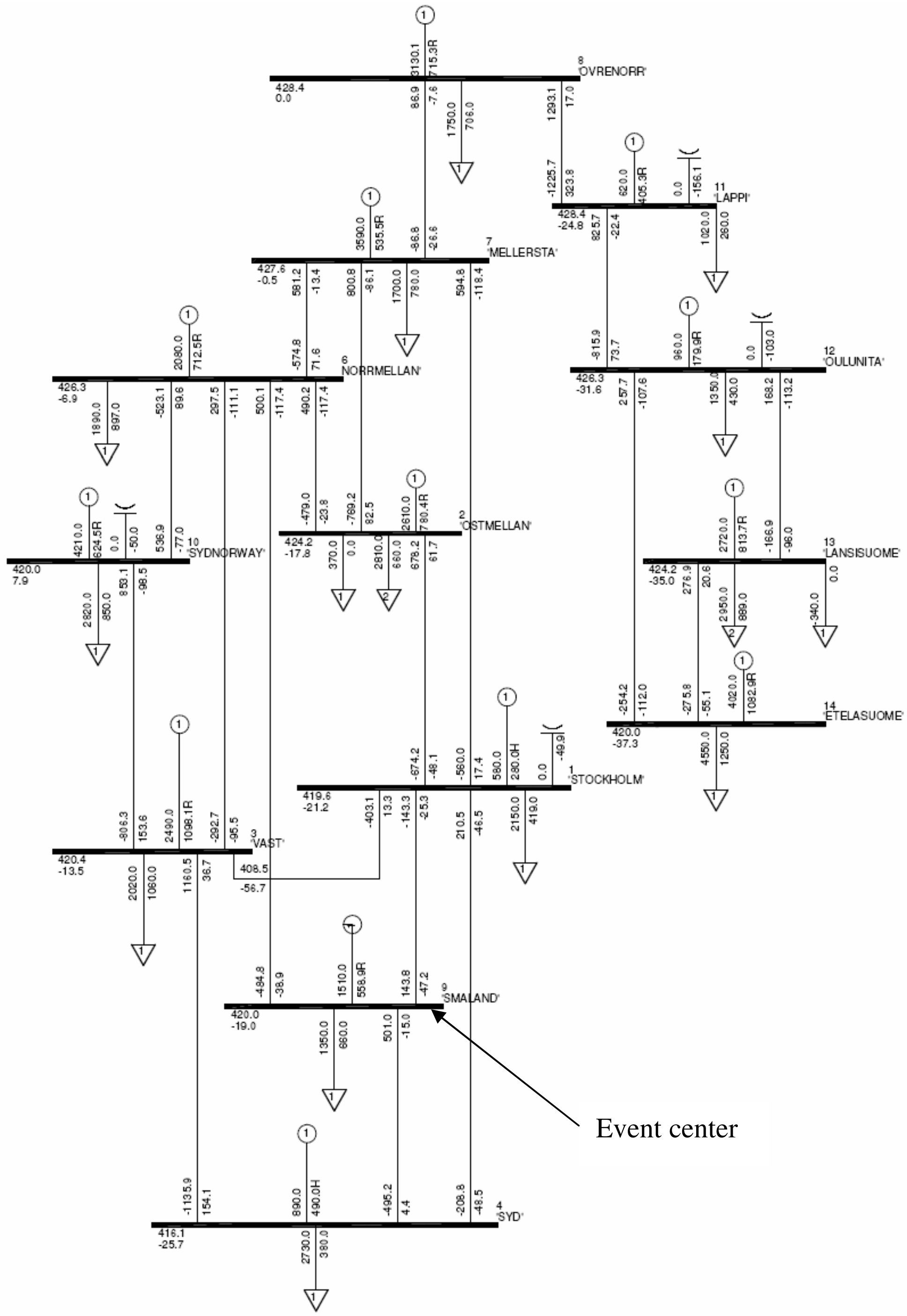

Fig 12: Power flow after the failure on 15-09-05

Phasor Data based Power System Event Detector

Tram Dao Thuy

Department of Electric Power Engineering
Chalmers University of Technology