Advanced Architectures and Control Concepts for

MORE MICROGRIDS

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WORK PACKAGE F

TASK TF8: Field test on a Multi-Microgrid (Bornholm)

DF7: Report on field test on MV island operated isolated

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List of abbreviations

LV	Low voltage
MV	Medium voltage
HV	High voltage
DNO	Distribution Network Operator
DTU	Technical University of Denmark
OESTKRAFT	Distribution Network operator for BORNHOLM
BORNHOLM	Name of the test site
TF8	Task TF8 of work package F from the MORE Microgrids project
CO	Confidential, only for members of the consortium

Contents

1. Executive Summary

When one wants to analyse how large scale DG affects network business, it is naturally to look at the power system in Denmark. Denmark has experienced a large scale introduction of Distributed Generation (DG). The situation here can be used as a case study for the future development elsewhere.

Being the Transmission System Operator in Denmark, Energinet.dk faces a great number of new challenges derived from an ambitious energy and environmental policy and a new market concept due to the liberalisation. New paradigms characterise the electricity market for generation and the transmission system since the framework and the conditions have changed dramatically within few years.

Energinet.dk has the job of balancing the power system taking into consideration that:

- the wind power production is unpredictable
- the CHP production is based on the district heating
- congestion must be managed in a transparent way
- the security of supply is ensured
- the market must function well, based on correct pricing.

Non-dispatchable production in Denmark may influence the market in the Nord Pool area by the amount of bound production.

TECHNICAL IMPACTS

Flow in 150/60 kV transformers
The flow towards the transmission system level causes problems with regards to regulating tap changes of the transformers and with regard to voltage profiles in the distribution network having lower voltages, at the points of transformation than at the points of in-feed of the Distributed Generators. Network Operators therefore often connect the generators at separate outlets where consumption is not connected.

Offshore Wind farms
The energy efficiency is expected to be much better for offshore wind farms than for onshore wind farms. Measurements indicate that the same amount of energy can be produced by half the capacity offshore than onshore. Utilisation time in the order of 4.000 hour is expected.

The control functions for a offshore wind farm in the Energinet.dk area are as follows:

- **Production limitation** set output to a maximum
- **Reserve** operate with a certain reserve downward and/or upwards
- **Balance control** set output downwards or upwards in steps
- **Grid protection interventions** set output to a lower value, in critical situations
- **Gradient limitations** adjust output gradient limit upwards and/or downwards

Each turbine handles its own frequency control. In addition, the reactive power can be controlled locally or centrally so that the wind farm's total consumption/intake of reactive power is kept within certain limits. Disconnection of the turbines in case of grid faults or too strong winds is also controlled individually.

Regulating power
Wind power and local CHP plants have displaced central units which are being decommissioned, as there are no longer commercial basis for them. It means that the regulating units disappear in areas where the need for regulating capacity is growing. The regulating must then be effected by the local CHP plants and the wind power. Energinet.dk is therefore working on getting these services from the DGs.

Short circuit power
The short-circuit power level has been reduced. The result has been:

- increased limitations on the use of HVDC links especially to Sweden
- increased risk of harmonics
- increased risk of voltage steps when connecting and disconnecting lines
- a risk that faults can be seen at a longer distance.

Priority to CHP and WT production
The energy policy has resulted in approximately 50 per cent of the energy production in the Energinet.dk area now being prioritised. This means that the Danish small-scale CHP production and the wind power cannot be regarded as secondary production and it cannot be closed down when needed.

Complex system
An obvious price for the Danish energy and environmental policy has been a very complex power system to operate. Balancing a power system like Energinet.dk can for the time being only be done if it is connected to areas with other types of production. This is not a situation that can be accepted in the long run.

CHP generation
From the very start the direct coupling of heat and power production was a major concern of the power utilities. A situation in which many CHP units made the base load electricity production and the large extraction and condensing power stations were to be dispatched by the power pool at peak load was not considered a satisfactory solution, neither by the utilities nor by the society.

System Protection
On the basis of experience, Energinet.dk has set some requirements on relay equipment and settings at local CHP units. Units ranging from 0 to 50 MW must satisfy the requirements.

However, in case of fast 3-pole re-closure local CHP units may be islanded during the dead time, and to avoid unit damage affected units are tripped before re-closure (0.3 s). It is impossible to apply time selectivity. Therefore, as primary protection an under-voltage relay is used, which measures the positive-sequence voltage, possibly supplemented with a ROCOF relay.

The ROCOF relay has given rise to quite a lot of forced outages of local CHP units. The reason is partly that some types of relays are sensitive to the phase shift resulting from short circuits and couplings in the network and partly that Energinet.dk originally recommended too sensitive settings on the ROCOF relay (df/dt > 1.5 Hz/s and df/dt< -0.7 Hz/s)

However, the strategy for system protection may have to be revised. 10-12 times per year Energinet.dk experiences simultaneous forced outages of many local CHP units.

OPERATIONAL IMPACTS

Positive and negative experiences are gained from the “Danish experiment”. The most significant positive experience is that is has been technically possible with such a penetration of DG in a conventional grid. With the caveat, that strong international connections have been necessary to balance the system.

As the overflow situation can become critical within the next few years we have to find ways of balancing the system by means of internal Danish measures. An analysis made in co-operation with the Danish Energy Agency states that the following devices are of interest:

- closing down wind turbines
- closing down local CHP plants
- introducing flexible loads (electrical vehicles)
- installing heat pumps

A new strategy
After the mixture of production and consumption in the same local networks the operational tasks have become far more complicated, particularly under emergency conditions.

The present control structure is based on a division of the electrical network into two parts: a **distribution network** connecting end-users to the electricity supply system and a **transmission network** connecting power plants and cross-border lines to the network. So far, little operational co-ordination has been required between the two networks, both under normal conditions and in emergency situations.

Therefore, the most important basis for a new strategy is the recognition that the distribution networks no longer can be **considered as passive appendages** to the transmission network, but that the entire network must be operated as a closely integrated unit. Organising cooperation on this task is a major challenge.

Furthermore, a number of technical improvements have to be developed and implemented. Conditions for central and local electricity production must be equalised bringing all power plants to contribute to system stability and flexibility.

Electricity production and consumption must be measured and switched separately. The quality of the current system analyses must be improved, and manual system control necessary during emergency operations must be organised in cooperation with the **distribution network operators**.

New principles
A systematic elimination of the weaknesses demonstrated above is possible, but **considerable time** and **some new equipment** will be required for supervision, measurements, analyses and control.

Several international studies have presented ideas for the integration of distributed electricity production. Some principles for use in Denmark have been identified as the basis for a long-term solution:

- A control hierarchy consists of a central control centre and 3-6 regional control centres. Each region consists of a number of local areas. Each local area is connected to the transmission system via one 150/60 kV substation. An **unambiguous operational responsibility** must be defined for each local area.

- The **balance of reactive power** within each local area must be kept within certain limits to be defined in a new set of rules. There must be a **local responsibility** for observing these rules and the control of local reactive resources (including condensers and local CHP plants) must be local as well.

- New rules for measuring must provide all necessary data for the regional control centres and to the extent necessary to Energinet.dk. Reliable information on the state of the system and data for accurate system analyses must be available at any time.

- During emergency operation it must be possible to switch loads and production units separately. The principle applies to both automatic load shedding by frequency relays and to the manual restoration after serious power failures.

- During normal operation only Energinet.dk's control centre will be manned 24 hours per day. In other system states (from alert to emergency) it must be possible to man the regional and local control centres concerned. Restoration after a complete system collapse will be the ultimate challenge. Procedures for this situation must be trained, but hopefully never used.

Cooperation required
A number of tasks must be solved together with the regional transmission operators and the distribution network operators in preparation for the implementation of these principles.

Mapping of production and consumption
From the very beginning a mapping of the distribution of production and consumption for all 60/10 kV terminals and of the equipment for measuring will be required.

Rules for Measurements, Generators and Communication
Furthermore, new rules must be prepared for a number of areas, including measurements, reactive power, local power plants and communication.

Procedures for Reactive power balance, curtailment of load and restoration
Finally, new procedures for local control of reactive balance, manual curtailment of load and production and for the restoration after system failures must be developed.

THE DISTRIBUTION SYSTEM

It is on this background that the distribution systems in Denmark has come into focus. For the time being research and demonstration are taken place in 3 “supply areas”. A supply area in Denmark will normally consists of a 150/60 kV transformer and a network at 60 kV, 10 kV and 0,4 kV voltage level. These three supply areas are:

- Holsted Energinet.dk and Sydenergi Connected to UCTE
- The Bornholm island DTU and EastPower Connected to NORDEL
- The Faroe Island SVV and Dong Energy Not Connected

The BORNHOLM island is one of the field test site for the European MORE Microgrids project.

In this field test DTU have “simulated” the situation where a DNO has the responsibility for operating a 132 kV Multi-Microgrid. EastPower several times in 2007, 2008 and 2009, demonstrated that they have the capability to run the power system in island mode.

The restoration process is trained every Thursday where a small diesel generator will be started. This generator will then be able to start one of the 4 diesel generators. This generator will be synchronized and run for a couple of hours before it will be disconnected.

To observe the state of the distribution system EastPower normally have MW and Mvar’s to his disposal on the 60 kV voltage level and Amps on the 10 kV feeder level. In this task a technique is demonstrated, were the amps on the feeders is supplemented with “fuzzy” estimated MW and Mvar values (Chapter 10).

Parameters for the generators is normally also hard to get. In this task it is demonstrated how to estimate these parameters on the basis of measurements from the system (Chapter 7).

Today it is normal practice to disconnect the Wind turbines when the grid is brought into planned island mode. This task has demonstrated the reason for this practice (Chapter 11) and have established a cooperation with Vestas (PhD study) to find schemes for bringing wind turbines into operation in island mode, thereby increasing the use of renewables.

All the elements in the Bornholm Power System has been described (Chapter 4, 5 and 6) and for being able to simulate the operation of the power system, a computer model has been established (Chapter 9). The input (Load and Production) is taken from the existing data base.

The simulations are evaluated against measurements (Chapter 10)

2. Objectives of task TF8

In this field test DTU will “simulate” the situation where a DNO has the responsibility for operating a 132 kV Multi-Microgrid. To observe the state of the distribution system a DNO normally have MW and Mvar’s to his disposal on the 60 kV voltage level and Amps on the 10 kV feeder level. In this task we will demonstrate a technique, were the amps on the feeders in supplemented with “fuzzy” estimated MW and Mvar values.

Parameters for the generators is normally also hard to get. In this task we will try to estimate these parameters on the basis of measurements from the system.

Today it is normal practice to disconnect the Windturbines when the grid is brought into planned island mode. It is the intention of this task to find the reason for this practice and suggest schemes for bringing windturbines into operation in island mode, thereby increasing the use of renewables.

The test will be divided in the following phases:

Describe all elements i a specific Multi-Microgrid f.ex.

Load, Lines, Substations, CHP units, Wind Turbines, Reactive resources

Establish

a computer model for the Multi-Microgrid
the forecasting functions: Load and Production
the normal security functions (Based on loadflow calculations)

Simulate the operation of the Multi-Microgrid

Evaluate the simulations againts measurements

Describe the Multi-Microgrid’s ability to:

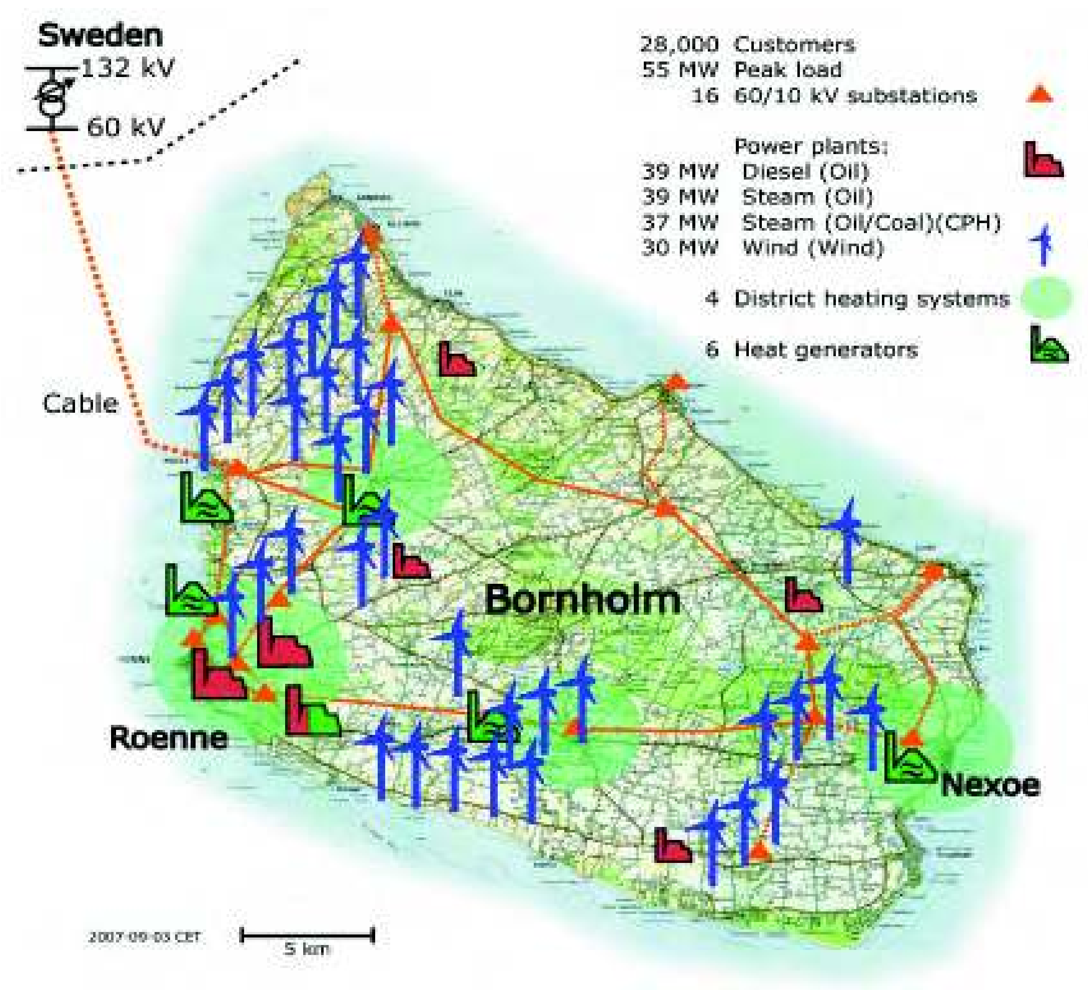
to balance the active and reactive power
to blackstart
to reconnect to the main grid

Demonstrate

island operation, model estimation, “fuzzy” state estimation

3. Location of the test site BORNHOLM

Field test in this task will be performed on the island of Bornholm. This island is situated just south of Sweden. A normal power system in Denmark connected to a primary 132/150 kV substation has a peak load between 50-60 MW.The peak load on Bornholm is 55 MW, and together with is ability to go into planned island mode makes it ideal for test and demonstration. The DNO of Bornholm is the company OESTKRAFT.



4. The Bornholm Power System

An Overview

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THE BORNHOLM POWER SYSTEM
An overview

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ABSTRACT: The island of Bornholm is a Danish island situated just south of Sweden. The ØSTKRAFT Company is the Distribution System Operator on the island supplying more than 27,000 customers. A normal distribution system in Denmark connected to a primary 132 kV or 150 kV substation has a peak load between 50-60 MW. The peak load at Bornholm was 63 MW in 2007. In many respects the distribution system on Bornholm has many of the characteristics known from other Danish distribution systems. With respect to areas, load and population Bornholm corresponds to roughly 1% of Denmark. Wind power covered 30.2% of the load in 2007, which is above the average penetration in Denmark. Its ability to go into planned island mode makes it special and a good "case" for research and demonstration of new technology. The key figures for the Bornholm distribution system is given in this paper.

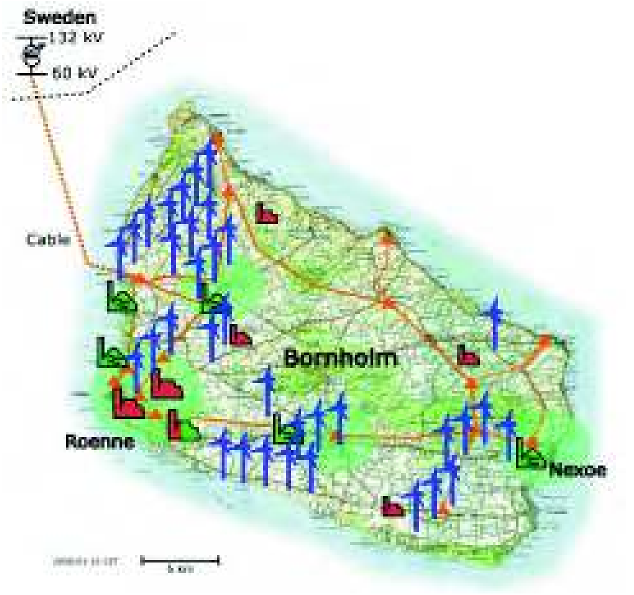

Figure 1. The island of Bornholm.

Keywords: Bornholm, Power System, Wind Power, Scada System, Settlement System, Key Figures.

Abbreviations:

OLTC	On-Load Tapchanger
TRF	Transformer
CHP	Combined Heat and Power
EXTRACT	"Extraction" mode of CHP Power Plant
PSO	Public Service Obligation
DSO	Distribution System Operator
TSO	Transmission System Operator

I. THE BORNHOLM POWER SYSTEM

The Bornholm power system consists of the following main components:

- The 132 kV substation in Sweden
- The connection between Sweden and Bornholm
- The 60 kV Network
- The 10 kV Network
- The 0.4 kV Network
- The Load
- The Customers
- The Production Capacity
- The Control Room
- The Communication System
- The Biogas Plant "Biokraft"
- The District Heating System

II. THE 132 kV SUBSTATION IN SWEDEN

E-ON is the DSO in the southen part of Sweden. The company owns the equipment in the TOMELILLA and BORRBY substations. From the 132 kV substation TOMELILLA, there is an overhead line to the 132 kV substation BORRBY. At the 132 kV BORRBY feeder in the TOMELILLA substation, the Scada system measures the following values:

- The Voltage in kV
- The Active Power in MW
- The Reactive Power in MVAr

In the BORRBY substation there is two 132/60 kV transformers. One of them supplies the connection to HASLE on Bornholm, the other BORRBY CITY. At the 60 kV HASLE and BORRBY CITY feeders, the Scada system measures the following values:

- The Voltage in kV
- The Active Power in MW
- The Reactive Power in MVAr

The E-ON scada system has the following archives:

- 10 seconds instantaneous values (14 days)
- 1 minut average values (1 month)
- 1 hour average values (1 year)

The transformer in the BORRBY substation cannot be operated as an OLTC transformer, because the tap changer is fixed. Consequently, the position is not transferred to

E-ON's control room in Malmø. Data for the transformer can be found in table 1.

Rating	Voltage	Short-Circuit Voltage, uk
63 MVA	135+-9x1.67% / 69 kV	9.997 %

Table 1. Data for the BORRBY 132/60 kV transformer.

III. THE CONNECTION TO SWEDEN

Energinet.dk is the TSO in Denmark. The company owns the equipment between the BORRBY substation in Sweden and the HASLE substation at Bornholm.

The 60 kV side of the transformer in the BORRBY substation is connected to the 60 kV substation HASLE at Bornholm, by the overhead lines/cables shown in table 2.

Type	Dimension [mm2]	Length [km]
Overhead Line	127 Cu	4.2
Cable	400 Cu	0.7
Cable (Offshore)	240 Cu	43.5
Overhead Line	400 Cu	1.4
		49.8

Table 2. Connection between BORRBY and HASLE.

The steady state electrical model (pi equivalent) for the connection between BORRBY and HASLE uses the constants shown in table 3.

R' [Ω /km]	X' [Ω /km]	B' [uS/km]
0.1402	0.1225	46.553

Table 3. Data for the connection BORRBY to HASLE

IV. THE 60 KV NETWORK AT BORNHOLM

Østkraft is the DSO at Bornholm. The company owns the equipment on the Bornholm island.

At the 60 kV BORRBY feeder in the HASLE substation, the Østkraft Scada system measures the following values:

- The Voltage in kV
- The Current in A
- The Active power in MW
- The Reactive power in MVAr

The Østkraft scada system has the following archives:

- 10 seconds instantaneous values (14 days)
- 1 minut average values (1 month)
- 1 hour average values (1 year)

At the 60 kV BORRBY feeder in the HASLE substation, the settlement system measures the following values:

- The Active Power in MW
- The Reactive Power in Mvar

As average values over 15 minuts.

The 60 kV network at Bornholm is meshed and concists of the following elements:

- 18 Substations
- 23 60/10 kV OLTC transformers 219 MVA
- 22 Cables and overhead lines
    - Length of overhead lines 73 km
    - Length of cables 58 km

These elements are connected as shown in figure 2.

Year	Name	Trf No	Trf [MVA]	10 kV Feeders
1959	Olsker	2	8.0	6
1959	Bodilsker	2	14.0	6
1967	Aakirkeby	2	16.0	10
1974	Østerlars	1	6.3	4
1977	Snorrebakken	1	10.0	6
1980	HASLE	2	20.0	7
1981	Nexø	2	20.0	6
1983	Rønne Syd	1	10.0	4
1984	Allinge	2	20.0	4
1988	Svaneke	1	10.0	6
1988	Viadukten	1	10.0	7
1989	Rønne Nord	1	10.0	6
1990	Poulsker	1	10.0	5
1994	Vesthavnen	1	10.0	4
1998	Gudhjem	1	4.0	4
	Værket	2	41.0	9
		23	**219.3**	**94**

Table 4. 60/10 kV substations.

Figure 2. The 60 kV network 2006.

In general the following are measured on the 10 kV side of a 60/10 kV transformer:

- Voltage in kV
- The Tap position
- Cos phi
- Current in A

In a number of 60 kV lines, the voltage and the current are also measured. Only one frequency measurement can be found in the Scada system (HASLE substation).

V. THE 10 KV NETWORK

The 60/10 kV OLTC Transformers keeps the 10 kV voltage to a value around 10.5 kV. The 10 kV Network concists of the following elements:

- Overhead Lines 247 km
- Cables 634 km
- Feeders 91
- Average feeders per substation 6

The Scada system measures the current at each feeder.

VI. THE 0.4 KV NETWORK

The 0.4 kV Network concists of the following elements:

- Overhead Lines 518 km
- Cables 1,341 km
- 998 10/0.4 kV Transformer 265 MVA
    - Average kVA/transformer 273
    - Average customer/transfomer 29

VII. THE LOAD

The 2007 load was as follows:

- Peak load 63 MW
- Energy 262 GWh
- Full load hours 4,152 h

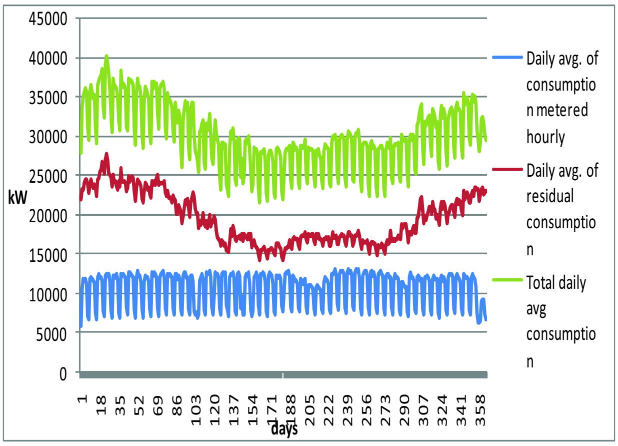

Figure 3. Daily average load in 2007 [5].

VIII. THE CUSTOMERS

The number of customers are 27,895. 1.08% of the customers or 302 have a consumption above 100,000 kWh/year. These customers active and reactive load is measured as 15 minutes average values.

Approximately 30% of the load comes from the 302 customers with a yearly load above 100,000 kWh

IX. THE PRODUCTION CAPACITY

The production capacity are as follows, see table 5 and appendix 1:

- 14 Diesel generators (Oil) 35 MW
- 1 Steam turbine(Oil) 25 MW
- 1 Steam turbine(Oil/Coal) 40 MW
- 35 Wind turbines 29 MW
- 1 Gas turbine (Biogas) 2 MW

The 14 diesel units and the 2 steam units are able to control both voltage (10.5 kV) and frequency. The 6 newest wind turbines are able to control voltage, production, ramp rates etc.

All production units with a generation above 100,000 kWh/year, are measured every 15 minutes. Both active and reactive energy is measured as average values.

Year	Id	Type	Fuel	Heat [MJ/s]	Power [MW]
1967		Diesel	Oil		5
1968		Diesel	Oil		5
1971		Diesel	Oil		5
1972		Diesel	Oil		5
1974	B5	Steam	Oil		25
1995	B6	Steam	Oil/Coal	0	37
			“Extract”	35	33
			“CHP”	35	16
2007	B7	Diesel	Oil		15
2008		Diesel	Biogas		2

Table 5. Data for Diesel, Steam and Biogas units.

The wind turbines generated 79 GWh in 2007. This corresponds to 30.2 % of the load.

X. THE CONTROL ROOM

The control room is able to set:

- The tap changers at all 60/10 kV transformers
- The capacitors in all 60/10 kV substations
- The voltage reference in the following units
    - 14 Diesel units 35 MW
    - 2 Steam turbines 65 MW
    - 6 Wind turbines 11 MW
- The frequency regulator in the following units
    - 14 Diesel units 35 MW
    - 2 Steam turbines 65 MW

- The production and ramp rates in the wind turbines
    - 6 Wind turbines 11 MW

The main tool at the control room is the Scada System for:

- The 60 kV and 10 kV Network (ABB)
- The 6 Wind turbines (VESTAS)
- The 14 Diesel units
- The 2 Steam turbines

The time resolution in the ABB NETWORK MANAGER is 10 seconds instantanous values, 1 minut average values or 1 hour average values.

The time resolution in the VESTAS ONLINE system is 10 minutes average values.

XI. THE COMMUNICATION SYSTEM

To support the communication between e.g. the relays and the RTU's in the substations, an optical fibre network has been established.

XII. BIOGAS PLANT

The 2 MW plant "BIOKRAFT" on Bornholm is the largest and most advanced biogas plant with high-tech separation in the world. It provides a yearly CO_2 reduction of 14,000 tons.

Yearly Energy Production

The plant produces approximately 6,000,000 m^3 biogas, which generates:
Electricity: Approximately 16,500 MWh
Heat: Approximately 8,000 MWh

Amount of fertilizer produced on a yearly basis:

Ammonium concentrate 5,300 tons
Phosphorus/potassium 5,600 tons
Bleed approximately 22,300 tons
Clean water approximately 50,000 tons

Capacity on a yearly basis

Pig manure approximately 62,000 tons
Cattle manure approximately 21,000 tons
Glycerol approximately 7,300 tons
Various fat waste, pulp approximately 3,600 tons

	Heat Production [MWh]	Number of users	Fuel Straw [%]	Oil [%]	Coal [%]	Waste [%]
RVV	154,731	5,000		2	68	30
Nexø	35,000	1,659	98	2		
Klemensker	8,900	275	98	2		
Lobbæk	6,700	160	85	15		
Østermarie	150	10		100		
Total	205,481	7,104	24	2	50	24

Table 6. Heat production at Bornholm 2006

XIII. DISTRICT HEATING

Total heating requirements for Bornholm are approximately 560,000 MWh/Year. Currently, this is covered by three heating sources: District heating, buildings with electric heating and individual boilers.

The district heating sector of Bornholm is made of five distribution areas. Data for these areas are given in table 6. For further information see ref [5].

XIV. RESEARCH

This section provides an overview of research and educational activities using the Bornholm power system as a "case". The activities are divided into 5 main subjects.

- Demand Response and Market
- Island Operation
- Wind power Integration
- Experimental Research platform
- Transportation

The overall objective of the research is to develop a smarter low carbon-emission electric power system which can handle an increased share of renewable energy and distributed generation, enable an open market and secure the reliability of supply. Further information regarding the activities can be found in ref [6].

Subject 1: Demand Response and Market

Demand as Frequency Controlled Reserve

This activity investigated the feasibility of demand as a frequency controlled normal and disturbance reserve. The project is done by CET and Ea Energy Analysis and supported by PSO funds.

Subject 2: Island Operation

EU More Microgrids

CET participates in an EU-funded project regarding island operation of distribution systems. Bornholm is used as a demonstration case.

Control Architecture for Intentional Islanding

A PhD project focuses on control architecture of future power systems specifically in relation to transition between normal operation and island operation. Data from Bornholm is used. The project is a part of the Nextgen project supported by Energinet.dk.

Subject 3: Wind Power Integration

More Wind

This activity focuses on the situation where energy from Wind turbines increases, from today's 22% to maybe 40%.

Coordinated Frequency Control

This activity includes a PhD project with the main objective to develop a dynamic model and control scheme implemented in a Power Factory simulation tool, design of active frequency control scheme for the Vestas wind turbines and full scale implementation at wind turbines on Bornholm. This is done by Centre for Electrical Technology and Vestas.

Subject 4: Experimental Research Platform

Dynamic Simulation Platform

A dynamic simulation model of Bornholm is developed using the Power Factory tool and validated.

PowerLabDK

CET has been granted a pre-project in order to concretize an experimental research platform for the future power system. The experimental research platform is expected to consist of laboratory facilities, for tests under controlled conditions and a full-scale demonstration system. See figure in appendix 2.

Phasor Measurement Units (PMU)

CET has developed novel measurement equipment, phasor measurement units (PMU's), which with high time resolution and accuracy has the ability to measure voltage angle differences in the power system. Two PMU's are preliminary installed at block 5 and block 6. The installations will be made permanent and an additional PMU will be located in HASLE.

Subject 5: Transportation

Vehicle to Grid and plug-in hybrid cars

The project developes and demonstrate vehicle to grid and plug-in hybrid cars, with the goal to make a very visible showcase for the 2009 Climate Summit in Copenhagen.

Balancing Wind with Electric cars

A PhD project regarding balancing wind power by electric vehicles focusing on fault tolerant control and operation has been suggested. Bornholm will be used as a show case.

XV. POTENTIAL FUTURE ACTIVITIES

This section provides an overview of potential future activities:

- Local online electric power market for real-time balancing and ancillary service provision
- Distribution network operation by use of D-var Syncroneous Condensors (AMSC)
- Distribution network on by use of fly wheels (Beacon Power)
- Physical Virtual Power Plant
- IEC61850 communication
- Demonstration of improved active power control by demand as frequency controlled reserve
- European implementation and demonstration of active distribution network (Ecogrid)

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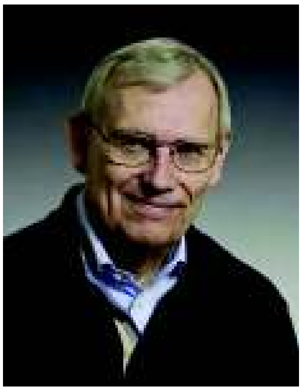
DTU Elektro, CET, October 2007

XVII. BIOGRAPHIES

Jacob Østergaard was born in Denmark 1969. He received his M.Sc.EE. degree in electrical engineering from The Technical University of Denmark in 1995. He has been working as Development engineer and area responsible for the Danish Research Institute for Danish Electric Utilities. Currently he is working for The Technical University of Denmark as professor in Electric Technology. His experience lies in the area of electricity production, transmission, distribution and demand. He is a member of IEEE. joe@elektro.dtu.dk



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APPENDIX 1
Data for Wind Turbines [2]

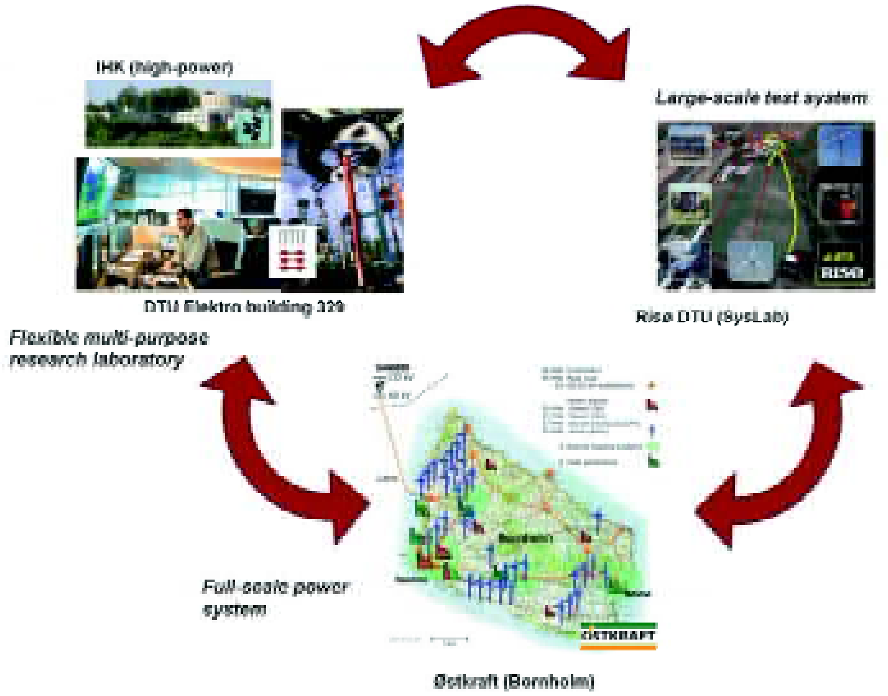
Year	Nominal power	Voltage	Area
	[kW]	[kV]	
1992	225	0.4	Rutsker
1992	225	0.4	Rutsker
1992	225	0.4	Rutsker
1996	225	0.4	Bodilsker
1996	225	0.4	Bodilsker
1996	225	0.4	Bodilsker
1980	55	0.4	Klemensker
1982	30	0.4	Bodilsker
1988	130	0.4	Nyker
1988	130	0.4	Nyker
1989	18	0.4	Vestermarie
1999	660	10.0	Rutsker
1999	11	0.4	Østermarie
2002	30	0.4	Rutsker
2002	660	10.0	Olsker
2002	900	10.0	Bodilsker
2002	900	10.0	Bodilsker
2002	900	10.0	Bodilsker
2002	800	10.0	Knudsker
2002	800	10.0	Knudsker
2002	800	10.0	Knudsker
2002	1,300	10.0	Rutsker
2002	1,300	10.0	Rutsker
2002	1,300	10.0	Rutsker
2002	1,300	10.0	Åker
2002	1,300	10.0	Åker
2002	1,300	10.0	Åker
2002	1,300	10.0	Åker
2002	1,300	10.0	Åker
2006	1,750	10.0	Rutsker
2006	1,750	10.0	Rutsker
2006	1,750	10.0	Rutsker
2006	2,000	10.0	Åker
2006	2,000	10.0	Åker
2006	2,000	10.0	Åker
	29,824		

Source: www.ens.dk

APPENDIX 2
PowerLabDK

PowerLabDK
A National Research Platform
for Electric Power and Energy

Concept of PowerLabDK



10 DTU Electrical Engineering, Technical University of Denmark Presentation name 17/04/2008

5. The Bornholm Power System

The Connection between Sweden and Bornholm

John Eli Nielsen

THE BORNHOLM POWER SYSTEM
The connection between Sweden and Bornholm

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ABSTRACT: The island of Bornholm is a Danish island situated just south of Sweden. The ØSTKRAFT Company is the Distribution System Operator on the island. A normal distribution system in Denmark connected to a primary 132 kV or 150 kV Substation has a peak load between 50-60 MW. The peak load at Bornholm is 55 MW. In many respects the distribution system on Bornholm has many of the characteristics known from other Danish distribution systems. Its ability to go into planned island mode makes it special and a good "case" for research and demonstration of new technology. The key figures for the 132 kV Substation in Sweden and the connection between Sweden and Bornholm, are given in this paper.

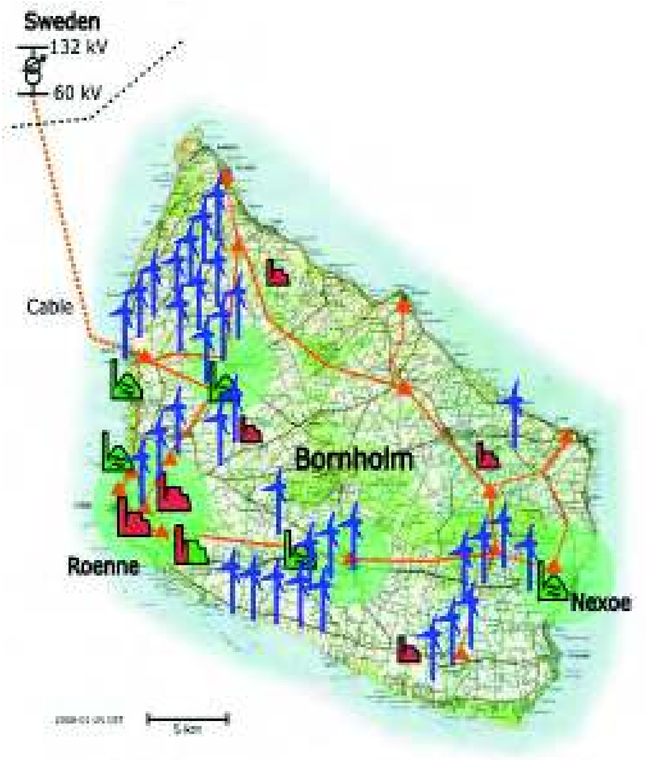


Figure 1 The island of the Bornholm

Keywords: Bornholm, Power System, Scada System, Settlement system, Key figures.

Abbreviations:

TSO	Transmission System Operator
DNO	Distribution Network Operator
OLTC	On Line Tap Changing transformer
TRF	Transformer
CAB	Cable

I. THE 132 kV SUBSTATION IN SWEDEN

E-ON is the DSO in the southen part of Sweden. The company owns the equipment in the TOMELILLA and BORRBY substations. From the 132 kV substation TOMELILLA, there is an overhead line to the 132 kV substation BORRBY. At the 132 kV BORRBY feeder in the TOMELILLA substation, the Scada system measures the following values:

- The Voltage in kV
- The Active Power in MW
- The Reactive Power in MVAr

In the BORRBY substation there is two 132/60 kV transformers. One of them supplies the connection to HASLE on Bornholm, the other BORRBY CITY. At the 60 kV HASLE and BORRBY CITY feeders, the Scada system measures the following values:

- The Voltage in kV
- The Active power in MW
- The Reactive power in MVAr

The E-ON scada system has the following archives:

- 10 seconds instantaneous values (14 days)
- 1 minut average values (1 month)
- 1 hour average values (1 year)

The transformer in the BORRBY substation cannot be operated as an OLTC transformer, because the tap changer is fixed. Consequently, the position is not transferred to E-ON's control room in Malmø. Data for the transformer can be found in table 1.

Station	BOR	
From Node, to node	BOR132, BOR060	
Rating	63,0	[MVA]
Rated	150/72,5	[kV]
Pos. seq er, ek	0,38 9,99	[%]
Zero seq er, ek	0,38 9,99	[%]
Tapchanger	135+-9x1,67%/69	[kV]
Max/Min	155/115	[kV]
Control node	HAS060	
Voltage	62,00+-0,50	[kV]

Table 1. Data for the BORRBY 132/60 kV transformer.

II. THE CONNECTION TO SWEDEN

Energinet.dk is the TSO in Denmark. The company owns the equipment between the BORRBY substation in Sweden and the HASLE substation at Bornholm.

The 60 kV side of the transformer in the BORRBY substation is connected to the 60 kV substation HASLE at Bornholm, by the overhead lines/cables shown in table 2.

Type	Dimension [mm2]	Length [km]
Overhead Line	3x1x 127 Cu	4.2
Cable	3x1x 400 Cu	0.7
Cable (Offshore)	3x1x 240 Cu	43.5
Overhead Line	3x1x 400 Cu	1.4
		49.8

Table 2. Connection between BORRBY and HASLE.

The steady state electrical model (pi equivalent) for the connection between BORRBY and HASLE uses the constants shown in table 3.

Type	R1 [Ω /km]	X1 [Ω /km]	C1 [uMho/km]
OHL 127 Cu	0.1580	0.3568	3.6463
CAB 400 Cu	0.1011	0.0990	61.3000
CAB 240 Cu	0.1403	0.1010	51.8000
CAB 400 Cu	0.1011	0.0990	61.3000

Table 3. Data for the connection BORRBY to HASLE

The steady state electrical model (pi equivalent) for the connection between BORRBY and HASLE uses the constants shown in table 4.

Type	R1 [Ω]	X1 [Ω]	B1 [uMho]	B2 [uMho]
OHL 127 cu	0.6636	1.4986	7.66	7.66
CAB 400 cu	0.0708	0.0693	21.46	21.46
CAB 240 cu	6.1031	4.3935	1,126.65	1,126.65
CAB 400 cu	0.1415	0.1386	42.91	42.91

Table 4. Pi equivalent for BORRBY to HASLE

III. THE HASLE SUBSTATION

At the 60 kV BORRBY feeder, the Scada system measures the following values:

- The Voltage in kV
- The Current in A
- The Active power in MW
- The Reactive power in MVAr

The Østkraft scada system has the following archives:

- 10 seconds instantaneous values (14 days)
- 1 minut average values (1 month)
- 1 hour average values (1 year)

At the 60 kV BORRBY feeder the Settlement system measures the following values:

- The Active power as average MWh pr 15 minuts
- The Reactive power as average Mvarh pr 15 minuts

IV. Data from 2007-09-10

In Appendix 4 , 5 and 6 is shown the data measured in Tomelilla, Borrby and Hasle Monday, Seeptember 10 2007.

V. Swedish Grid Code

According to the Swedish grid Code, Østkraft and/or Energinet.dk should be able to Exchange active power with E-On without exchanging any reactive power on the while high voltage side of the transformer

VI. Conclusion

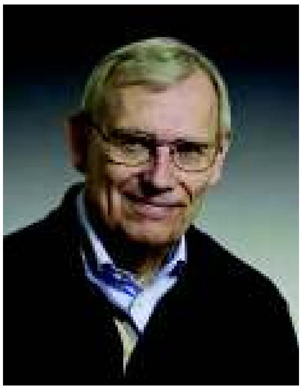
Data can today be exchanged between Østkraft, Energinet.dk and E-On by the Elcom protocol. It is therefore suggested that Østkraft and Energinet.dk ask E-On for data (MW, Mvar, Voltage and breaker positions) on both side of the Borrby transformer, to be shown in the Scada systems in Ballerup and Rønne. E-On could of course be interested to see the same sort of data from the Hasle substation.

It it also suggested that the tapchanger on the Borrby transformer is re-designed, so the variations in Voltage comming from the 132 kV side of the transformer could be eliminated.

VII. REFERENCES

[1] Data from E-ON
2007-09-10_TLA-BOY 02.xls
[2] Data from Østkraft
2007-09-10_Hasle.xls

VIII. BIOGRAPHY



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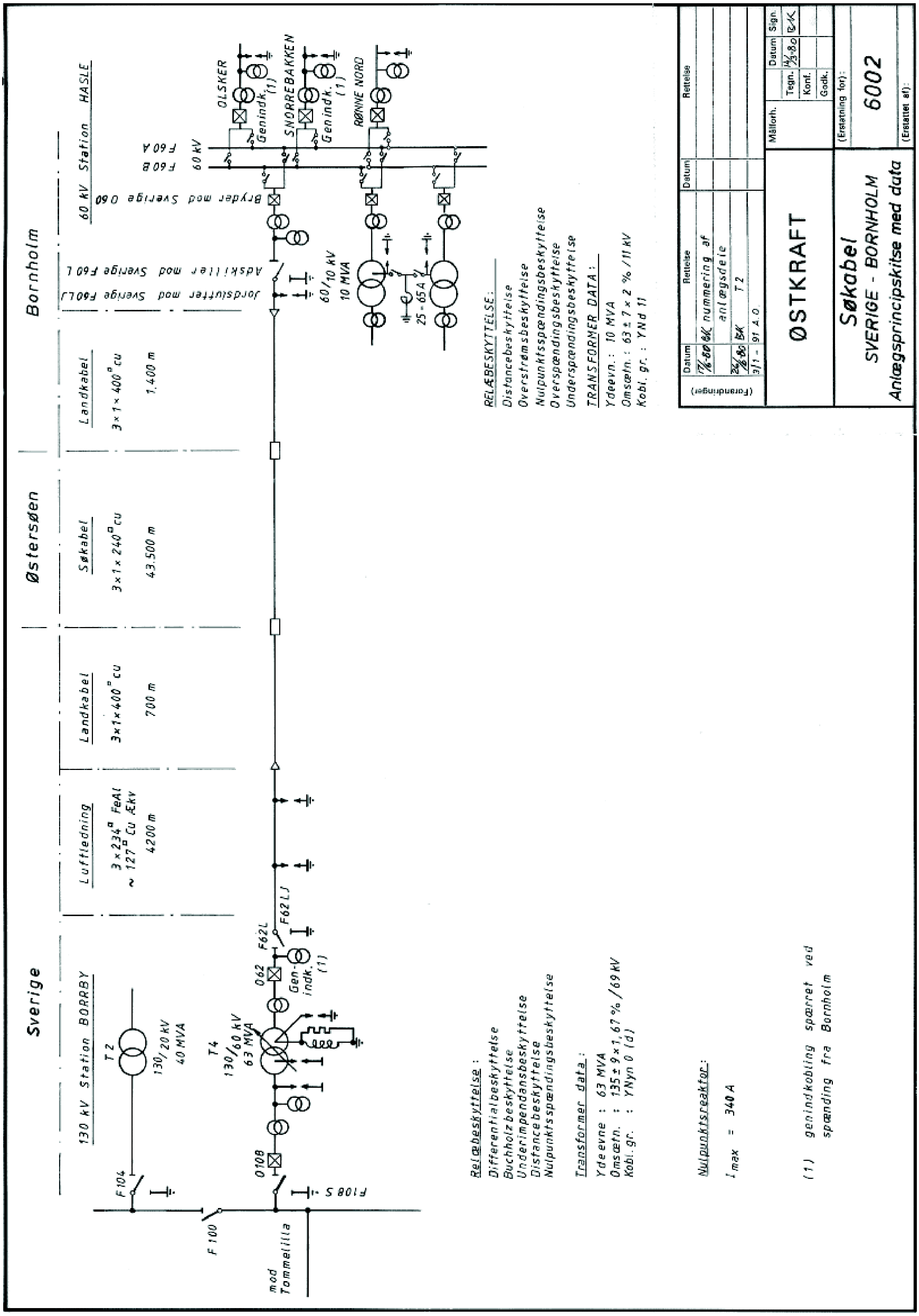
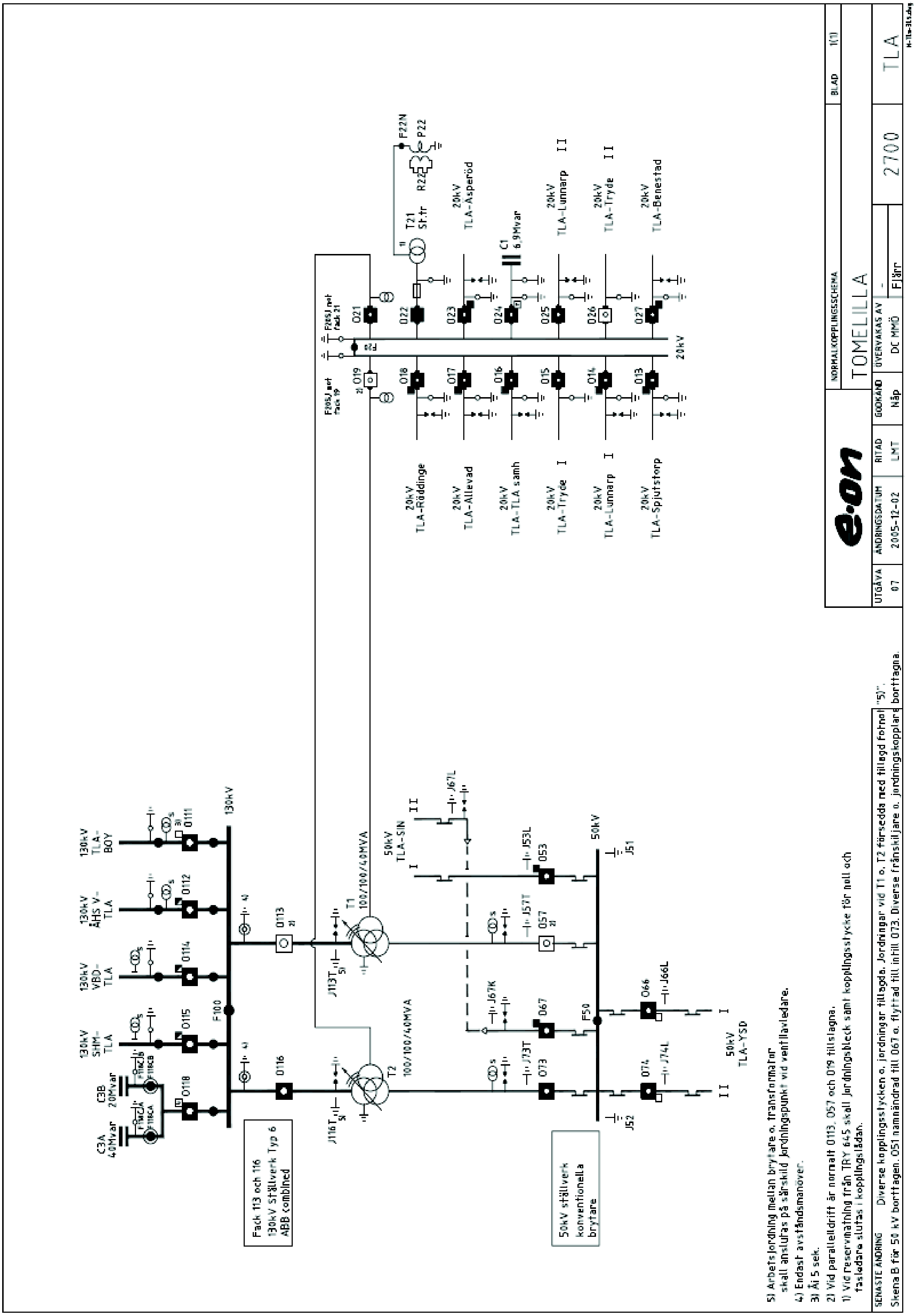
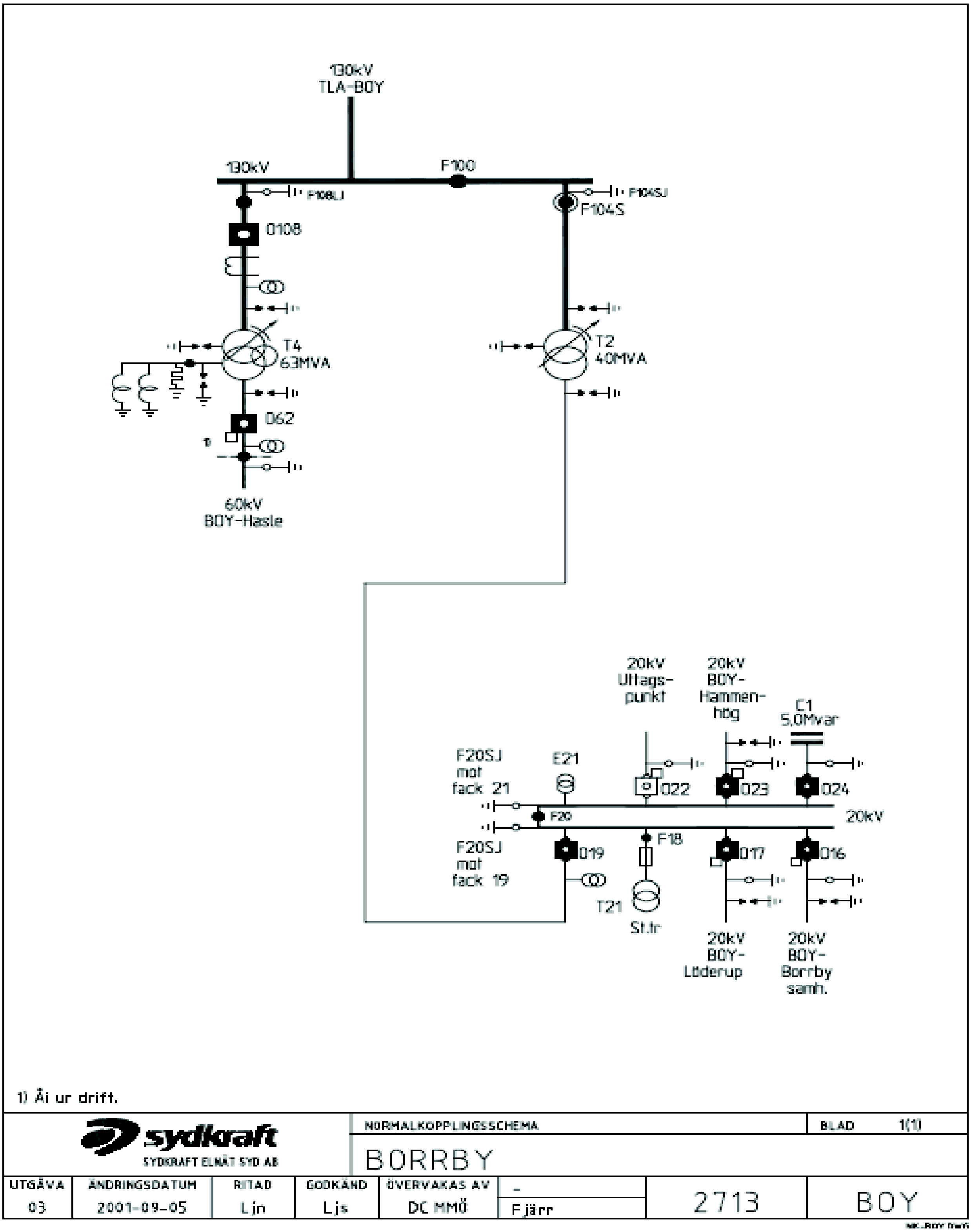
Appendix 1 The connection to Sweden



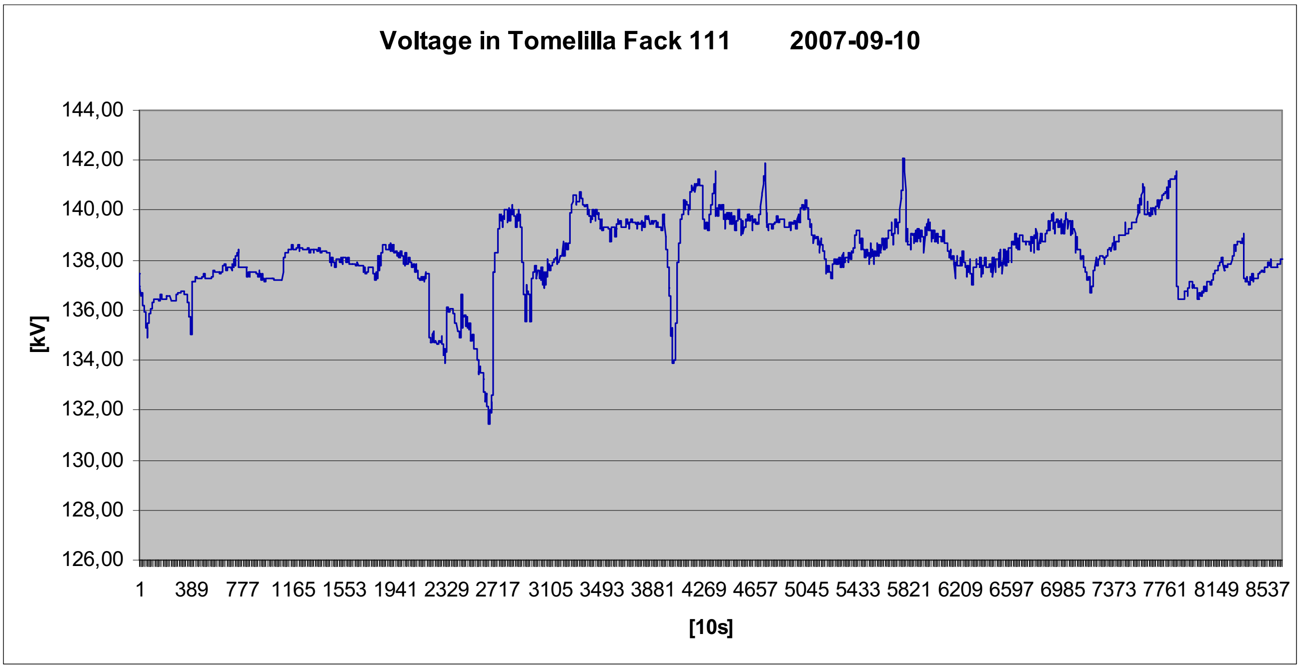
Appendix 2 Substation Tomelilla (TLA)



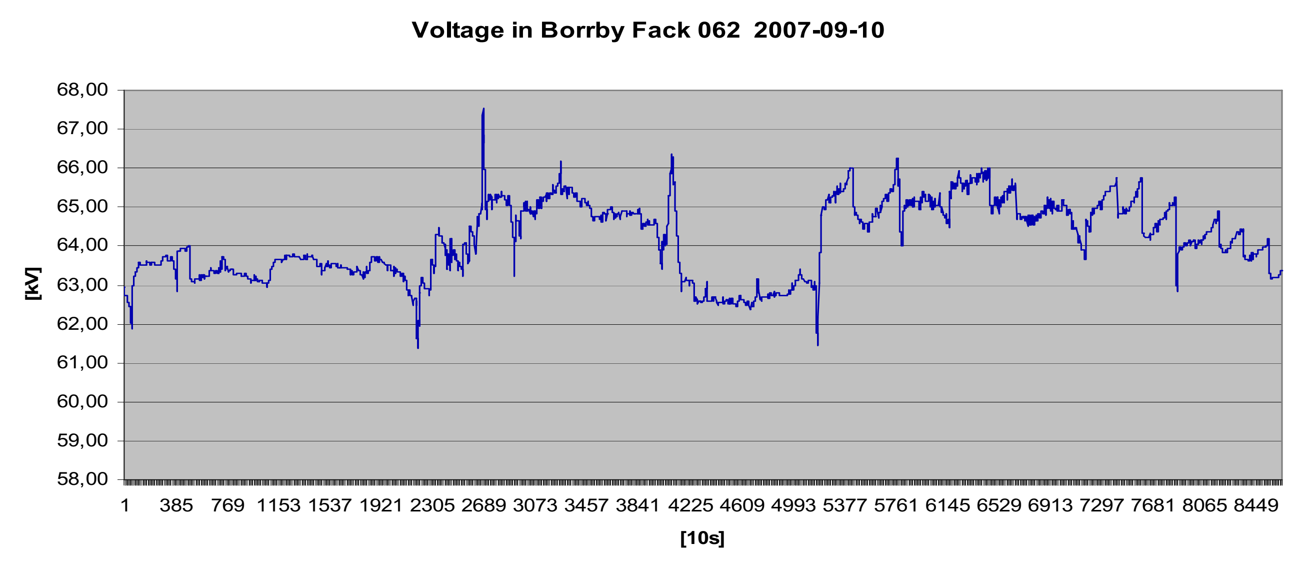
Appendix 3 Substation Borrby (BOY)

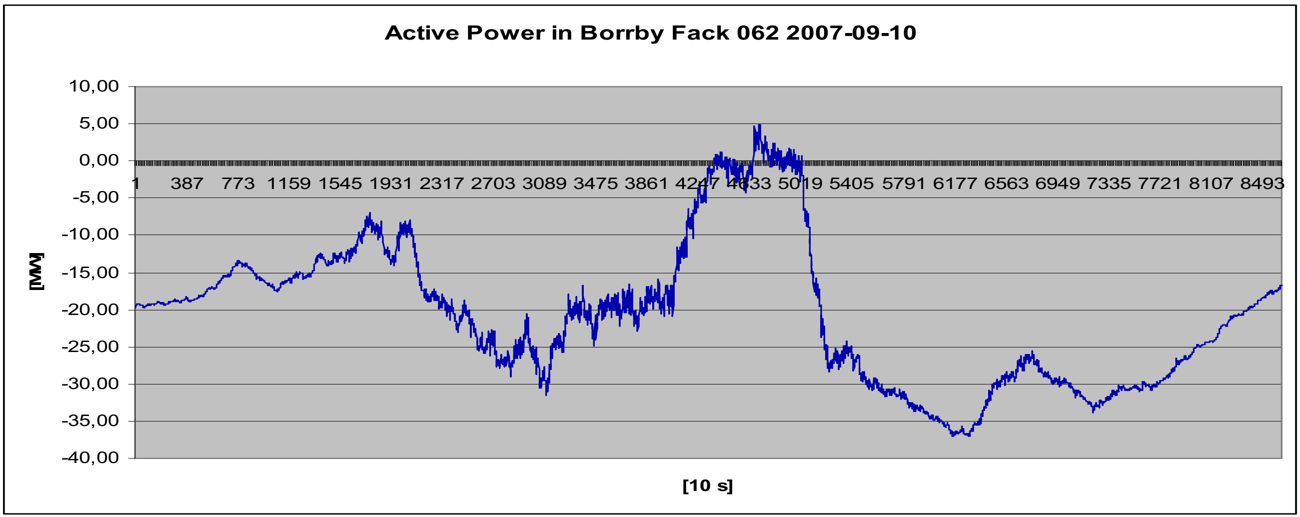


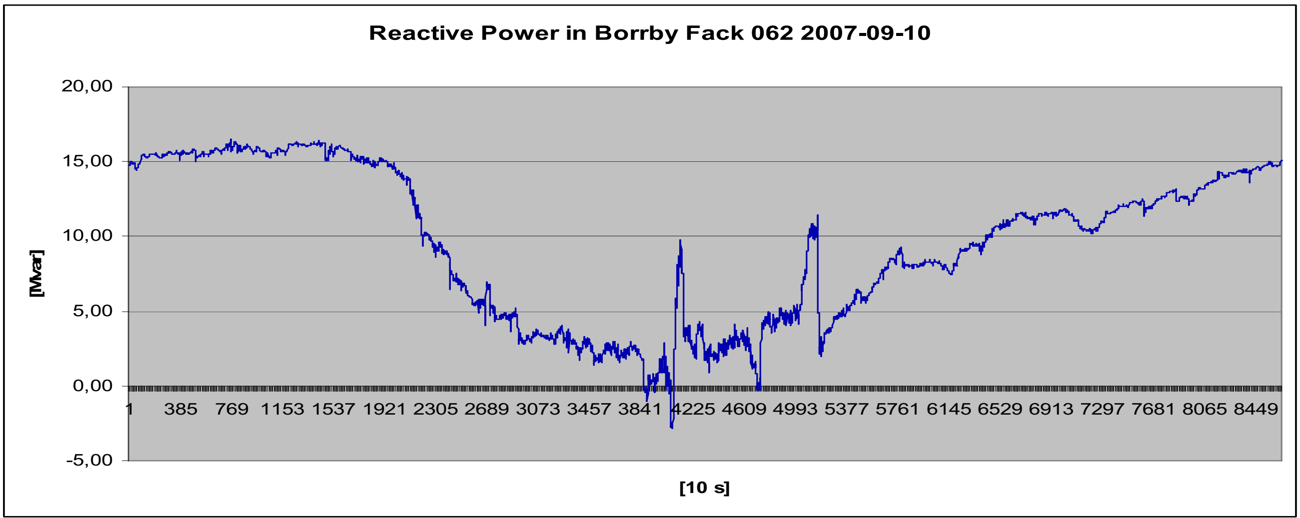
Appendix 4 Voltage in Tomelilla Fack 111 2007-09-10



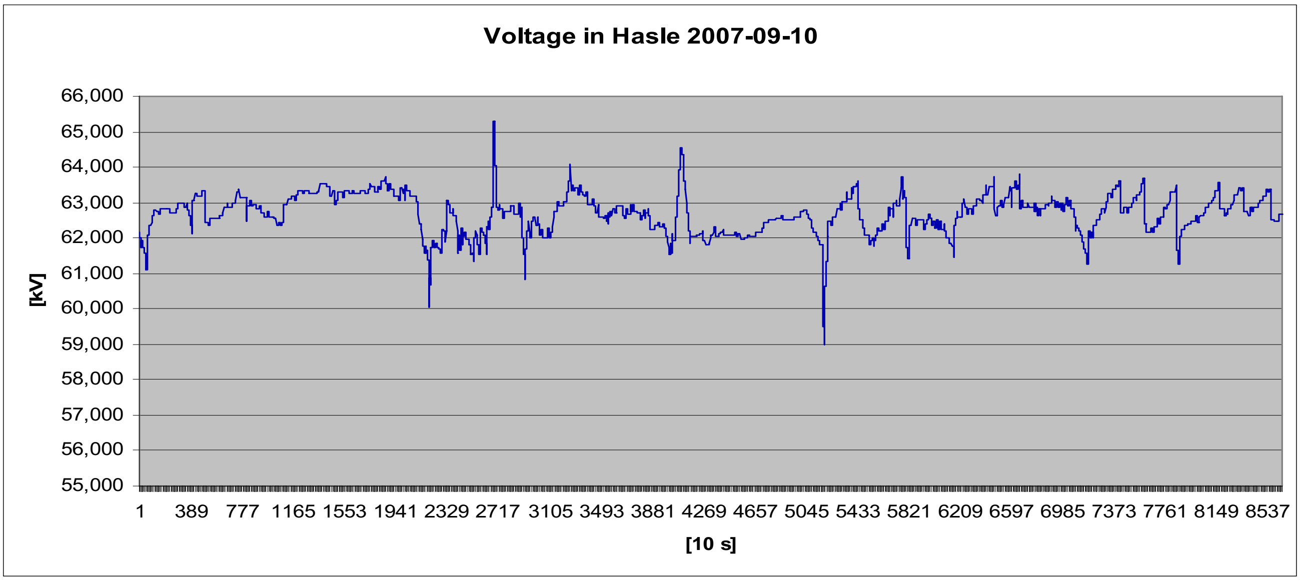
Appendix 5 Voltage, Active Power and Reactive Power in Borrby Fack 062 2007-09-10

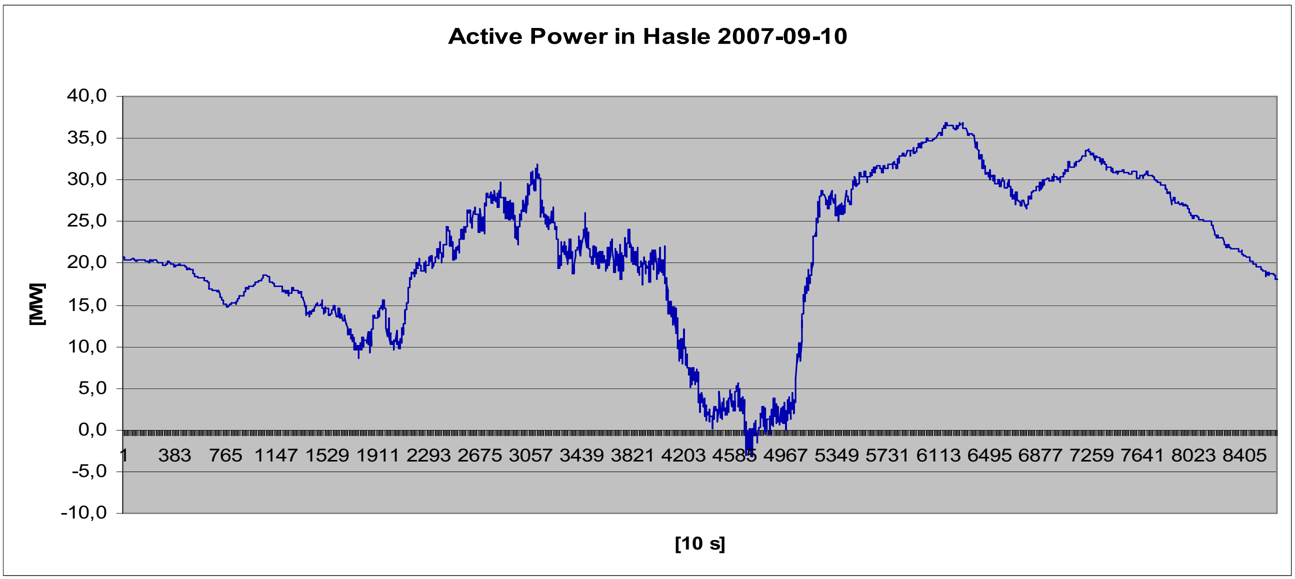


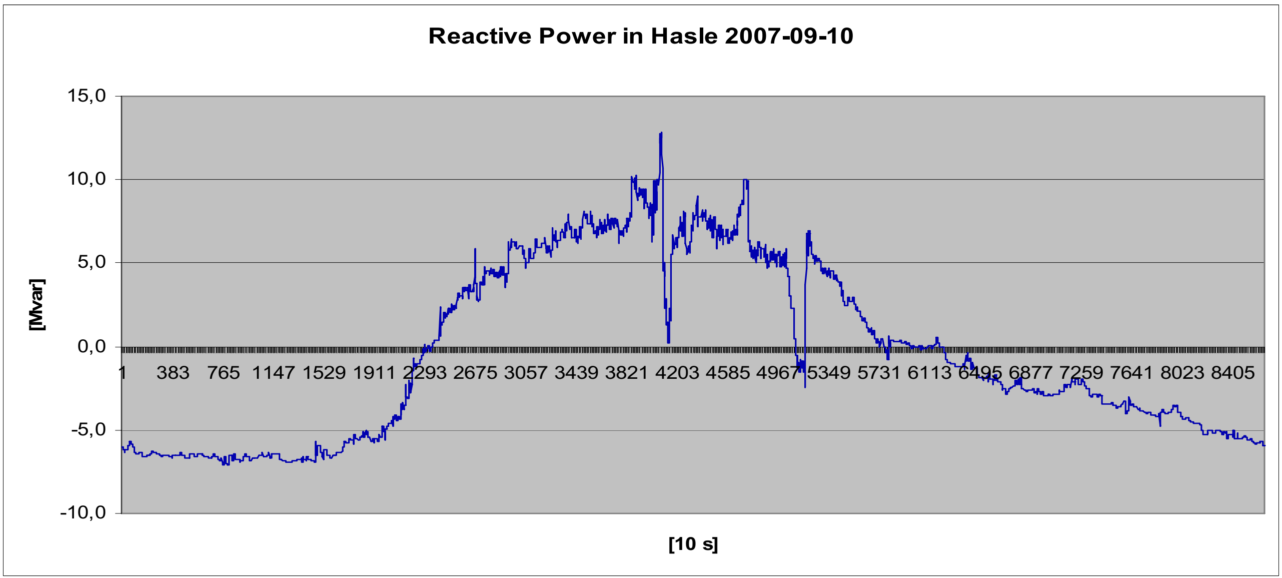




Appendix 6 Voltage, Active Power and Reactive Power in Hasle 2007-09-10







Appendix 7. Data for 132/60 kV transformer in BORRBY

Station	Node	Node		Rating	Rated	Syn	Syn	Syn	Nul	Nul	Tapchanger	Max	Min	Control	Voltage
Id	From	To	Id	[MVA]	[kV]	er [%]	ex [%]	ek [%]	er [%]	ex [%]		[kV]	[kV]	Node	[kV]
BOR	BOR132	BOR060	1	63,0	150/72,5	0,38	9,99	9,99	0,38	9,99	135+-9x1,67%/69 kV	155	115	HAS060	62,00+-0,50

Utgåva 1

Fabrikat Asea | Typ TBA 43 | Tillv.nr 7176 292

Best.brev 9C 53/1-IKS | Beställd enl. | Provad den | Provningsprot.

Omsättning kV	155,29 / 69	135 / 69	121,5 / 69	114,71 / 69		Isolationsnivå kV	Uppl. 550	Nedl. 325
Belastning: Upplindning A	234	269	299	299		Provsp. 1 min kV	150	140
Medellindning A						Märksp. (Un) kV	135	69
Nedlindning A	527	527	527	527		+Reglering %	9x1,67	
						—Reglering %	9x1,67	
Eff ONAF/ MVA	63	63	63	59,4		Ekv.schema ohm		
Eff ONAN MVA	38	38	38	36		vid bas kV		
Max.eff vid 0° MVA						Koppling	YN	yno 2)
ek %	10,6	9,99	9,78	9,26				
Pk75 kW						Io % 0,187 vid Un	Io % 1,08 vid 1,1 Un	
Zo 1) ohm	56,2	49,9		44,6		Po kW 37,3		

Strömtransf.	i 135 kV lindn. 3 st	Omsättning 300-600 /2 / / A	1 mätkärna
	i 135 kV lindn. st	Omsättning 600-1200/2 / / A	2 reläkärnor
	i 69 kV lindn. 3 st	Omsättning 600-1200/2 / / A	1 mätk, 2 reläkärnor 600/1200/2 A

Kompletterande uppgifter, omkopplingsmöjligheter mm.

1) På 135 kV-lindning

2) Transformatorn har d-kopplad utjämningslindning (10 kV)

Genomföringar: 135 kV: GOB 650 LF 123 113-B
Nolluttag: GOB 380 LF 123 095-B
69 kV: GOB 325 LF 123 089-B
Utj lindn: DIN 24/630

Transformator		Märkeffekt MVA	Märkomsättning kV	Station	
T 20 207	3 fas	63	155,29-114,71/69	BOY	T

Sydkraft Transformatorkort

Appendix 8. Data for 60 kV Cables and Overhead lines

From	To	Id	Type	Type	Length	R1	X1	C1	R1	X1	B1	B2	Max	Max	Max	Max
					m	Ω/	Ω/	uMho/	Ω	Ω	uMho	uMho	Amp	Amp	Amp	Amp
						km	km	km					v5C	v20C	v30C	
BOR	**HAS**				**49.800**				**6,9790**	**6,1000**	**1.010,27**	**1.387,09**	**465**	**465**	**465**	**600**
BOR	HAS	1	OHL	3x1x234 IBIS+None	4.200	0,1580	0,3568	3,6463	0,6636	1,4986	7,66	7,66	465	465	465	600
BOR	HAS	2	CAB	3x1x400 PEX Cu+382Pb+107Al	700	0,1011	0,0990	61,3000	0,0708	0,0693	21,46	21,46	465	465	465	600
BOR	HAS	3	CAB	3x1x240 PEX Cu+345Pb+990Al	43.500	0,1403	0,1010	51,8000	6,1031	4,3935	1.126,65	1.126,65	465	465	465	600
BOR	HAS	4	CAB	3x1x400 PEX Cu+382Pb+1074Al	1.400	0,1011	0,0990	61,3000	0,1415	0,1386	42,91	42,91	465	465	465	600

6. The Bornholm Power System

The 60 kV Network

John Eli Nielsen

THE BORNHOLM POWER SYSTEM
The 60 kV Network

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ABSTRACT: The island of Bornholm is a Danish island situated just south of Sweden. The ØSTKRAFT Company is the Distribution System Operator on the island. A normal distribution system in Denmark connected to a primary 132 kV or 150 kV Substation has a peak load between 50-60 MW. The peak load at Bornholm is 55 MW. In many respects the distribution system on Bornholm has many of the characteristics known from other Danish distribution systems. Its ability to go into planned island mode makes it special and a good "case" for research and demonstration of new technology. The key figures for the 60 kV Network at Bornholm are given in this paper.

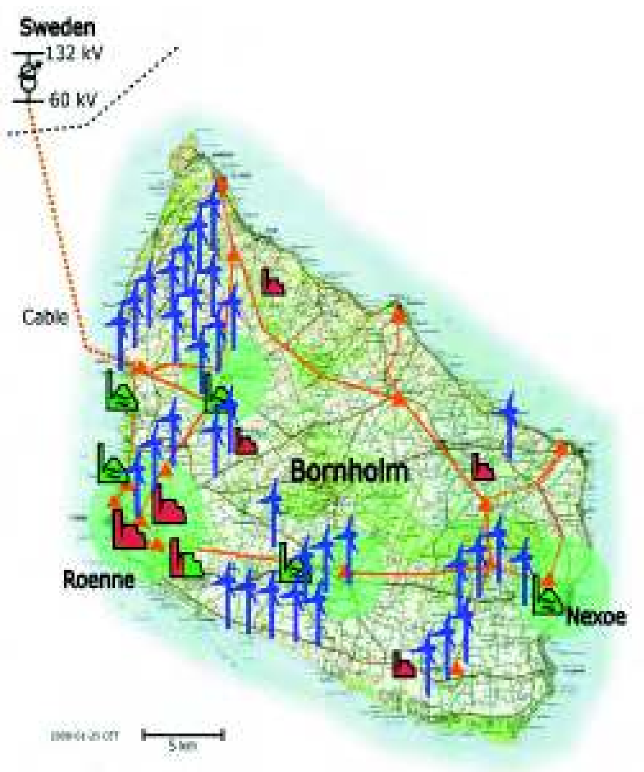


Figure 1 The island of the Bornholm

Keywords: Bornholm, Power System, 60 kV Network Key figures.

I. THE 60 KV NETWORK

The 60 kV Network is meshed and concists of the following elements:

- Nodes 18
- 60/10 kV OLTC Transformers 22/215 MVA
- Cables and lines 22
- Length of Overhead Lines 73 km
- Length of Cables 58 km

These elements are connected as shown in figure 2. Data for the elements can be found in the Appendices

Figure 2 The 60 kV network 2006

In general the following are measured for a 60/10 kV transformer:

- Voltage in kV (primary and secondary)
- Current in A (primary and secondary)
- The Tap position
- Cos phi
- MW and Mvar on the secondary side

Only one frequency measurement can be found in the Scada system (HASLE substation).

The Oestkraft Scada system has archieves for 10 seconds Instantaneous values, 1 minutes average values and 1 hour average values.

II. MEASUREMENTS

To be able to perform a loadflow calculation you need data and measurements. The data for the Bornholm Power System is given in Appendix 2 and 3. In Appendix 4 to 7 is analyzed what measurements are needed asap, for being able to do a fair good loadflow calculation for the Bornholm Power System.

III. BALANCING

Sunday, February 1st 2009, at 00:49 hours, there was a situation in the Bornholm Power System where all load where covered by Wind Power. No production took place at the central Power plant, and there was no active power interchange with Sweden. Regarding reactive Power 5.1 Mvar was sent to Sweden. The voltage is the HAS060 station was 64.325 kV.

Station	Felt	Id	MW	Mvar
HAS060	Sweden	Borrby	0.0	-5.1
VÆR010	Diesel	Diesel	0.0	0.0
VÆR010	Blok 5	Blok 5	0.0	0.0
VÆR010	Blok 6	Blok 6	0.0	0.0
VÆR010	Blok 7	Blok 7	0.0	0.0
BOD	NXV	VP Gadeby	2.373	**0.000**
HAS	VIN	VP Hasle	3.499	**0.000**
HAS	VIN	VP Vysteby	4.990	0.369
OLS	KRU	VP Krusegård	1.324	**0.000**
ÅKI	BIO	Biokraft	321	-0.049
ÅKI	KAV	VP Kalby	5.387	-0.387
ÅKI	SOV	VP Sose	5.704	-1.278

Table 1.
Production data from Network Manager and Sonwin
Numbers in red are estimated data

	Station	kV	Trin	Ampere	Cos phi
1	ALL	10.781	5	113.4	0.998
2	BOD	10.642	5	71.5	0.620
3	GUD	10.573	9	62.9	0.999
4	HAS	10.412	5	358.0	**0.500**
5	NEX	10.573	5	121.4	0.971
6	OLS	10.621	9	46.4	**0.500**
7	POU	10.649	5	45.5	0.999
8	RNO	10.515	5	140.4	0.985
9	RSY	10.635	5	90.2	**0.500**
10	SNO	10.625	5	37.2	**0.500**
11	SVA	10.670	5	88.2	0.993
12	VES	10.520	5	82.7	0.692
13	VIA	10.553	5	127.3	0.981
14	ØST	10.549	4	69.8	0.938
15	ÅKI	10.606	5	497.7	0.497

Table 2.
Load data from Network Manager
Numbers in red are false data.
They are estimated to be 0.850.

A PowerWorld [2] model for Bornholm has been setup, on the basis of the data mentioned in the appendices, together with the data coming from table 1 and 2. An indication of the result are given in appendix 9 and table 3.

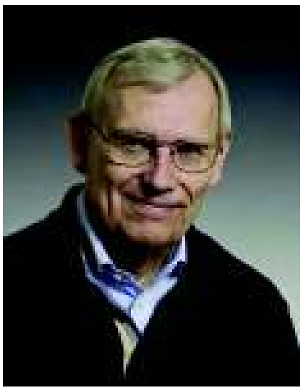
	Station	Ampere	Ampere	Ampere
		Measured	Calculated	Difference
1	ALL	113	114	1
2	BOD	72	72	0
3	GUD	63	63	0
4	HAS	358	369	**11**
5	NEX	121	121	0
6	OLS	46	42	4
7	POU	46	46	0
8	RNO	140	139	1
9	RSY	90	91	1
10	SNO	37	37	0
11	SVA	88	89	1
12	VES	83	82	1
13	VIA	127	127	0
14	ØST	70	70	0
15	ÅKI	498	485	**13**

Table 3.
Measured and computed ampere through transformers.

IV. REFERENCES

[1] www.oestkraft.dk
"Yearly Report", 2006
[2] www.powerworld.com

V. BIOGRAPHY



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Appendix 1 Substations

BOR	Borrby	135/69 kV
ALL	Allinge	63/11 kV
BOD	Bodilsker	63/11 kV
DAL	Dalslunde	Connection
GUD	Gudhjem	63/11 kV
HAS	Hasle	63/11 kV
NEX	Nexø	63/11 kV
OLS	Olsker	63/11 kV
POU	Poulsker	63/11 kV
SNO	Snorrebakken	63/11 kV
SVA	Svaneke	63/11 kV
RNO	Rønne Nord	63/11 kV
RSY	Rønne Syd	63/11 kV
VES	Vesthavnen	63/11 kV
VIA	Viadukten	63/11 kV
VÆR	Værket	63/11 kV
ØST	Østerlars	63/11 kV
ÅKI	Åkirkeby	63/11 kV

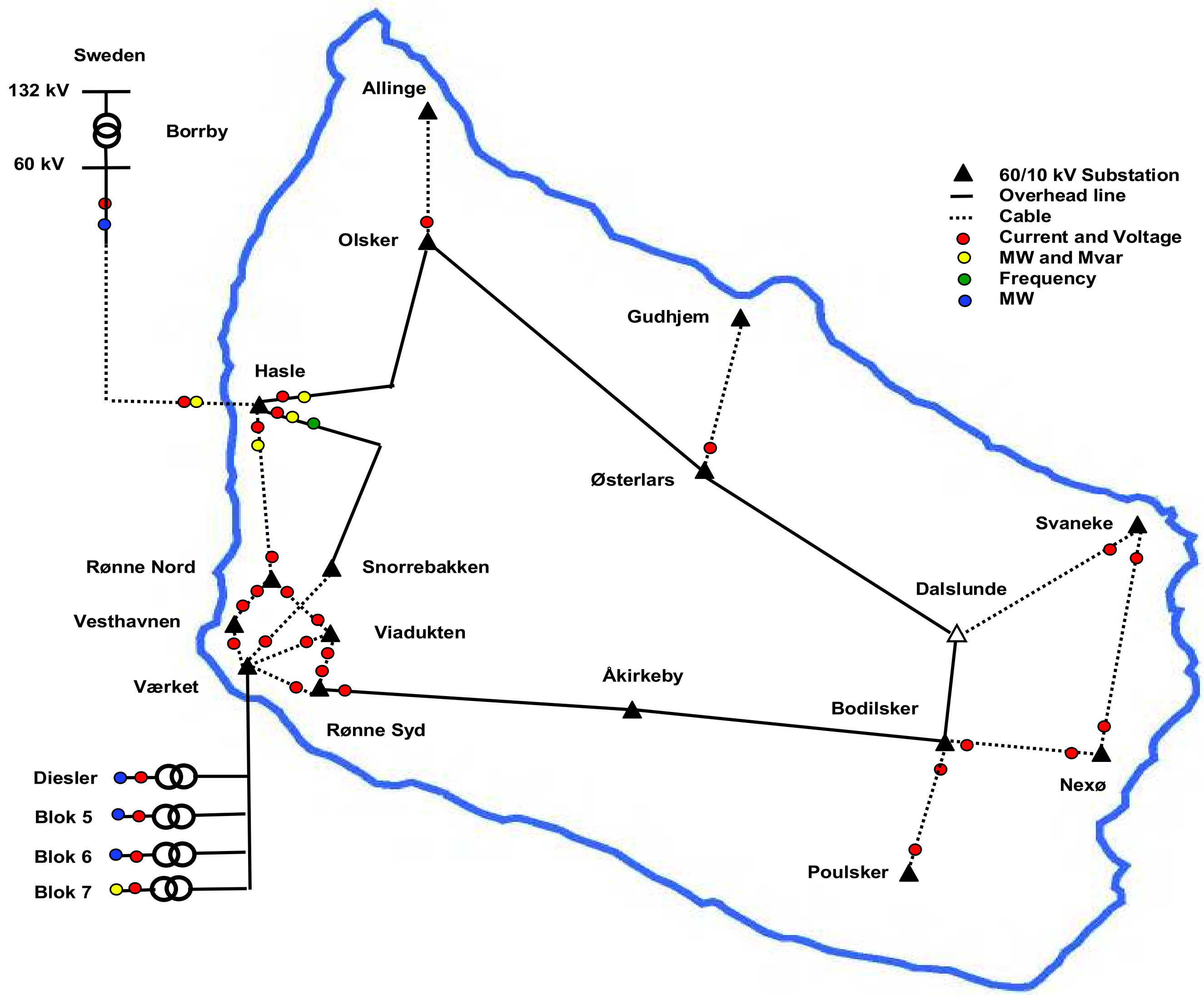
Appendix 2. Data for transformers

Station Id	Node From	Node To	Id	Rating [MVA]	Rated [kV]	Syn er [%]	Syn ex [%]	Syn ek [%]	Nul er [%]	Nul ex [%]	Tapchanger	Max [kV]	Min [kV]	Control Node	Voltage [kV]
ALL	ALL060	ALL010	1	10,0	72/12	0,61	8,40	8,40	0,61	7,50	63+-7x2%/11 kV	72	54	ALL010	10,50+-1,6%
ALL	ALL060	ALL010	2	10,0	72/12	0,53	8,04	8,04	0,53	7,24	63+-7x2%/11 kV	72	54	ALL010	10,50+-1,6%
BOD	BOD060	BOD010	1	4,0	72/12	0,30	7,20	7,30	0,30	7,20	60+-9x1,7%/10 kV	69	51	BOD010	10,50+-1,7%
BOD	BOD060	BOD010	2	10,0	72/12	0,54	8,90	8,87	0,54	7,50	63+-7x2%/11 kV	72	54	BOD010	10,50+-1,7%
DAL															
GUD	GUD060	GUD010	1	4,0	72/12	0,30	7,20	7,30	0,30	7,20	60+-9x1,7%/10 kV	69	51	GUD010	10,60+-1,4%
HAS	HAS060	HAS010	1	10,0	72/12	0,54	8,50	8,87	0,54	7,33	63+-7x2%/11 kV	72	54	HAS010	10,50+-1,6%
HAS	HAS060	HAS010	2	10,0	72/12	0,54	8,10	8,10	0,54	7,33	63+-7x2%/11 kV	72	54	HAS010	10,50+-1,6%
NEX	NEX060	NEX010	1	10,0	72/12	0,62	8,50	8,50	0,62	8,50	63+-7x2%/11 kV	72	54	NEX010	10,60+-1,6%
NEX	NEX060	NEX010	2	10,0	72/12	0,61	8,40	8,40	0,61	8,40	63+-7x2%/11 kV	72	54	NEX010	10,60+-1,6%
OLS	OLS060	OLS010	1	4,0	72/12	0,30	7,40	7,30	0,30	7,40	60+-9x1,7%/10 kV	69	51	OSL010	10,50+-1,5%
OLS	OSL060	OSL010	2	4,0	72/12	0,30	7,40	7,30	0,30	7,40	60+-9x1,7%/10 kV	69	51	OSL010	10,50+-1,5%
POU	POU060	POU010	1	10,0	72/12	0,59	8,14	8,14	0,59	3,81	63+-7x2%/11 kV	72	54	POU010	10,50+-1,7%
SNO	SNO060	SNO010	1	10,0	72/12	0,54	8,60	8,87	0,54	8,60	63+-7x2%/11 kV	72	54	SNO010	10,50+-1,2%
SVA	SVA060	SVA010	1	10,0	72/12	0,54	8,30	8,30	0,54	8,30	63+-7x2%/11 kV	72	54	SVA010	10,50+-1,6%
RNO	RNO060	RNO010	1	10,0	72/12	0,58	7,94	7,94	0,58	7,40	63+-7x2%/11 kV	72	54	RN0010	10,50+-1,6%
RSY	RSY060	RSY010	1	10,0	72/12	0,62	8,30	8,30	0,62	8,30	63+-7x2%/11 kV	72	54	RSY010	10,50+-1,6%
VES	VES060	VES010	1	10,0	72/12	0,54	8,10	8,10	0,54	7,33	63+-7x2%/11 kV	72	54	VES010	10,50+-1,7%
VIA	VIA060	VIA010	1	10,0	72/12	0,54	7,90	7,90	0,54	7,90	63+-7x2%/11 kV	72	54	VIA010	10,50+-1,6%
VÆR	VÆR060	VÆR010	1	16,0	72/12	0,56	8,39	8,50	0,56	8,39	63+-7x2%/11 kV	72	54	O14010	10,50+-1,5%
VÆR	VÆR060	VÆR010	2	25,0	72/12	0,40	9,00	9,00	0,40	7,81	63+-7x2%/11 kV	72	54	VÆR010	10,50+-1,5%
ØST	ØST060	ØST010	1	6,3	72/12	0,70	8,60	8,50	0,70	8,60	63+-7x2%/11 kV	72	54	ØST010	10,40+-1,5%
ÅKI	ÅKI060	ÅKI010	1	10,0	72/12	0,54	8,80	8,87	0,54	7,50	63+-7x2%/11 kV	72	54	AKI010	10,60+-1,6%
ÅKI	ÅKI060	ÅKI010	2	6,0	72/12	0,30	7,30	8,80	0,30	7,30	63+-7x2%/10 kV	69	51	AKI010	10,60+-1,6%
				219,3											

Appendix 3 Data for 60 kV Cables and Overhead lines

From	To	Id	Type	Type	Length m	R1 Ω/ km	X1 Ω/ km	C1 uMho/ km	R1 Ω	X1 Ω	B1 uMho	B2 uMho	Max Amp v5C	Max Amp v20C	Max Amp v30C
ALL	OLS		CAB	3x1x150 PEX Al+25 Cu	4.276	0,2280	0,1460	44,0000	**0,9749**	**0,6243**	**94,07**	**94,07**	**325**	**325**	**325**
BOD	DAL		OHL	3x1x130 StAl+50Fe	4.138	0,2860	0,4086	2,8212	**1,1835**	**1,6908**	**5,84**	**5,84**	**430**	**360**	**300**
BOD	NEX		CAB	3x1x095 PEX Al+25 Cu	3.477	0,3520	0,1580	37,7000	**1,2239**	**0,5494**	**65,54**	**65,54**	**255**	**255**	**255**
BOD	POU		CAB	3x1x150 PEX Al+25 Cu	5.950	0,2280	0,1460	44,0000	**1,3566**	**0,8687**	**130,90**	**130,90**	**325**	**325**	**325**
BOD	ÅKI		OHL	3x1x130 StAl+50Fe	10.891	0,2860	0,4086	2,8212	**3,1148**	**4,4501**	**15,36**	**15,36**	**430**	**360**	**300**
DAL	SVA		CAB	3x1x150 PEX Al+25 Cu	7.531	0,2280	0,1460	44,0000	**1,7171**	**1,0995**	**165,68**	**165,68**	**325**	**325**	**325**
DAL	ØST		OHL	3x1x130 StAl+50Fe	9.924	0,2860	0,4086	2,8212	**2,8383**	**4,0549**	**14,00**	**14,00**	**430**	**360**	**300**
HAS	RNO		CAB	3x1x240 PEX Al+35 Cu	7.434	0,1390	0,1330	53,4000	**1,0333**	**0,9887**	**198,49**	**198,49**	**425**	**425**	**425**
HAS	OLS				11.407				**3,2624**	**4,6425**	**16,16**	**16,16**	**430**	**360**	**300**
HAS	OLS	1	OHL	3x1x130 StAl+50Fe	4.589	0,2860	0,4046	2,8498	1,3125	1,8567	6,54	6,54	430	360	300
HAS	OLS	2	OHL	3x1x130 StAl+50Fe	6.818	0,2860	0,4086	2,8212	1,9499	2,7858	9,62	9,62	430	360	300
HAS	SNO				9.805				**2,8042**	**3,9880**	**13,90**	**13,90**	**430**	**360**	**300**
HAS	SNO	1	OHL	3x1x130 StAl+50Fe	4.588	0,2860	0,4046	2,8498	1,3122	1,8563	6,54	6,54	430	360	300
HAS	SNO	2	OHL	3x1x130 StAl+50Fe	5.217	0,2860	0,4086	2,8212	1,4921	2,1317	7,36	7,36	430	360	300
NEX	SVA		CAB	3x1x150 PEX Al+25 Cu	9.780	0,2280	0,1460	44,0000	**2,2298**	**1,4279**	**215,16**	**215,16**	**325**	**325**	**325**
RNO	VIA		CAB	3x1x240 PEX Al+35 Cu	1.834	0,1390	0,1330	53,4000	**0,2549**	**0,2439**	**48,97**	**48,97**	**425**	**425**	**425**
OLS	ØST		OHL	3x1x130 StAl+50Fe	13.050	0,2860	0,4086	2,8212	**3,7323**	**5,3322**	**18,41**	**18,41**	**430**	**360**	**300**
VÆR	SNO				4.151				**0,9075**	**0,7030**	**196,22**	**109,60**	**300**	**300**	**300**
VÆR	SNO	1	OHL	3x1x130 StAl+50Fe	698	0,2860	0,4086	2,8212	0,1996	0,2852	0,98	0,98	300	300	300
VÆR	SNO	2	CAB	1x3x095 APBF Cu+Bz&Cu	3.453	0,2050	0,1210	88,0000	0,7079	0,4178	151,93	151,93	300	300	300
RSY	VIA		CAB	3x1x240 PEX Al+35 Cu	1.674	0,1390	0,1330	53,4000	**0,2327**	**0,2226**	**44,70**	**44,70**	**425**	**425**	**425**
RSY	VÆR		CAB	1x3x095 APBF Cu	2.861	0,2050	0,1210	88,0000	**0,5865**	**0,3462**	**125,88**	**125,88**	**300**	**300**	**300**
RSY	ÅKI		OHL	3x1x130 StAl+50Fe	10.995	0,2860	0,4086	2,8212	**3,1446**	**4,4926**	**15,51**	**15,51**	**430**	**360**	**300**
VES	RNO		CAB	3x1x300 PEX Al+35 Cu	2.200	0,1110	0,1290	56,5000	**0,2442**	**0,2838**	**62,15**	**62,15**	**480**	**480**	**480**
VES	VÆR		CAB	3x1x300 PEX Al+35 Cu	1.800	0,1110	0,1290	56,5000	**0,1998**	**0,2322**	**50,85**	**50,85**	**480**	**480**	**480**
VIA	VÆR		CAB	3x1x300 PEX Al+35Cu	1.481	0,1110	0,1290	56,5000	**0,1644**	**0,1910**	**41,84**	**41,84**	**480**	**480**	**480**
ØST	GUD		CAB	3x1x150 PEX Al+25 Cu	6.600	0,2280	0,1460	44,0000	**1,5048**	**0,9636**	**145,20**	**145,20**	**325**	**325**	**325**

Appendix 4 Measurements in the Bornholm 60 kV network



Apendix 5. 60 kV Transformers measurements

Station Id	Node From	Node To	Id	Rating [MVA]	Voltage Primary	Voltage Secondary	Current Primary	Current Secondary	Tap position	Cos (phi)	"MW" Secondary	"Mvar" Secondary	Sonwin 4 kvadrant meter
ALL	ALL060	ALL010	1	10,0	**no**	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
ALL	ALL060	ALL010	2	10,0	**no**	yes	**no**	yes	yes	Yes	**No2**	**No2**	
BOD	BOD060	BOD010	1	4,0	yes	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
BOD	BOD060	BOD010	2	10,0	yes	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
GUD	GUD060	GUD010	1	4,0	**no**	yes	**no**	yes	yes	Yes	**No2**	**No2**	
HAS	HAS060	HAS010	1	10,0	yes	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
HAS	HAS060	HAS010	2	10,0	yes	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
NEX	NEX060	NEX010	1	10,0	yes	yes	**no**	yes	yes	Yes	**No2**	**No2**	
NEX	NEX060	NEX010	2	10,0	yes	yes	**no**	yes	yes	Yes	**No2**	**No2**	
OLS	OLS060	OLS010	1	4,0	yes	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
OLS	OSL060	OSL010	2	4,0	yes	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
POU	POU060	POU010	1	10,0	yes	yes	**no**	yes	yes	Yes	**No2**	**No2**	
SNO	SNO060	SNO010	1	10,0	**no**	yes	**no**	yes	yes	**(Yes1)**	**No2**	**No2**	
SVA	SVA060	SVA010	1	10,0	yes	yes	**no**	yes	yes	Yes	**No2**	**No2**	
RNO	RNO060	RNO010	1	10,0	yes	yes	**no**	yes	yes	Yes	**No2**	**No2**	
RSY	RSY060	RSY010	1	10,0	yes	yes	**no**	yes	yes	yes	**No2**	**No2**	
VES	VES060	VES010	1	10,0	yes	yes	**no**	yes	yes	yes	**No2**	**No2**	
VIA	VIA060	VIA010	1	10,0	yes	yes	**no**	yes	yes	yes	**No2**	**No2**	
ØST	ØST060	ØST010	1	6,3	yes	yes	**no**	yes	yes	yes	**No2**	**No2**	
ÅKI	ÅKI060	ÅKI010	1	10,0	**no**	yes	**no**	yes	yes	**(No1)**	yes	yes	
ÅKI	ÅKI060	ÅKI010	2	6,0	**no**	yes	**no**	yes	yes	**(No1)**	yes	yes	

(Yes1) Is it suggested that these meters are repaired asap.
No1 It is suggested that these measurement are established asap.
(No1) It ordered.
No2 It is suggested that these measurement are established..

Appendix 6. Measurements in 60 kV Cables and Overhead lines

From	To	Id	Type	Type	Length m	Current and voltage From to	Current and voltage To from	MW and Mvar From to	MW and Mvar To from
ALL	OLS		CAB	3x1x150 PEX Al+25 Cu	4.276		yes		
BOD	DAL		OHL	3x1x130 StAl+50Fe	4.138				
BOD	NEX		CAB	3x1x095 PEX Al+25 Cu	3.477	yes	yes		
BOD	POU		CAB	3x1x150 PEX Al+25 Cu	5.950	yes	yes		
BOD	ÅKI		OHL	3x1x130 StAl+50Fe	10.891				
BOR	HAS				49.800	yes	yes		yes
BOR	HAS	1	OHL	3x1x234 IBIS+None	4.200	yes	yes		
DAL	SVA		CAB	3x1x150 PEX Al+25 Cu	7.531		yes		
DAL	ØST		OHL	3x1x130 StAl+50Fe	9.924				
HAS	RNO		CAB	3x1x240 PEX Al+35 Cu	7.434	yes	yes	(Yes)	
HAS	OLS				11.407	yes		(Yes)	
HAS	SNO				9.805	yes		(Yes)	
NEX	SVA		CAB	3x1x150 PEX Al+25 Cu	9.780	yes	yes		
RNO	VIA		CAB	3x1x240 PEX Al+35 Cu	1.834	yes	yes		
OLS	ØST		OHL	3x1x130 StAl+50Fe	13.050				
VÆR	SNO				4.151		yes		
RSY	VIA		CAB	3x1x240 PEX Al+35 Cu	1.674	yes	yes		
RSY	VÆR		CAB	1x3x095 APBF Cu	2.861	yes			
RSY	ÅKI		OHL	3x1x130 StAl+50Fe	10.995	yes			
VES	RNO		CAB	3x1x300 PEX Al+35 Cu	2.200	yes	yes		
VES	VÆR		CAB	3x1x300 PEX Al+35 Cu	1.800	yes			
VIA	VÆR		CAB	3x1x300 PEX Al+35Cu	1.481	yes			
ØST	GUD		CAB	3x1x150 PEX Al+25 Cu	6.600	yes			

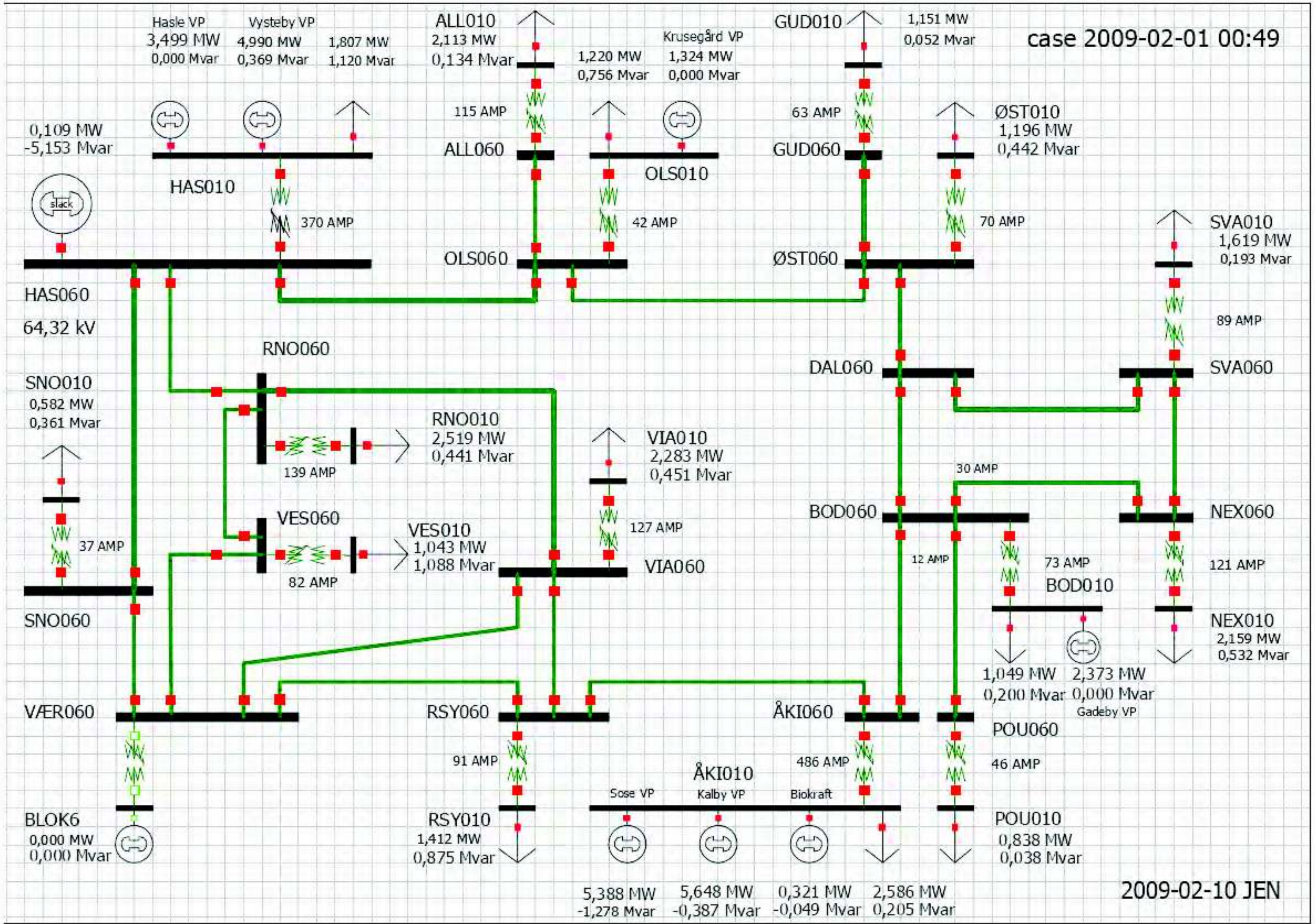
(Yes) Meters present, but shows wrong values. Should be repaired asap.

Appendix 7. Generator measurements

Station	**Felt**	**Id**	**Scada** Network Manager **Ampere**	**Scada** Network Manager **MW**	**Scada** Network Manager **Mvar**	**Settlement** Sonwin **MW**	**Settlement** Sonwin **Mvar**
BOD	NXV	VP Gadeby	Yes	No	No	Yes	**(Yes)**
HAS	VIN	VP Hasle	Yes	No	No	Yes	**(Yes)**
		VP Vysteby	Yes	No	No	Yes	Yes
OLS	KRU	VP Krusegård	Yes	No	No	Yes	**(Yes)**
ÅKI	BIO	Biokraft	Yes	Yes	Yes	Yes	Yes
ÅKI	KAV	VP Kalby	Yes	Yes	Yes	Yes	Yes
ÅKI	SOV	VP Sose	Yes	Yes	Yes	Yes	Yes
VÆR	Diesel	Diesel	Yes	Yes	No	?	?
VÆR	Blok 5	Blok 5	Yes	Yes	No	?	?
VÆR	Blok 6	Blok 6	Yes	Yes	**No**	**No**	**No**
VÆR	Blok 7	Blok 7	Yes	Yes	Yes	Yes	Yes

No It is suggested that these measurement are established asap.
(Yes) This value are measured, but not stores. It is suggested that they are stored asap.
? This means that this value must be investigated.

Appendix 8. Balancing the Bornholm Power system - Case 2009-02-01 00:49



7. Island Operation 2007

Dynamic Modeling of the Power System of Bornholm

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Dynamic Modelling

- of the power system on Bornholm

MSc Thesis

Katrine Laursen Heilmann
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Dynamic modelling of the power system on Bornholm

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Abstract

The Danish island of Bornholm has recently become a test site for the power system technologies of the future. Many ongoing research projects on Bornholm are aiming to implement new technologies, such as intelligent grid architectures, sustainable energy sources and advanced grid control schemes.
Many of these project have a common requirement: A reliable model of the Bornholm power grid, capable of running steady state, as well as dynamic simulations. In this thesis, it is described how a model capable of this is constructed. Different theoretical aspects of determining unknown model parameters from measurements are examined, and the stability issues of an isolated power system, as Bornholm can be, are described. The model is built from data sources supplied by the distribution system operator, Østkraft. Unavailable data is estimated, measured or typical values are used. The resulting model is capable of performing dynamic simulations of the isolated Bornholm grid, under balanced conditions. With some limitations to the precision, the model is also capable of simulating unbalanced conditions.
The steady state model is validated using SCADA-measurements for comparison. Based on high resolution measurements from the central power plant on Bornholm, the turbine governors are tuned to reproduce a frequency response similar to a measured disturbance. It is concluded, that it is probable that the dynamic model is representative of the actual system, but the recorded data is insufficient to validate the model. Measurements were not available for validating the excitation systems.
Finally, suggestions are made on the future use of the model, and on the possibilities of upgrading it.

Resumé

Det er besluttet at Bornholm i nærmeste fremtid skal kunne bruges som et såkaldt ”Energi-laboratorium”, hvor nye teknologier til fremtidens elforsyningsnet kan afprøves. Mange igangværende forskningsprojekter på Bornholm, søger at implementere nye teknologier, såsom intelligente net-arkitekturer, vedvarende energikilder og avancerede reguleringssystemer. Fælles for mange af disse projekter er, at de har behov for en pålidelig model af det bornholmske el-net, der er i stand til at simulere statisk såvel som dynamisk. I denne afhandling, beskrives hvordan en sådan model er opbygget. Forskellige teoretiske aspekter vedrørende bestemmelsen af ukendte modelparametere udfra målinger gennemgås, og stabiliteten af et isoleret system, som Bornholm kan være, beskrives.
Modellen opbygges på baggrund af data udleveret af Østkraft. Manglende data estimeres, måles eller der benyttes typiske værdier. Den færdige model kan bruges til, at gennemføre simuleringer på det isolerede bornholmske net, forudsat symmetriske forhold.
Modellen kan også anvendes til simuleringer på nettet under visse asymmetriske forhold, dog med begrænsninger. Den stationære model er verificeret ved hjælp af sammenligninger med målinger fra SCADA-systemet.
Baseret på højt opløselige målinger af respons fra det centrale kraftværk i Rønne, justeres turbine-reguleringen således, at en målt frekvensforstyrrelse kan genskabes. Det konkluderes, at den dynamiske model sandsynligvis er repræsentativ for det virkelige el-net, men det opsamlede måledata er ikke tilstrækkeligt til en egentlig validering. Målinger til validering af mangetiseringssystemerne, var ikke tilgængelige. Endeligt har vi opstilley forslag til fremtidige brug af modellen, og muligheder for opgradering.

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Chapter 1

Introduction

The awareness in the society of the consequences of using fossil fuel in the energy sector, has increased the focus on sustainable energy generation. The Danish government as well as the population is concerned, and the demand for a reduction of greenhouse gas emission is significant. Besides the environmental issues, the liberalization of the power market, in 1998 [11], has contributed to the integration of additional sustainable energy generation units, concurrent with a stagnation in the construction of new conventional power plants. There is no longer an economic incentive, and therefore no central power plant was expanded since 2001 [10].
Beside the economical incentive, the Danish government decided that in year 2025, 36 % of the the energy supply must come from sustainable energy sources [9]. Since most sustainable energy generations units are small, the political attitude promotes a decentralisation of the electric power production system.

Sustainable power generation mostly depends on meteorological parameters like rain or wind, and therefore long term variations in the potential power output occurs. This is not an issue to the same extent with conventional power plants. Short term variations of e.g. wind speed, are also a fundamental issue in power system and are described in section 3.1. Both long and short term variations affects the security of supply, especially in highly decentralized power production systems. To utilize and handle this decentralization, new control schemes must be developed.

One way of restructuring and benefit from the decentralization, is to sectionalize the power system into smaller areas, which can operate independently without interconnections to larger systems. Each section must be able to maintain the balance between demand and generation, and a decentralization meets this demand. A control strategy for maintaining frequency and voltage must be present, and a strategy for reconnecting between island- and interconnected operation is needed. Sectionalized power systems should be able to switch between the two operation modes. Interconnected operation is preferable in most situations, because of the economically benefit resulting from producing power where it is cheapest. When a fault in the transmission network occurs, switching into sectionalized operation will sustain the power supply to the costumers. With proper monitoring and control it might be possible to lower the impact on costumers during a disturbance, since the control system detects the fault and sectionalizes the network before the black out. What kind of control system, and what kind of precautions that has to be taken are described in 3.

Presently the power system in Denmark and the rest of the world is based on central generation in power plants, and therefore the power network in general is not structured in a manner where sections, suitable for testing island operation, are easily established. The power system on Bornholm is an exception, since it can operate in both island mode and interconnected with the Nordic power system.

The generation is based on a combination of conventional generation and a high share of sustainable generation. The power plant in Rønne is able to absorb some of the fluctuations from the wind turbines and demand. Units based on synchronous generators, like those used in the power plant, are suitable for absorbing small signal variations, due to a combination of energy stored in the rotating parts, a strong connection between the generator and the electric grid and relatively fast control systems. The Rønne power plant can supply the costumers when the meteorological conditions prevent the wind turbines from operating.
Another Danish island, Samsø, located in Kattegat has an even higher share of distributed generation, consisting of sustainable energy generation like wind turbines and photo voltaic cells. For this reason Samsø could be considered interesting for experimental purposes, but since the system cannot operate in islanding mode and is dependant on the interconnection with Jutland to maintain voltage and frequency stability, it is not suitable for this purpose.

For this reason Energinet.dk[1], Østkraft[2] and Centre for Electric Technology, CET[3] has decided to make the power system on Bornholm a test site for future power system technologies. Besides the ability of islanding, the power system is suitable since it is a small system and the impact from a disturbance can be detected. Regarding Bornholm as a test site, a dynamic model of the power system must be developed. This task, among others, is described in this thesis.

[1]The transmission operator in Denmark
[2]The power company on Bornholm.
[3]CET is a centre under Ørsted•DTU

1.1 Problem statement

On request from the Danish TSO, Energinet.dk, and CET, a model of the electric power system on Bornhom should be built. Bornholm is the focus point of several research projects, due to its ability to operate isolated from other power systems (island operation).
This master thesis is related to the EU project called More Microgrid[4].

The construction of a dynamic model is done in the simulation tool PowerFactory from DIgSILENT using data supplied by Østkraft. Measurements of current, voltage and frequency are performed on the generators at the Rønne power plant, for determination of some model parameters. These measurements were done using phasor measurement units (PMU).
The SCADA-system[5], used by the power plant staff for monitoring the status of the electric grid, is the basis for constructing and validating the load flow model.

The following questions are answered in this thesis:

- How is a dynamic model of the power system on Bornholm constructed, what considerations are done?
- Can a method for estimating parameters in control systems and generators be found, and how can it be utilized in the context of this thesis?
- How does the responses from the dynamic model differ from the measurements and what causes these differences?
- For what purposes can a model of the power network on Bornholm be used, and how will it be useful when making Bornholm a test site for future power system technologies?

[4]A project description is available at `http://www.dtu.dk/centre/cet/English/research/projects/10-jen.aspx`.

[5]Supervisory Control And Data Acquisition.

Chapter 2

The power network on Bornholm

Bornholm is a Danish island in The Baltic Sea with an area of $588.53\ km^2$ and 43.000 citizens [12]. Besides the resident population, the island has a lot of tourism during the summer period, and therefore a large amount of summer cottages. The population on Bornholm is therefore varying depending on the season. This must be taken into consideration, when operating and maintaining the power system on Bornholm.

2.1 Voltage levels in the power system on Bornholm

The transmissions system on Bornholm is divided into a 60, 10 and 0.4 kV grid. The 60 kV grid forms a circle to which fifteen 60/10 kV transformer substations are connected. From the transformers the power is distributed to the 972, 10/0.4 kV transformers[1] and then to the 27.895 costumers [14]. In table 2.1 one will find the length of the cables and overhead lines for the three voltage levels.

[1]The number includes industrial sub-stations.

High voltage					Low voltage		
Overhead line		Cable		Total [km]	Overhead line	Cable	Total [km]
60 kV	10 kV	60 kV	10 kV		0.4 kV	0.4 kV	
73	247	58	643	1021	518	1341	1859

Table 2.1: Length of cable and overhead lines on voltage level 60, 10 and 0.4 kV in the power system on Bornholm [14].

2.2 Power supply on Bornholm

The power network on Bornholm was built for island operation, and though there is a submarine cable connecting the island to the Nordic system, the system still has the ability of islanding. The system is controlled from the power pant in Rønne. Here the operators buy and sell power at the power market, and during islanding they ensure the balance between consumption and generation. The control of the power system on Bornholm to some extent resembles the control of the entire power network in Denmark, but in some ways is simpler.

In the Danish power system, the responsibility of operation is divided between the transmission system operator, TSO, the distribution system operators, DSO, and the power plant operators. The TSO in Denmark has the responsibility of the overall security of supply. The TSO ensures balance between production and consumption, and decides which power plant must increase their production. The TSO owns the transmission network and has the responsibility of maintaining and upgrading it, in order to keep the transmission capacity sufficient. The DSOs have a similar responsibility of the distribution network. The power plant operators ensure that the power plant is capable of supplying power and ancillary services wanted by the TSOs.

The production, distribution and transmission levels exist in the power system on Bornholm, but are all controlled by the same operators, which is the staff at the power plant in Rønne. This makes the communication between the three levels simpler, and disturbances in the Bornholm power grid can be quickly detected and corrected by the staff.

2.2.1 Interconnection between Sweden and Bornholm

The electrical power consumption on Bornholm is primarily supplied through the 60 kV submarine cable between Sweden and Bornholm. The cable was installed in 1980 [14] and has a rated transmission capacity of 68.6 MVA[2]. The interconnection to Sweden consists of four parts. 4.2 km overhead line in Sweden starting at the 130/60 kV transformer in Borrby and ending at the coast. 0.7 km land cable connects the coast and the actual shoreline and is connected to 43.5 km of submarine cable. The submarine cable ends at the shoreline near Hasle and from here 1.4 km land cable ends the interconnection at the transformer station in Hasle [32].

The Swedish TSO, E.ON Sweden, requires the transmission of reactive power through the sea cable, to be as close to zero as possible. Through the interconnection, it is possible to supply the consumption of active power in most operational

[2]The rated current at nominal voltage, 60 kV is stated to be 660 A [32].

Production unit	Total [MW]
Unit 5	25
Unit 6	34.8
Diesels (Unit 7)	15
Old diesels	19.5
Bio-gas units	2
Wind turbines	29.8

Table 2.2: Distribution of electrical power in the electrical power production system on Bornholm.

situations, but occasionally the peak load exceeds the maximum transmission capacity, and local generation is necessary.

2.2.2 Power generation on Bornholm

In situations where the eletrical transmission capacity on the sea cable is insufficient or not available, the power supply is generated on the island. There are different types of generation units on Bornholm. The largest amount of generation is done in the power plant in Rønne, which contains; 14 diesel units, an oil-fired unit and a coal-fired unit. The power plant also covers the need for central heating to the consumers in the Rønne area. Because of the central heating demand, unit 6 is often running in spite of the possibility of buying cheaper power elsewhere in the Nord Pool system [3].
The power supply on Bornholm also contains different types of renewable energy generation units. A large amount of wind turbines are present on the island. Some are outdated, small, fixed speed turbines and others are newer models which can control frequency and electrical power output.
Another type of renewable energy generation present, is a bio-gas power plant with a installed electric capacity of 2 MW.

All together these generation units have an installed capacity of 122.52 MVA and can supply the peak load on Bornholm. In the following section a detailed description of the generation units can be found. The distribution of active power in the production system on Bornholm is displayed in table 2.2.

[3]Nord Pool is the spot market for trade of electrical power in the Scandinavian power network.

Unit 5 of Rønne power plant

Unit 5 of the power plant in Rønne was installed in 1974 [14] and is a combination of a boiler from Vølund Energy Systems and a Brown Boveri steam turbine and generator. The generator has a rated power of 29.4 MVA, and the nominal voltage is 10.5 kV. Oil is the fuel used and the generator is equipped with a voltage controller and a turbine governor. Further description can be found in chapter 5. Unit 5 is used to control voltage and frequency during island operation. The model and types of generator and turbine components for unit 5, and the remaining units on the power plant in Rønne are listed in table 2.3.

Unit 6 of Rønne power plant

Unit 6 was installed in 1995 and is a combined heat and power production unit. The boiler was provided by Vølund Energy Systems and has a power capacity of 140 ton/hour. The generator and steam turbine were produced by ASEA Brown Boveri (ABB). The synchronous generator has two poles and a rated apparent power of 46.80 MVA. Unit 6 is equipped with a power factor controller system, an excitation system, a turbine governor and an constant power controller. These controller features are primarily used in islanding mode, as the frequency and voltage stability normally is maintained by the interconnection to the Scandinavian power system. For a more detailed description of the controllers on the generators see 5.

Diesel units in Rønne power plant

Rønne power plant has 14 diesel generators. Ten of these were installed in August 2007, because the installed generator capacity on Bornholm was insufficient for covering a peak load higher than normal. These experiences were obtained during 51 days of involuntary islanding due to a repair of the submarine cable, when is was damaged by an anchor on the 22. of December 2005. The total installed active power capacity was at that time around 80 MW (excluding wind turbines, which are not in operation during islanding) and the peak load normally does not exceed 55 MW [14]. Still the security of supply was threatened, because this winter was unusually cold and therefore lead to a higher peak load than expected. The ten new diesel units are identical, and have a total apparent power of 16.44 MVA. They are Leroy Somer AC generators with 4 pole salient poles. The diesel units are equipped with automatic voltage regulators.
Before the installation of the new diesel generators, the power plant's emergency generation consisted of four diesel machines, which was installed around 1970[4].

[4]In 1967, 1968, 1971 and 1972 a diesel generators was installed.

The diesel machines are usually used during islanding to cover peak load situations. They are able to start very quickly, but have a high fuel cost and low efficiency. The diesels are also used to provide ancillary services and reserve power in interconnected operation [16]. The technical specifications for the diesel machines are listed in table 2.3

Renewable energy on Bornholm

As mentioned earlier the power system on Bornholm contains a large amount of wind turbines, 34 turbines with a total installed capacity of 29.8 MW [17]. In 2006 Østkraft installed six new wind turbine: three Vestas V80, 2 MW and three V60, 1.75 MW turbines. These new turbines are able to control the power output. The remaining wind turbines are primarily older turbines under private ownership. Half of the wind turbines have a rated power over 800 kW and the smallest wind turbine is 11 kW. In appendix A.1 the wind turbines are listed with type and electrical power capacity.
Another renewable generation unit is the bio-gas power plant, located in Åkirkeby on the southern part of Bornholm. The power plant was completed in 2007 and has a capacity of 2 MW. The biogas used in the combustion is extracted from slurry.

Generator					
Unit	5	6	Old diesel		New diesel
Type	Brown Boveri 27B400, 2 pole	ABB WX 16L -044 LLT, 2 pole	Four Bush X, pole, Salient		Ten Leoroy Somer 4 pole, Salient
Nominal apparent power MVA	29.40	46.80	2 machines 5.825	2 machines 6.335	1.644
Power factor $\cos \phi$	0.85	0.85	0.80	0.80	0.92
Rotations per min	3000	3000	500	500	1500
Turbine					
Unit		High pressure		Low pressure	
5		Brown Boveri 27B400			
6		G40 (ABB TUR)		LT22 (ABB STALL)	

Table 2.3: Type data for generators and turbines on the power plant in Rønne.

Chapter 3

Island operation and stability problems in power systems

Island operation is primarily employed in small, remote areas where the demand for power is modest, due to low population density e.g. in villages in Greenland and Norway. In such areas the production and power network is constructed to support island operation. Typically there are few producing units and the control is maintained by one machine or at a single power plant only.
Still most power systems are large, because large and interconnected power systems are an economic advantage [1]. Interconnection of different areas with different generation forms, makes it possible to buy the power where it is cheapest. For example on days with strong wind, the price in Jutland is typically lower than in Norway.

The reason for investigating island operation, is the increasing amount of distributed generation. The fact that the most new production units are installed on distribution level, has changed the demand for control in order to maintain the system stability. Optional sectioning could be a new power system architecture which would strengthen the system stability, and at the same time benefit from the increasing amount of local generation. In order to develop a suitable control structure, knowledge of the existing system is necessary, and renovation of the distributed power generation units have to include installation of relays and other control equipment, improving fault ride-through and black-start capabilities [5]. Island operation transfers the responsibility of frequency and voltage control from the central units, to the smaller combined heat and power units [5]. If no suitable control structure is applied, the stability of the islanded section, can be hard to maintain due to high penetration of distributed generation compared to synchronous generators, which are the foundation for maintaining stability in the traditional power system architecture.

The following sections therefore contain a general introduction of stability issues. Afterwards problem regarding islanding and operation in island mode are introduced and then the island operation of the Bornholm power system is accounted for.

3.1 Stability in power systems

Power system stability is an important subject in electric engineering. If it is not sustained it could lead to outages and thereby economic losses for society. According to Vice-President of Powertech Labs inc. British Colombia, P. Kundur, power system stability (page 17 in reference [1]) is defined as:

> *.. that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. .*

Different types of stability issues are to be considered, e.g. rotor angle stability and voltage stability. An introduction to these phenomena will follow.

3.1.1 Rotor angle stability

A synchronous generator is generating power by a direct current excitation of the field winding in the rotor. A rotating magnetic field in the field windings will induce an alternating voltage in the three phases of the stator. The frequency of the current and voltage in the stator windings depends on the speed of the rotor. The frequency of the voltages and currents, are in synchronism with the mechanical rotor velocity, hence synchronous machine.

The correlation between the power transfer to the loads, and the rotor angle is very non-linear. The angle difference, or angle separation, is the sum of the angle that the generator rotor leads the field in the stator windings, the angle between the generator and the consumer, and the internal angle of the consumer. If the consumer is represented by a motor, the internal angle is the angle, which the rotor field lags the revolving field of the stator.

When connecting a number of synchronous machines, the rotor frequency in all machines must be equal, otherwise the frequency of the power output would not be in synchronism. When one synchronous machine is faster than the others, the rotor angle of the faster machine will become larger relative to the rest of the machines. This will result in an increased angle separation and increased power transmission until a certain limit. Above this limit, usually 90^o, the increased angle separation will decrease the power transmitted, which will increase the angle separation further and the system can become unstable.

The rotor angle stability depends on that the generator rotor positions in the system, after a disturbance, results in sufficient torque to re-establish the steady state operation. The rotor angle stability is affected if one or a group of synchronous machines are getting out of step. If the torque in each machine is not sufficient for regaining synchronism, it can lead to non periodical changes in the rotor angle separation. Rotor angle stability is split into two categories; small signal and transient.

Small signal rotor angle instability

Small signal rotor angle instability occurs continously in the power system, due to variations in load and production. A form of small signal variation is the steady-state type, where the rotor angle is enlarged because of lack of synchronizing torque. Another form is rotor oscillations with increasing amplitude. The oscillations occur in generators where the damping torque is not sufficient to absorb the small signal variations. Oscillations is the main small signal rotor angle stability problem in the power system and have several modes [1].
It can occur as a local phenomenon where one generating unit is oscillating relative to the rest of the system, or it can occur as one group of generators oscillate against another. Groups of machines oscillating against each other is often seen where two internally strong connected areas, are weakly interconnected. The small signal instability can also be related to the control of the system, poor tuning of exciters and turbine governors or because of HVDC-converters and static Var compensators. The shaft between the turbine and generator can also cause small signal instabilities.

Transient instability

Transient instability concerns instability due to large transient disturbances and involves large excursions of the generator angle. The transient rotor angle stability is affected by the relationship between rotor angle separation and the power transfer. The response is dependant on the initial conditions and how severe the fault is. Transient stability is often maintained, because precautions are taken in the construction phase. For example different types of faults' effect on the stability are investigated and attempted avoided.
Transient faults have three different behaviours, these are listed here, and their response are shown in figure 3.1.

- Case 1: The rotor angle is increased to its maximum value, and then it decreases the amplitude oscillatory until a steady state is obtained.
- Case 2: Usually referred to as the first swing instability. The rotor angle is increasing until synchronism is lost. The rotor angle does not return to steady state because of lack of synchronizing torque.
- Case 3: The third instability will maintain stability in the first swing and then become unstable. This response often occurs due to an initial condition containing small signal instability.

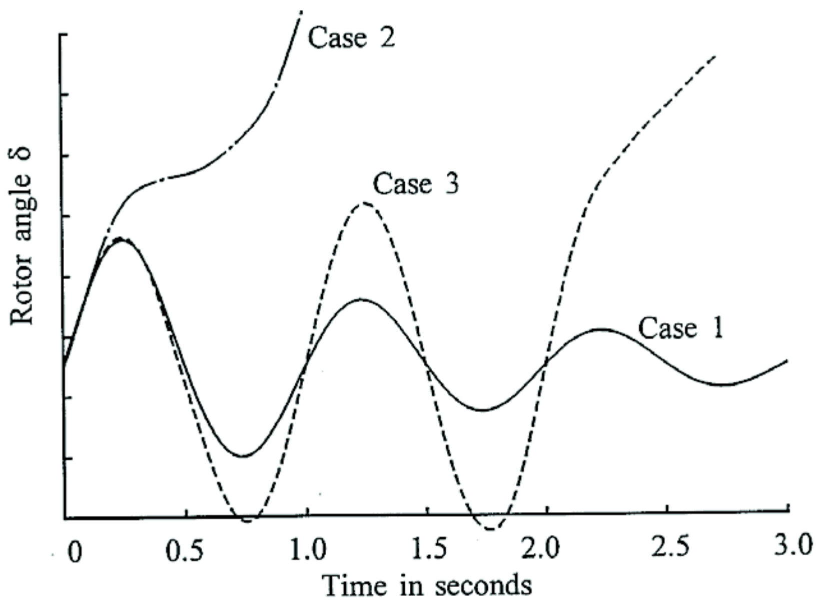


Figure 3.1: Rotor angle response to a transient disturbance.

3.1.2 Voltage stability

Voltage stability concerns the ability of maintaining an acceptable stable voltage on every busbar in the power system, both during steady state operation and after a fault. The main reason for voltage instability is lack of reactive power in the system: It can be caused by the transmission of active and reactive power through inductive transmission lines. Voltage instability is often related to rotor angle instability. If the rotor angle separation is out of step, e.g. a gradual decrease of synchronism, the voltage will drop. Voltage stability is maintained if the voltage on all busbars in the power system increases as the reactive load on the same

busbar rises. If this criterion is not fulfilled on one busbar, the system is voltage unstable per definition [1].
The voltage stability depends on the voltage, the active and the reactive power in the system. In figure 3.2 the relationship between the three quantities is shown. The dotted line indicates the limit for an acceptable operation point. A sudden change in the power factor will lead to a rise in reactive power output and thereby the operating point is located under the dotted line, hence the operation conditions will be unsatisfying and maybe unstable.
Voltage stability issues can be divided into large disturbances that will cause voltage instability, and small disturbances. Large disturbance could be system faults like a loss of a generator. Small disturbances could occur due to fluctuations in the demand.

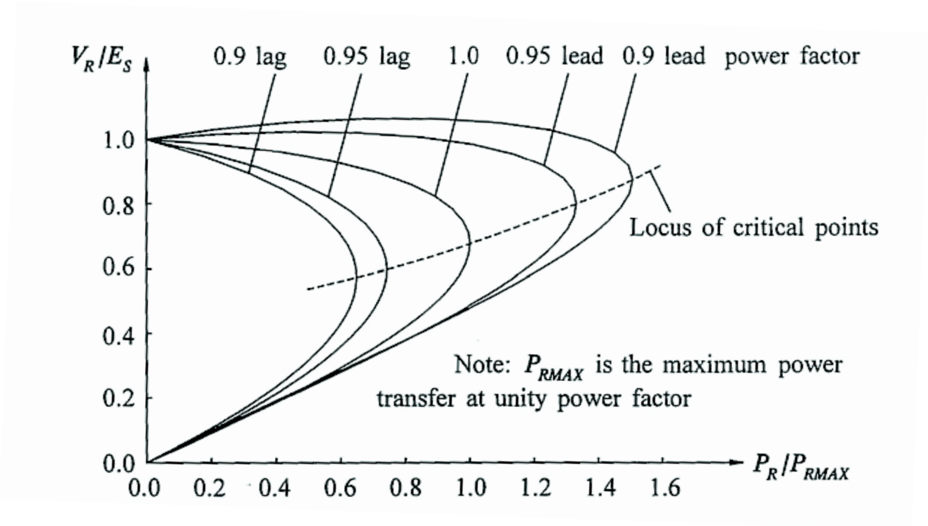


Figure 3.2: Voltage-power characteristics with different load-power factors.

3.2 Stability in island operated power systems

Island operation is manageable if the production structure is rather simple, meaning few generating units and a one-way power flow from the highest voltage level to the lowest where the consumers are connected. One problem that has to be taken into account in island operated systems as well as interconnected, is the requirement of balance between installed power capacity and the demand. In areas that are built for islanding purposes, this requirement is usually fulfilled. If the intention is to sectionize a large system into smaller, and run them individually, it may be a problem to keep the balance in all situations. Instability can occur from lack of active and reactive power, and thereby cause both voltage and rotor angle instability. In order to predict problems regarding the load/production balance, the control structure must include measurements of these quantities. Besides that, the synchronous generators, large wind turbines and wind farms within the area, must be able to control the active power output [5].

Small signal instability will especially become a problem, in areas where the installed generation is unable to absorb the small ongoing variations in load and production. This is typically areas with high penetration of wind turbines, but without the corresponding amount of synchronous machine to absorb the small disturbances. The rotating energy in the system is not sufficient. High wind power penetration might be possible, if the wind turbines in the system are equipped with power electronics enabling them to control their active power output.
Reactive power compensation, can be implemented in the power network, in order to reduce the voltage fluctuations resulting from the reactive consumption of asynchronous generators and overhead lines. Whether this form of compensation is necessary, depends on the grid. If the grid is built with a large amount of cables, which are capacitive, the opposite problem might occur. Voltage stability is also dependant on automatic voltage control on the synchronous machines.

3.3 Island operation of the power system on Bornholm

Islanding of the Bornholm power system is a rare operation mode, the supply is normally maintained by the submarine cable. Still in some situations it is necessary to electrically disconnect Bornholm from the remaining Nordic power network. Island operation for exaxmple occurs in connection with maintenance of the submarine cable or substations. In these situations the disconnection is planned, and the staff on the power plant is prepared. On occasion, island operation has occurred due to unexpected disconnections. The supply on Bornholm can not survived an unscheduled transition into island operation, because most of the time the generators on Bornholm are not running. The power system on Bornholm is however able to perform a dead-start of the supply. This can be done by using a small diesel motor to magnetize the larger diesels, and then step by step start up the conventional units, and reconnect the consumers on Bornholm.

The installed generation capacity on Bornholm is sufficient to supply the consumers in general, as described in chapter 2. The grid on Bornholm mainly consists of cables and in some situation the generators on the power plant has to absorb reactive power from the grid in order to reduce the voltage. The reactive power absorbed from the grid in order to magnetize the asynchronous machines in the wind turbines, are consequently no problem during island operation. Still most of the wind turbines are out of operation during islanding, because the staff expects that the turbine governor on the units are insufficient for reducing the frequency fluctuations resulting from fast changes in wind speed. The Vestas wind turbines are equipped with a constant power controller, and should therefore not cause frequency instability. The power electronic used in the controller though, can affect the power quality by inducing harmonics.

The control on Bornholm during island operation is maintained by the exciter and turbine governor on unit 5, in spite the fact that unit 6 is newer and therefore likely to be equipped with newer and better control systems. The reason for that is that unit 6 supplies most of the demand, and is fired with coal, which is cheaper than oil. Unit 6 is set to a fixed power output using a built in control option. If a larger disturbance occurs, the turbine governor stabilizes the frequency at lower frequency, and the stationary fault is corrected by the staff on the power plant, by changing the set point of the turbine. The fluctuations of the voltage are smoothened by the excitation system, and the stationary voltage set point is adjusted manually by the staff.
Before restoring the electrical interconnection between Bornholm and Sweden, the production is turned down on the units, and the frequency is synchronized with the Nordic grid. Østkraft has synchronization equipment for this purpose.

During week 37, 2007 Bornholm was isolated from the Nordic grid due to rutine repairs of the substation in Sweden. This proved to be an opportunity to perform rare high resolution measurements of the system dynamics during genuine islanding conditions, and to observe the procedures utilized by the control room staff in order to handle this type of operation.

Chapter 4

Determination of generator and control parameters

When modelling a power system, with a desire to use the result for reliable dynamic simulations, it is highly important that the parameters used in the building, is as close to the reality as possible. Most of the generator and control system parameters can be found in the data sheet enclosed when the unit is installed. The problem is that gradually the parameters changes when the machine ages, and sometimes the staff has to tune the control system in order to meet new demands in the power system.
The power plant in Rønne is an older installation, and therefore one must expect that the previous mentioned changes could be a reality. Additionally it is not always possible to extract all required data from the available material. Therefore we chose to combine the information in the data sheets with collected measurement data from the actual units in Rønne, and thereby determine the parameters needed.

How others set up test procedures in order to derive parameters for modelling of power systems, and how the wanted parameters can be extracted from the measured data is explained in this chapter. Afterwards a description of the method used for determination of the parameters belonging to the power plant in Rønne is presented.

4.1 Determination of parameters for dynamic modelling by measurements

When modelling generator and control system, a mathematic model of the components is used for describing the system components. In general this mathematic model is a set of differential equations. To set up this kind of model it is necessary to describe the connection between the different components in the system. For this purpose the physical laws are used. Usually setting up a mathematic model involves four phases [6];

- Delimitation and definition of the system.
- Determination of the mathematic equations of the system.
- Setting the parameters, describing the system.
- Building the model.

In the delimitation phase, the level of detail of the model is decided. It is necessary and reasonable to simplify the model compared to the actual system, so the mathematic model only represent effects of importance [6]. In this first phase, another task is to determine what are the in- and outputs. In relation to this task it can be useful to make the block diagram for the system being modelled. This can give an overview of how the system components are connected, and what signals connects which components. A general block diagram of a power plan is shown in figure 4.1. The signals are not included in the figure, because they are different depending on the type of power plant. The parameter setting phase concerns determining the parameters, characteristic for each power plant. The generator parameters are e.g. saturation values, reactances, transient and subtransient reactances in the direct and quadrature axis. The control systems are described by time constants, limiters and gains among others.

The mathematic model is used for developing a transfer function for each component in the model. The transfer functions contains information of the dynamic properties and are defined as the Laplace transformed output divided by the Laplace transformed input. Equation (4.1) shows the mathematic expression of the general case.

$$G(t) = \frac{\mathcal{L}(y(t))}{\mathcal{L}(u(t))} = \frac{b_m s^m + ... + b_1 s + b_0}{a_n s^n + ... a_1 s + a_0} \tag{4.1}$$

The method, which we have decided to base the derivation of the parameters needed for the model of the Rønne power plant, is described in section 4.1.1. From here and on it is referred to as ”the extended method”. This test method

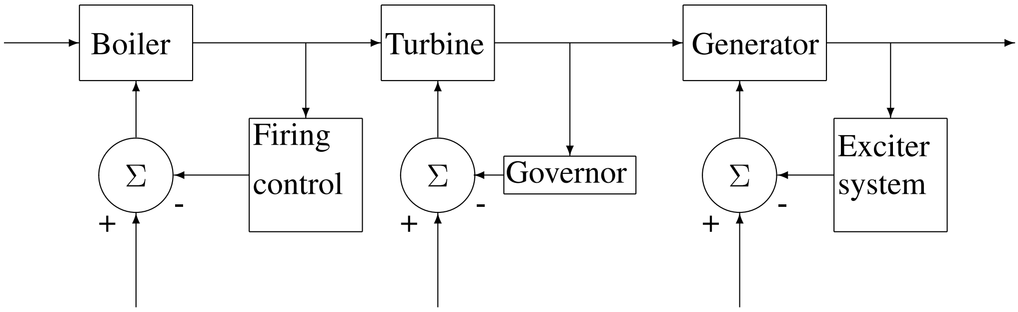


Figure 4.1: Power plant

is selected because it permits the derivation of parameters, based on knowledge of the structure and components on real life power plants. Such as if the rotor is salient or round, whether it is a diesel machine or steam turbine unit, or if the exciter is static or rotating. On the other hand the control unit circuits are not needed, and that kind of detailed information on the Rønne power plant is not in our possession. Furthermore the method described in 4.1.1 has been used several times for parameter derivation with satisfying results, see e.g. reference [2].

4.1.1 Description of "The extended method"

The derivation is based on staged tests and is divided in two parts; steady state tests for identification of reactances in the direct and quadrature axis and saturation values. The second part of the tests is a set of dynamic tests from which the remaining parameters for the governor and exciter can be derived. The method is described in reference [LN Hannett et al. USA].

4.1.2 Steady state test

The steady state measurements involve both on-line and off-line tests. During the first part of the steady state test the generator is running off-line at rated speed. The field currents, I_f, field voltage, U_f, and terminal voltage, U_t, are measured. These tests will be used to identify the saturation values. The measured signals for all tests, steady state and dynamic, are listed in table 4.1.

Signal monitored	
Name	Symbol
Field current	I_f
Field voltage	U_f
Generator phase to phase voltage	U_t
Generator armature current	I_f
Exciter field voltage	
Turbine speed	
Control signal out of governor	
Power angle	ϕ

Table 4.1: Signals measured for derivation of generator, exciter and turbine governor parameters.

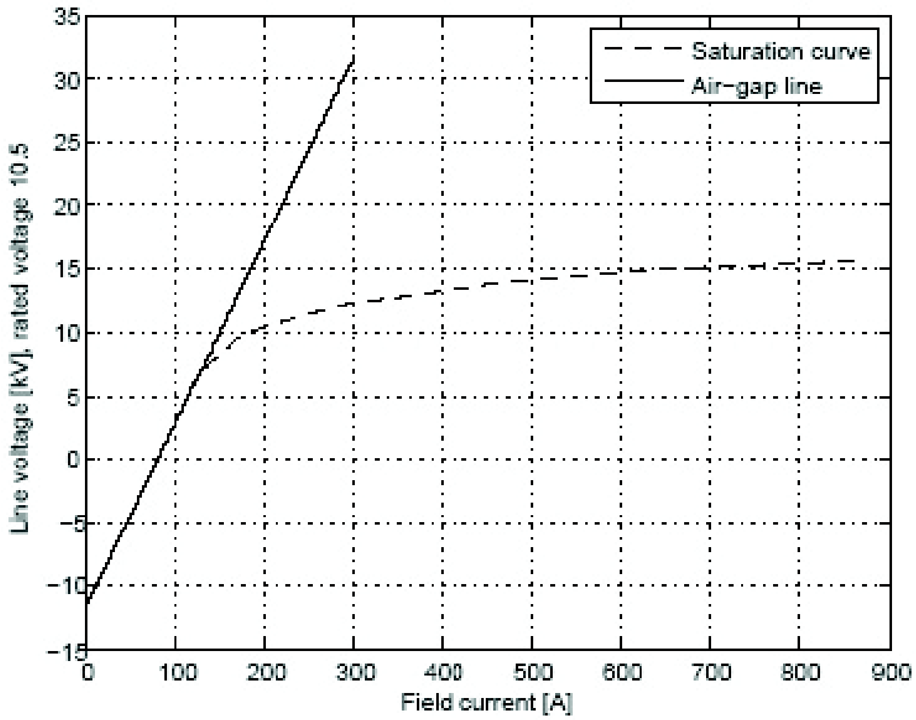


Figure 4.2: Plot of field current versus terminal voltage and air-gap line for a diesel unit, rated voltage 10.5 kV.

Magnetic saturation values

The degree of magnetic saturation in the rotor and stator iron, is of interest because of its effect on the generator reactances[1]. It is identified from the relationship between the air-gap line and the open circuit plot of the terminal voltage versus the field current, see figure 4.2. The air-gap line in the figure is the tangent on the lower part of the curve, and indicates the field current required to overcome the magnetomotive force (MMF) or reluctance of the air-gap [1].
The figure reveals that the open circuit plot is divided into a linear and a nonlinear part. For low values of field current the saturation curve is linear and the rotor and stator iron is not yet saturated. At a certain point the saturation curve becomes nonlinear and the rotor and stator iron is seen going towards full magnetic saturation [1]. As the field current is increased, the generator reactances will decrease, but the degree of magnetic saturation will affect the coherence. The coherence between the field current and the reactances will be linear in the first part of the sequence. Then the relationship becomes nonlinear, which results in a need for a larger increase of the current to accomplish the same increase in voltage as in the linear part of the relationship. As the degree of magnetic saturation approaches its upper limit, the most suited areas of the iron core for magnetization, are no longer available, and only less suitable areas remain. Therefore the increase in voltage, at this degree of saturation, demands a larger current and this effect is reflected in the generator reactances.

In general, satisfactory definitions of the saturation function can be done by two points [1]. $S_E(1.0)$ and $S_E(1.2)$, are the parameters used to describe the saturation of the stator and rotor iron when modelling e.g. in Power Factory, and can be obtained using the open circuit data plotted in figure 4.2. The value of $S_E(1.0)$, can be found from the field current and the value of the air-gap line corresponding to the rated voltage. Likewise the saturation parameter for $S_E(1.2)$ is found using the values of the current corresponding to terminal voltage at 1.2 pu. The mathematical expression is shown in equation (4.2). It is a rule of thumb that the rotor and stator iron is completely saturated at terminal voltage 1.2 pu. and therefore one of the saturation parameters necessary in the model building is $S_E(1.2)$. $S_E(1.0)$ is located in the nonlinear part of the open circuit plot. Here the stator and rotor iron is gradually becoming saturated.

$$S_E(U_t) = \frac{I(U_t)_{Airgap} - I(U_t)_{sat}}{I(U_t)_{sat}} \tag{4.2}$$

Another possibility is to determine the saturation values by using the approxima-

[1] X_d, X_q, X'_d, X'_q, X''_d and X''_q

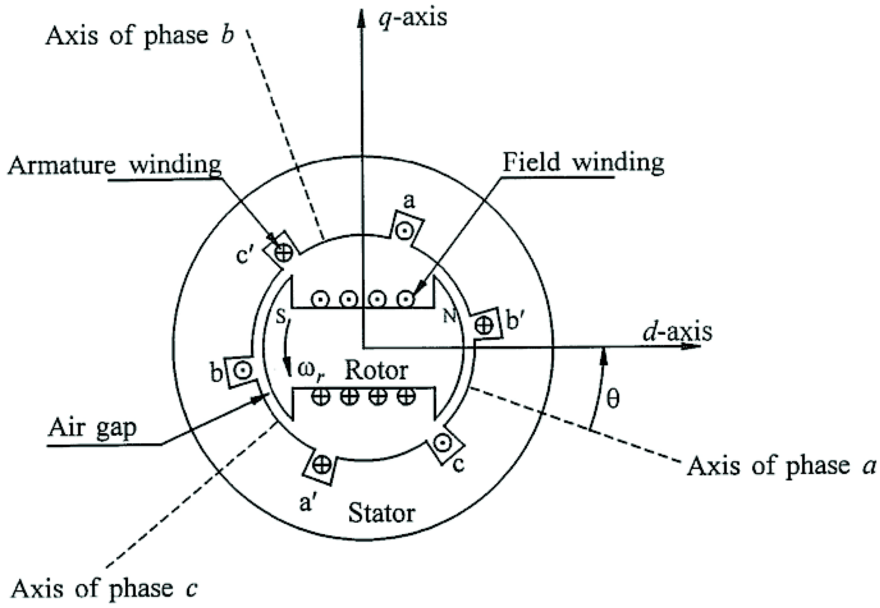


Figure 4.3: Sketch of synchronous machine.

tion shown in equation (4.3). $S_E(U_t)$ is the saturation parameter as a function of the terminal voltage, and the constants, a and b, are found by using a set of two points from the saturation curve [2].

$$S_E(U_t) = a \cdot e^{(b\ U_t)} \tag{4.3}$$

Reactances in the direct and quadrature axis

In figure 4.3 a schematic diagram of a three phase synchronous machine is shown. The two essential elements of a synchronous machine, is the field and the armature, or in other terms the rotor and stator. The field windings are producing a magnetic field from a DC current, which induces an alternating voltage in the armature windings. The direct axis, d-axis is aligned with the rotor magnetic field and the q-axis is perpendicular to the d-axis, based on a standard definition [1]. X_d and X_q are the reactances in the d- and q-axes direction. They represent the inductive effect of the armature magnetomotive force by separately accounting for its d- and q-axis components. The armature voltage and current represented as dq components in one phase is shown in figure 4.4. As the figure illustrates the phasor value of the terminal current and voltage is the complex sum of the d and

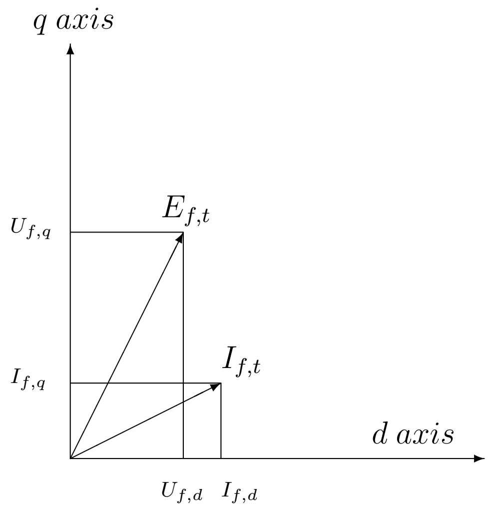


Figure 4.4: Representation of the dq components of the armature voltage and current as phase values.

q components.

$$E_{f,t} = U_{f,d} + j \cdot U_{f,q}$$

The values of the axis reactances needed for the model are the unsaturated values, and the purpose of the second part of the steady state tests are to determine those. The tests are done on-line at a given load while the excitation is varied to change the reactive power output, and from the responses determine X_d and X_q. In that way the measured currents will be aligned on the d or q axis, this is done in order to measure on the q- or d-axis responses separately. The extended method proposes to do four tests: two with the synchronous machine feeding reactive power into the grid, and two where it is consuming.
The synchronous machine is assumed to have a round rotor;

$$X_d = X_q = X_S$$

Where X_S is the synchronous reactance [1]. From the measured signals the synchronous reactance can be calculated per phase as shown in equation (4.4) [4]. I_f is the phase armature current and ϕ is the power angle.

$$X_S = \frac{-j \cdot U_t}{I_f \cdot \cos(\phi)} \tag{4.4}$$

The reactances X_d and X_q can also be determined by comparing responses from simulations of the generator, with actual measurements. In the test, used for

derivation of X_q, the generator is supplying an active load at unity power factor. The proper value of X_q is obtained when the reactance in the model gives the same value of the power angle as the measured.
X_d is determined from its effect on the field current. The active power is set to zero while changing the reactive output. The value of X_d is changed in the model until the simulated field currents coincides with the measured.

4.1.3 Modelling transient performance of synchronous machines

When a sudden change in the load occurs it will lead to a change in the armature current. The response will have a transition phase and then return to a stationary value different from the initial.
A fault current is split in three components. Two AC-components, where one decays rapidly, in a couple of cycles, right after the fault. This part of the response will decay with the subtransient time constants, T_d'' and T_q''. The other AC-component decays relatively slowly, in several seconds. The corresponding time constants are called the transient time constants, T_d' and T_q'. The third component is a decaying DC-component, corresponding to the decaying alternating current in the field winding. In figure 4.5 a current response is plotted. The three phases of a disturbance response are marked on the figure.

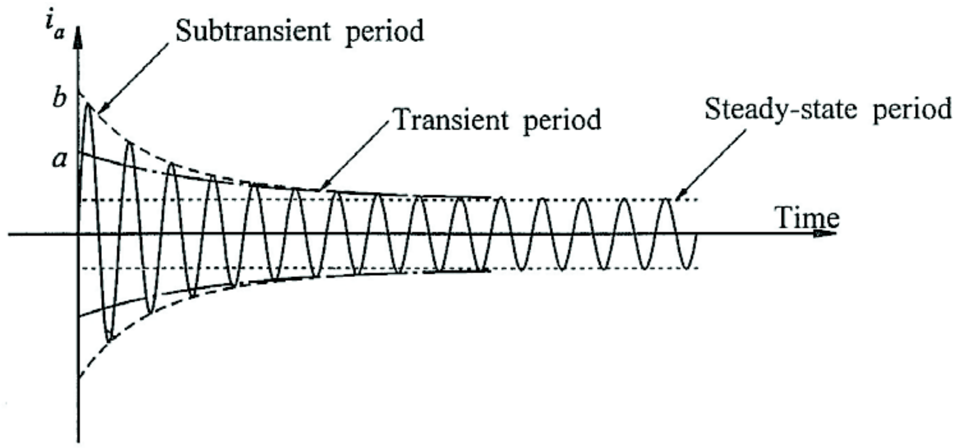


Figure 4.5: Current response, showing the subtransient, transient and stationary phases.

In some cases the transient time constants are valid for the entire fault response, depending on the duration of the decay. In models of generators without damper windings, the transient time constants and reactances, X'_d and X'_q, are sufficient for representing the response [1]. When simulating e.g. a short circuit, the decay time of the current is very fast and the subtransient reactances, X''_d and X''_q, and time constants are to be used. Load rejections can be used for derivation of the transient and subtransient parameters.

4.1.4 Dynamic tests

The objective of the dynamic tests are to measure a response from the control system, induced by a disturbance and thereby determine the time constants, transient and subtransient reactances. Minimum wear on the unit as well as minimum disturbance in the power system is desired.
The parameters of the exciter and turbine governor monitored, depends on the type of equipment. For example if the exciter is a brushless system it is necessary to measure the exciter field voltage and current during the on-line tests, as well as the parameters mentioned in table 4.1.

Measurements

The extended method proposes to subject the machine to load rejections, while supplying part of the demand in order to determine the dynamic parameters. Table 4.2 shows the initial conditions, for the dynamic tests, proposed in reference [LN Hannett et al. USA]. The distribution between active and reactive load depends on the equipment measured on.

	Initial load % of MVA		
Test	P	Q	Condition of Excitation System
1	0	-30	Manual control
2	0	-30	AVR control[2]
3	0	25	AVR control
4	10	-1	Manual control
5	25	-5	AVR control

Table 4.2: Initial conditions for dynamic tests for determination of excitation system and turbine governor parameters, as well as transient reactances [LN Hannett et al. USA].

In the direct axis tests, test 1, 2 and 3, the distribution of the loads must give a steady state condition, so that the armature current is completely aligned with the direct axis like in figure 4.6. The figure shows the phasor diagram for the direct axis test.
The initial loads for test 2 and 3, are supposed to change the terminal voltage to the extent that the AVR, will hit its upper limit. This ensures that the nonlinearities of the exciter are exercised.
The initial conditions of the load in the second test, must additionally limit the absorption of reactive power so that the field voltage does not drop under a certain limit, in order to maintain stable operation of the generator. The generator can not run in stable operation, if the field voltage is under a certain limit, because it will result in an insufficient synchronizing torque. The lower limit of the field voltage depends on the type of machine.
In test 3 the synchronous machine is supplying reactive power to the grid. The amount of reactive power should not allow the terminal voltage to exceed the limits for over-voltage defined for the particular generator. If the limit is exceeded the aging of the isolation material can be accelerated. If the voltage is too high for a longer period, the aging can lead to a arc-over. Regarding steady state tests, over-voltage must therefore be avoided.

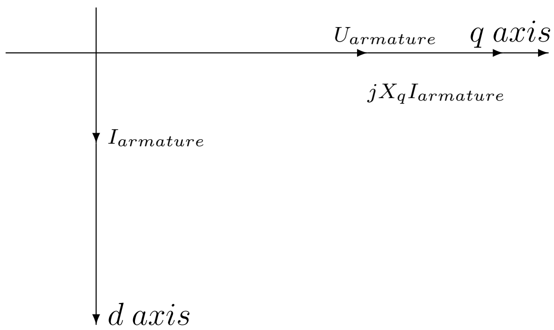


Figure 4.6: Phasor diagram for direct axis test.

The initial value of reactive power in test 4 is determined by the power angle, and power factor when drawing the phasor diagram for the quadrature axis test. The phasor diagram in figure 4.7 shows that the steady state conditions for test 4 and 5, are achieved by aligning the armature current on the quadrature axis.
Test 4 provides a small change in the load, to induce a small response from the turbine governor, and test 5 is supposed to cause the governor to hit its limit.

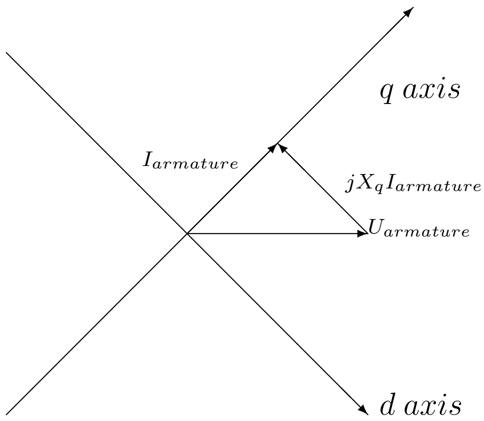


Figure 4.7: Phasor diagram for quadrature axis test.

Derivation of dynamic parameters

The first step in the determination of the dynamic parameters for control system and generator parameters is to choose model structures which represents the actual system. Usually templates of different types of e.g. power plants, turbine governors and exciters exist in the simulation software. Different model types need different parameters, and therefore choosing an appropriate model is essential. If modelling a hydro power plant one should choose a model that resembles that, and so one. The exciter model should include all the significant nonlinearities.
As mentioned earlier the parameters necessary for modelling exciter and turbine governors, are found by an iterative process where the parameters are changed in the model until the response from the simulation matches the measured.

4.2 Measurements on Bornholm

An essential part of the verification process, is the comparison between measurements and simulations. Having reliable measurements of as many system variables as possible, makes the process of building and validating scenarios both easier and more accurate.

Setting up measurement equipment and learning how to store and retrieve data efficiently, can however be a very time consuming process. During this project we relied on both paper based transcriptions of control room measurements, SCADA-system logs and data measured by two phasor measurement units.

4.2.1 SCADA-system transcripts and logs

For the first half of the time frame of this project, we exclusively used screen dumps and paper transcriptions of measurements for verification purposes. Each 6 hours or so, the power plant operators noted the system voltages and currents from the SCADA-system in a form, and these are currently stored at the Rønne powerplant. During the last half of the period, the SCADA-system was set up to log this data in an easily accessible format, with a resolution of 10 seconds, gradually being converted to 10 minute values for long term storage.

The stored variables are the line currents and voltages in the 60 kV network, and the current and voltage on the low voltage side of the 60/10 kV-transformers. Furthermore, one frequency measurement in Hasle, and a log of all tap changer actions are stored.
The SCADA-logs are set up to measure and store the angle between current and voltage as well, but the physical measurements are presently not functioning.
As described in chapter 6, the measurements from the substations in Rønne and Åkirkeby are not functioning yet, and certain discrepancies in the current and voltage measurements of the same lines have been observed.

4.2.2 Phasor measurement units

In connection with this project as well as other related research activites from CET, it was decided to install high resolution measurement equipment of the phasor measurement unit type, at the powerplant in Rønne.
The phasor measurement unit was developed and built at the Technical University of Denmark, and is capable of measuring voltage, current, phase and frequency with a resolution of 20 ms, in all three phases simultaneously. These measurements are time stamped through the use of a GPS connection[3], enabling the precise comparison between concurrent measurements from different PMUs.
The PMUs are connected to the internet through an IP-connection, permitting remote configuration and downloading of data. The power plant units were chosen for the installation, since these units are responsible for controlling the frequency and voltage in the Bornholm electric grid.

Out of concern for not endangering the security of the system, it was decided to make the current measurements with galvanic seperation. This was done by installing current transformers of the type Garre X21R-A2454 in the measurment circuits of the units. The winding ratio on the current transformer were adjusted to comply with respectively 1 A and 5 A current transformer in the measurement

[3]Global Positioning System

circuits of unit 5 and 6. This ensures the maximum dynamic signal range, and the least amount of noise. As mentioned, the PMU is capable of measuring the current in all three phases, but since the units are only fitted with one current transformer, only one current measurement was made. This is sufficient to provide reliable measurements of the phase assuming balanced conditions.

The voltage signal is taken directly from the existing voltage transformers at the generator terminals. The frequency is calculated from the voltage signal. The PMUs were online for the duration of the isolated operation, and made measurements valuable for validation purposes.

4.3 Determination of generator and control system parameters for the units in Rønne

In the modelling of the power system on Bornholm, the parameters used are primarily coming from the documentation of the units enclosed by the manufacturer. The documentation supplies most of the parameters normally derived from the open circuit tests, meaning e.g. the generator constants such as, X_d, X_q, rated power, voltage and current. The saturation values are found from measurements done in connection with the installation. The inertia of the generators can also be found in the documentation. For detailed description on where to find the generator and turbine parameters see section 5.
In order to build a complete dynamic model, the control systems must be represented. This requires values for time constants, limiters and gains. Unfortunately there are no descriptions of these parameters in the collected material, and they have to be determined from measurements.

As mentioned previously, we chose to use the derivation method described in 4.1.1 as a basis for our measurement and parameter determinations. Unfortunately, it was not possible to test the power plant units to the extent described. The foundation for validating the model of the power system on Bornholm, are comparisons between measurements and simulation results, like it is the case in the extended method. In both methods, the demand for high resolution measurements is essential, because it enables the possibility of detecting fast variations in the responses.

The measurements were performed on unit 5 and 6 only, and no off-line measurements were performed. The reason for choosing these two units is, that they handle the primary supply during island operation. Furthermore there was no time for building and installing measurement equipment on the diesel units or the bio-gas power plant. This is a reasonable limitation, as the diesels only operate during high load situations, which usually occurs in the winter. The islanding was done in September and without use of the diesels. The bio-gas units was not investigated further as they are not contributing to the control of the electric grid on Bornholm. The large Vestas wind turbines, referred to in chapter 2, have the capability of being used for control purposes, but this option is not yet standard procedure. Unfortunately we had no access to detailed models of control devices in wind turbines, or detailed mechanical models. Among others, these are the reasons for not including the wind power control option in the model. How the wind turbines are modeled is described in chapter 5.

Models of the turbine governor and exciter systems, are based on knowledge of the type of model provided by the staff of the power plant. Standard IEEE models are found in the Power Factory model library. The derivation demands a suitable set of initial parameters of the generator, turbine and control systems, to be used as a starting point for the iterative process. Therefore standard values for machines of the same size are found in the literature as described in 5.

4.3.1 Differences between the actual and the extended method for derivations of parameters

Responses from disturbances are highly important for tuning the values of the dynamic parameters. To verify the exciter model, measurements of voltage disturbances are needed. In order to verify the turbine governor, a change in the rotational speed, meaning the frequency, is needed. As a staged test, this is done by inducing a sudden change in the active power balance.

During the islanding of the power system on Bornholm it was not possible to perform the tests described in section 4.1.1. Island operation is a delicate operation mode, and the staff on the power plant's main concern was therefore to ensure the security of supply. No staged tests could be done, and therefore neither unit 5 nor 6 was subjected to any staged load rejection or other kind of planned disturbances. Instead the measurement equipment logged data from unit 5 and 6 during the island operation. The disturbance responses used in the model validation were found in this data. For validating the turbine governor model, we hoped to find disturbances in the balance of the active power in the loggings, the disturbances found are described in section 6.

Another important simplification of the method, is that the amount of signals monitored and logged is less than in the extended method. As will be described in details in section 4.2 the signals measured on unit 5 and 6 were the current in the measuring circuit, and the three phase voltages on the terminals. Most of the signals used for parameter derivation, listed in table 4.1, was not accessible, and was therefore not monitored. The signals exists, but the physical layout made them impossible to measure within the time frame of this project.

4.4 Evaluation of the used test method

It would have been preferable if we had had the opportunity of performing staged tests. In that way it would have been possible to control the disturbances, making sure there was enough data for a validation of the dynamics in the model. To perform a staged test causing a voltage or frequency disturbance, one could use the diesel generators, by letting them supply a minor part of the load and then disconnect the diesel generator.
The current was only measured in one phase. By measuring the current in the protection circuit instead, it would be possible to measure the current in all three phases. The reason for not doing so, is that if the measuring equipment should fail, it could cause the protection devices to fail as well. The main concern is to sustain the security of supply, and it is important to point out the measurement equipment is not conflicting with this requirement. Measurements of the current in all three phases, could have been used to validate system dynamics in case of non-symmetrical disturbances.

The way measurements for parameter derivation and validation of the exciter and turbine governor are executed, in many ways differ from the test schedule in section 4.1.1. Nevertheless we believe that the measurements can be used to derive a reasonable dynamic model representing generators and control systems on the Rønne power plant, given sufficient measured events. One way of evaluating the final model, is to evaluate the correlation between the simulated and the measured responses. One essential point should be kept in mind: The parameters of the final model must give satisfying correlation in different scenarios, not just in the one used for adjustments.

For future upgrades of the model, the parameter derivation and thereby the dynamic model, would benefit from using the extended test method, including measurement of more signals and the performing of staged tests. By increasing the number of signals measured it would be possible to verify the generator data, which would improve the reliability of the model. As mentioned earlier, unit 5 and 6 were installed respectively 24 and 13 years ago, and the characteristics alters over time. Measuring more signals would enhance the possibility of checking, how an adjustment of a parameter would affect the responses on the other signals and improve the basis for concluding that the model is valid.

Chapter 5

Modelling of Bornholm power system

This chapter describes the construction of the model of the Bornholm power system itself. The process, the data sources and the choices made during the modelling are described in detail, and the purpose, uses and limitations in the model are accounted for.

5.1 Introduction to modelling

In the field of modern power system engineering, having detailed models, of the systems you are analyzing, is becoming increasingly vital. This is due to the fact that the complexity of modern power systems is continuously increasing, as advanced control systems, architectures and power electronic components are being developed and implemented into the grid. Depending on the type of model, it can be used to simulate events that are vital to ensure the grids' stability, for example frequency or voltage deviations caused by loss of production capacity, lightning surges and short-circuits.
New technologies and their influence on an existing system can be analyzed, and pave the way for smoother integration while maintaining the security of supply.

5.1.1 The simulation software "PowerFactory"

The software package PowerFactory from DIgSILENT, has recently become the standard with many utility companies, transmission system operators and universities. This is primarily due to the graphical user interface and the wide range of functionalities implemented in the newer versions. PowerFactory can be used to model power systems of any size using components through the integrated library

of IEEE-models, which can then be adjusted according to the modelling task at hand. User models can be developed within PowerFactory's block-diagram interface, or shared between users and integrated into the relevant power system model.
PowerFactory is the simulation software currently used by both CET and Energinet.dk. For this reason, PowerFactory is the obvious choice for this modelling task.

PowerFactory can handle both load flow simulations and dynamic simulations through the same interface, and can simulate on 3-phase as well as 1-phase systems along with both AC and DC technologies. By adjusting the simulation parameters and algorithms, the user can reduce the time consumption of the calculations, while maintaining a high level of accuracy. Simulations with fast transients, e.g. when using models of HVDC, STATCOM and other components with fast switching, will require a smaller time-step than slower transients to generate a reliable and stable simulation.

5.1.2 Modelling of a power system

When starting a modelling assignment, one should always consider the desired application of the model beforehand. What kind of scenarios and events should the model be capable of reliably simulating, and how critical is the accuracy of the simulations?
For example, for some system planning purposes a load flow model is sufficient, and all system dynamics can be disregarded. For a simulation of the fault ride-through capabilities of a wind turbine, the dynamics are essential. In regards to the system dynamics, it is also important to estimate the durations of the simulated events. For example when simulating fast switching of power electronics, the model should be capable of simulating electromagnetic transients, and the analyzed models should be constructed with this in mind. In many cases EMT-simulations require more advanced models and parameters to be defined, which may be hard to obtain.

5.2 Model of Bornholm

The purpose of this project is to create a dynamic model as accurate as possible within the timeframe. Later on this model could be devloped further, and used for simulating the integration of demand-side options for frequency control, besides other projects as described in 7.

The primary simulation parameters in this project are those influencing on the frequency and voltage response of the system. The 3-phase grid representation, inertia and control systems, will therefore be the initial focus point of the model. Modelling is to some extent always a work in progress, and though not necessary for most of the research activites that are expected to utilize this model, parameters used for the simulation of electromagnetic transients will be applied when easily obtainable.
Due to the primary usage of the model, and the time frame allocated for the modelling, the model will be limited to simulating on a balanced 3-phase network, meaning that positive-sequence parameters will be prioritized. When available, the zero- and negative sequence parameters have been added, but a few are missing. The limitation resulting from this, is that unbalanced networks cannot be simulated. Furthermore, certain protection systems such as distance relays cannot be simulated reliably within this model. The primary application of the model, is to simulate the causes and consequences of fluctuations in frequency and voltage, and not to simulate short circuits.

The power system components in the model of the Bornholm grid will now be described, and the parameters and sources used will be accounted for.

5.2.1 Basic topology and layout

As described in 2.1 the basic topology of the Bornholm grid is a 60 kV ring-structure, with an underlying network of 10kV and 0.4 kV substations. Since the focus in this project is on large scale disturbances affecting the entire grid, such as loss of production, the low voltage network (<10 kV) is not modelled. The topology and station names are based on figure 5.1, which is the current layout as of 1st of January, 2007. For sake of clarity, the stations and lines are graphically placed corresponding to their approximate geographical location, though not to scale. Cables are drawn with dotted lines and overhead lines with full lines. The resulting model topology is shown in figure 5.2 as it is displayed graphically in PowerFactory.

5.2.2 Cables and overhead lines

Each cable and overhead line in the transmission grid is represented by a lumped PI-model, shown in figure 5.3. The parameters for each line is known from reference [20]. Contained in this spreadsheet are the resistance, reactance and susceptance per kilometre, both positive and negative sequence, as well as the rated current and total lengths.
The lumped PI-model is useful for simulating both transient responses and steady-

Figure 5.1: Map of Bornholm with 60 kV-grid.

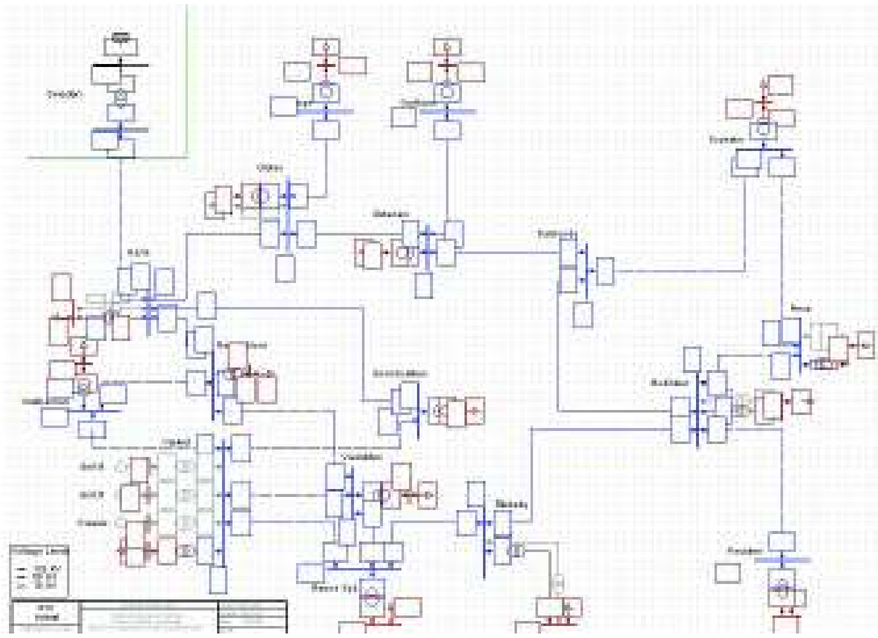


Figure 5.2: Graphical display of model in PowerFactory.

state conditions, as long as the total length of the the line is lower than 250 km. In the case of Bornholm, this limitation will not be encountered.

5.2.3 Low voltage grid

For some purposes of modelling, the low voltage grid could be neglected and represented only by a load directly connected to a substation, but in the Bornholm case, the large amount of cables in the low voltage grid is the main cause of high-voltage problems due to the relative high capacitance of the cables. Because of over-voltages it could for example become neccesary to operate the power plant generators under-magnetized, thereby decreasing transient voltage stability. The low voltage network itself is represented by a capacitor with a capacitance corresponding to the amount of cables under each substation. Data for the low voltage grid was taken from the [21].

Due to this simplification, the capacitive contribution to the grid is only dependant on the voltage, and not on the current in the modelled low voltage network. This simplification should have very small implications on the simulations since the contribution from reactive current is quite small, and the reductions in simulation and modelling time are assumed to justify this simplification, since the low voltage network consists of more than 1000 substations.

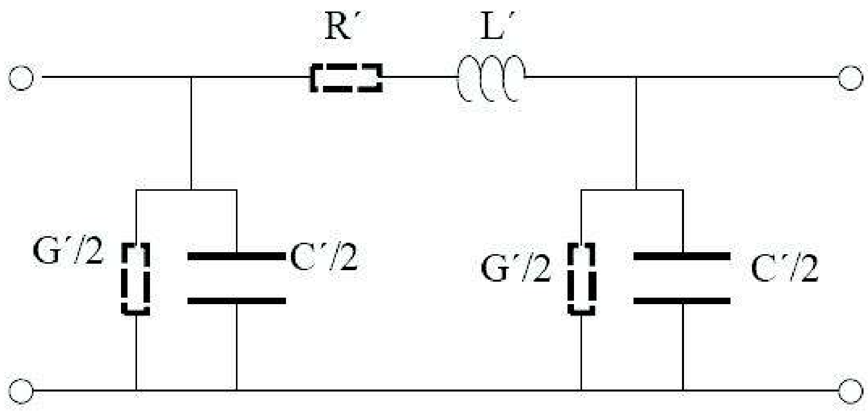


Figure 5.3: Lumped PI-equivalent of transmission line.

5.2.4 The Swedish interconnection

The Swedish interconnection from Hasle consists of sections of various types of both land and sea cable. The cable is therefore modelled in the same way as the other 60 kV lines, only in this case with the total resistance and reactance being the sum of all sections. Data for the interconnection is contained in reference [22].

For most simulation purposes in this project, Bornholm is operating isolated thus without the cable. However should the need arise, the cable can be used for simulation purposes. The Nordic grid, to which the cable is connected, is merely represented by a fixed voltage source. The user should be aware of this simplification, should the model be used for dynamic studies in interconnected mode.

5.2.5 Loads

The majority of the consumers on Bornholm are located on the 0.4 kV low voltage grid connected to each of the 10/60 kV transformers. In this model a load of both active- and reactive power is inserted on the 10 kV busbar in each substation. Based on experience, it is assumed that the loads are not constant impedance loads, and so a dependency of voltage is implemented. Since no updated measurements or knowledge of the loads' composition on Bornholm are available, the default parameters for voltage dependency are implemented. Frequency dependency is also a possibility, but since we have no knowledge of this, this is not included in the model.

There are no SCADA-measurements of the phase between the voltage and the current, so the distribution between active and reactive power is unknown. The active/reactive power ratio and size of the loads implemented in the model, is based on load flow simulations made by Elkraft Consult in 1992 [33]. Using these distributions, the current of the loads are scaled to match those of a high load situation in the SCADA system loggings. This is the most accurate known source of data for the loads, and should provide a reasonable guess at the composition of the loads.

5.2.6 60/10 kV Transformers

Some of the substations in the Bornholm power system network are equipped with two parallel 60/10 kV-transformers supplying the distribution grid. In order to keep the short circuit current below certain limits, only one of these transformers is operating under normal circumstances. Other smaller substation only has one 60/10 kV-transformer.
According to data from Østkraft [23], all 60/10 kV-transformers are Y-connected on the high voltage side with a neutral, and D-connected on the low voltage side. The vector group is defined in PowerFactory as YNd11 as per IEC standards. The neutrals are in some substations connected to an arc suppression coil. This is described in reference [24]. The standard transformer model used can be seen in figure 5.4. The positive sequence impedance of the transformers is defined by their short circuit voltage, U_k, and is given in the schematic found in reference [25]. This impedance is assumed to be distributed equally among the leakage impedance on the high and low voltage side. The ratio between the reactive and resistive component of the transformer impedance, is taken from the same reference, and so is the rated apparent power. The resistive part defines the copper losses during operation. Since data was unavailable, the magnetizing impedance is disregarded. For this reason, the model can not simulate the no-load losses of the transformers, as well as phenomenons such as ferro-resonance and saturation occuring during faults.

5.2.7 Under load tap changers

All 60/10 kV transformers on Bornholm are fitted with an under-load tap changer (ULTC), automatically altering the winding ratio to increase or decrease voltage on the low-voltage side. According to correspondence with Østkraft [23], each ULTC has 15 steps with a voltage change per tap of 2% of nominal voltage. The tap changer is symmetric, so step 8 corresponds to the neutral tap. The change in the transformer impedance and copper losses due to the change in winding ratio is

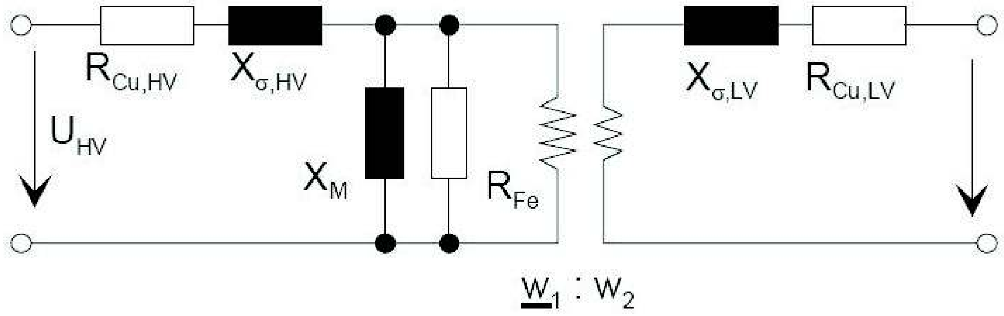


Figure 5.4: Transformer equivalent.

not modelled, since the data was not available. As such, the ULTC is considered ideal.

5.2.8 Switched shunts

Ten of the Bornholm 60/10 kV substations, have a switched capacitor installed, rated at 2 Mvar at a nominal voltage of 12 kV according to the reference [26]. These capacitors were formerly used to increase the voltage during high load situations, but since the cabling of the low voltage grid they are rarely used anymore. They are nevertheless modelled since it is relatively simple to do so.

5.2.9 Under-frequency relays

All 60/10 kV substations are fitted with under-frequency relays, configured to disconnect consumers in case of a major frequency disturbance. Without this security measure, the power plant in Rønne could be disconnected during a severe disturbance and, in case of isolated operation, could cause Bornholm to black-out. By intentionally disconnecting parts of the load, the remainder of the electric grid can be kept stable during such a disturbance. Each under-frequency relay has intervals of frequency and duration which will cause the relay to trigger. The under-frequency relays operate according to the load-shedding plan enclosed as reference [27], and they are setup in the same manner in the model. As the frequency drops below 48.6 Hz for more than 0.15 s, the first five 60/10 kV-transformer will be disconnected.

5.2.10 Power plant

As described in greater detail in chapter 2, Bornholm has one powerplant supplying the island with electricity. The powerplant units are modelled by the capabilities of the generators and transformers, and the synchrononus, transient and subtransient parameters. The powerplant units, and the way they are modelled, are described in the next sections.

Rønne

As mentioned in chapter 2, the primary power production capacity on Bornholm is provided by the central power plant in Rønne. This plant consists of two thermal units, with a combined capacity of 76 MVA. The generators are connected to the grid through two step-up transformers as described later on. The diesel units are included in this model, but the control systems could not be verified.
The thermal units control both voltage and frequency on Bornholm during isolated operation, and are capable of doing so through the use of control systems for the exciter and the turbine. The control systems are described in detail later.

Generators

Data for both the generator in unit 5, unit 6 and the diesels are taken from datasheets supplied by Østkraft in reference [28] The generators on the thermal units are turbo generators of the round rotor type, and the diesels are fitted with a salient pole rotor. Some of the synchronous, transient and subtransient parameters are given directly in [28], but others are not. For the missing parameters, typical values for units of their respective size have been used. These values were found in [3]. All values are the unsaturated values. Saturation parameters are implemented as well, as shown in section 5.2.10. Table 5.1 and table 5.2 displays the generator parameters for unit 5 and 6. The parameters in bold are the ones given in the datasheet. The inertia time constant H, rated to apparent power, is calculated from the moment of inertia given in the datasheet using equation (5.1) [3]. J is the moment of inertia, w_0 is the nominal rotational speed in radians per second and S_n is the nominal apparent power of the unit.

$$H = \frac{0.5 \cdot J \cdot w_0^2 \cdot 10^{-6}}{S_n} \tag{5.1}$$

Using this formula, the inertia time constant of unit 5 (generator and turbine) is found to be $H = 4.35\ s$. Unfortunately, only the moment of the inertia of the generator, and not the turbine in unit 6 is known, so estimations must be made. As demonstrated in chapter 6, the inertia time constant of unit 6 can be assumed to be approximately $H = 4.2\ s$.

Parameter	Value
Nominal apparent power	29.4MVA
Nominal power factor	0.85
Nominal voltage	10.5 kV
$\boldsymbol{X_d}$	1.57
X_q	1.57
$\boldsymbol{X'_d}$	0.16
X'_q	0.715
$\boldsymbol{X''_d}$	0.125
X''_q	0.120
$\boldsymbol{T'_{d0}}$	5.1
T'_{q0}	1.5
T''_{d0}	0.059
T''_{d0}	0.21

Table 5.1: Generator parameters Unit 5.

Parameter	Value
Nominal apparent power	46.8MVA
Nominal power factor	0.85
Nominal voltage	10.5 kV
X_d	2.294
X_q	2.294
$\boldsymbol{X'_d}$	0.249
X'_q	0.85
$\boldsymbol{X''_d}$	0.169
X''_q	0.116
$\boldsymbol{T'_{d0}}$	4.702
T'_{q0}	1.5
$\boldsymbol{T''_{d0}}$	0.013
T''_{d0}	0.21

Table 5.2: Generator parameters Unit 6.

Step-up transformers

Step-up transformers are the transformers connecting the generators to the grid. In general they are modelled in much the same way as the 60/10 kV-transformers, using the same equivalent model and parameters. One difference is that, the step-up transformers are not equipped with automatic tap changers, and the tap setting is done manually. Østkraft has supplied us with the photographies seen in figure B.3 and figure B.4 in appendix B of the nameplates from both step-up transformers. Based on these photographs, we have extracted the parameters for nominal voltage, current, short circuit voltage and resistive ratio used in the modelling. From the nameplates it is furthermore concluded that the step-up transformer on unit 5 is operating in tap 3 with the ratio 10.5/66 kV. Østkraft informed us that the step-up transformer on unit 6 is in tap 4 with the ratio 10.5/64.35 kV. A test report [29] supplies information on the core losses in the step-up transformers.

Saturation

Increasing the magnetizing current beyond a certain point, will cause saturation to occur in the rotor. This phenomenon can be taken into account when modelling the generator, by utilizing simulation of main flux saturation in PowerFactory. The saturation parameters are defined as described in section 4.1.2, and requires the parameters $S_E(1.0)$ and $S_E(1.2)$ to be calculated from measurements. The curves for determination of the saturation parameters is found in the appendix B.1.

Unit 5

$$S_E(1.0) = \frac{275\ A - 240\ A}{240\ A} = 0.146$$

$$S_E(1.2) = \frac{475\ A - 1.2 \cdot 240\ A}{1.2 \cdot 240\ A} = 0.649$$

Unit 6

$$S_E(1.0) = \frac{1.0\, pu. - 0.9\, pu.}{0.9\, pu.} = 0.111$$

$$S_E(1.2) = \frac{1.3\, pu. - 1.2 \cdot\ 0.9\, pu.}{1.2 \cdot 0.9\, pu.} = 0.204$$

Turbine governors

The thermal unit models have been fitted with speed governing systems. Since we have no accurate knowledge of the governors, the standard IEEE model IEESGO has been used. This is a generic steam turbine governor model, which can be used to represent a range of different models depending on the parameters. The

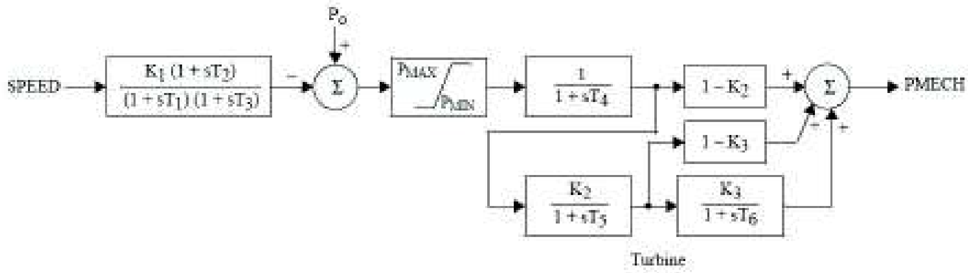


Figure 5.5: Block diagram of IEESGO turbine governor

IEESGO represents a simple speed governing system, without fast-valving capabilites or boiler controls. On figure5.5 is shown the block diagram of the IEESGO turbine governor.

The neccesary parameters for this model are displayed in table 5.3. As a first guess, parameter values from [3] are used for a turbine governor of the approximate MVA rating. From Østkraft we know that unit 5 only consists of a high pressure turbine, and unit 6 produces approximately 80% in the high pressure turbine and 20% in the low pressure turbine. This gives us the parameters K_2 and K_3 for both units. In chapter 6 it will be demonstrated how the remaining parameters are adjusted to reproduce a measured response to a known disturbance. The diesel units are fitted with a IEEE model called DEGOV. This is a model of a Woodward type mechanical controller, resembling the actual governors. The parameters used are default parameters from reference [3] since we have no measurements to verify the operation of the diesels speed governor.

Voltage controllers

According to Østkraft, the thermal units are fitted with respectively ABB COMPATROL and UNITROL type excitation systems. Both are of the static excitation type.
According to reference [18], these excitation systems can be accurately represented by the IEEE model ESST1A. The block diagram of the ESST1A model can be seen in figure 5.6. Depending on the exact model of excitation system, the presence of power system stabilizers and other factors, the model can be adjusted with different topologies by setting the relevant switches seen in figure 5.6.
As will be described later, we have no measurements that can be used to adjust or validate the models for the excitation systems. Instead the set of parameters displayed in table B.1 in appendix B.3 are used. The parameters are typical values

Parameter	Description
K_1	Controller gain
T_1	Governor time constant
T_2	Governor derivative time constant
T_3	Servo time constant
P_max	Maximum gate limit
P_min	Minimum gate limit
T_4	Steam chest & inlet piping time constant
K_2	High pressure turbine factor
T_5	Reheater timer constant
K_3	Low pressure turbine factor
T_6	Intermediate & low pressure time constant

Table 5.3: IEESGO parameters

for the ESST1A model, according to reference [18].

Biogas

As described in chapter 2, Bornholm has two biogas-unit of 2 MW in total. These units are simply supplying power, and are modelled as uncontrolled synchronous salient pole generators, operating with a fixed production regardless of the grid frequency and voltage. The data for these generators are taken from [3] and are typical values for synchronous generators of their approximate size. As will be demonstrated in chapter 6, the biogas units are not part of the dynamic verification and parameter adjustment, since they were not operating during the events used for validation. Therefore, typical values can safely be used for the biogas units in this context. Further information on the exact build-up of these generators could in the future be obtained by contacting the owner, Biokraft A/S.

5.2.11 Wind turbines

As described in the chapter 2, Bornholm has an installed wind turbine capacity of 29.8 MW. Most turbines are of older fixed-speed types, and others are modern double-fed induction generators. Since no dynamic model of such a modern wind turbine could be obtained, all turbines are simply modelled as asynchronous generators with default parameters. The wind turbines are aggregated into 6 generators, representing the total amount of wind power connected to a given substation. The wind turbines are not compensated with capacitors, since the real life

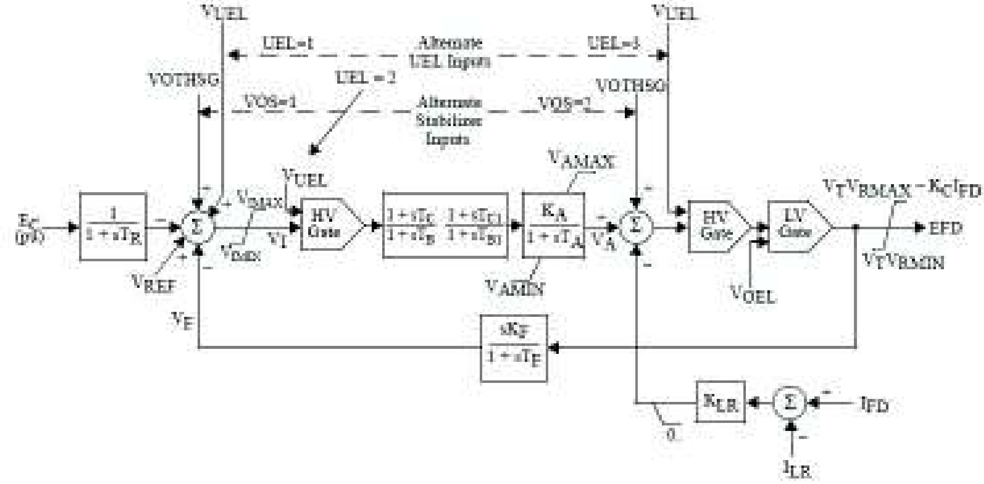


Figure 5.6: Block diagram of ESST1A static excitation system

wind turbines uses advanced power electronic control schemes to compensate for their reactive consumption. In order to make this simplification reasonable, the verification of the model is only based on scenarios where no, or very few, wind turbines were operating, as is the case during islanding operation. This representation of the wind turbines should not be used with dynamic simulations.
Measurements of the reactive and active power contribution of each cluster of wind turbines, should be known before using them for load flow simulations with significant amounts of wind power. In the future, the asynchronous generators could be replaced with updated dynamic models, should they become available.

Chapter 6

Verification of Bornholm model

The verification process is basically a comparison between measured and simulated quantities. This step is crucial in order to ensure the reliability of the model, and to identify sources of error in the model for future improvements. The verification is split up in two primary parts: the steady-state load flow verification, and a validation of the system dynamics. This process will now be described in greater detail, and the results of the comparison will be displayed.

6.1 Verification of load-flow model

The first part of the verification is the validation of the load-flow model. In this step, simulated currents and voltages will be compared to measured values from the SCADA-system. The validity of the load-flow model depends on the following issues:

- Grid configuration. Tap changer settings, disconnected lines, disconnected transformers and switched shunts.
- Impedances of lines, transformers and generators.
- Load distribution of active and reactive power, and dependency on voltage.
- Representation of the capacity in the low voltage grid.

Based on SCADA-loggings, the model will be configured to resemble the actual recorded scenario, to the greatest possible extent. Comparing the simulation to the SCADA-values will enable us to determine, to what extent the model represents the actual grid under steady-state conditions. To keep the number of error sources to a minimum, the scenarios will be chosen as to keep them as simple as possible. This means that scenarios are chosen where unknown properties, such as wind power contribution, are not present.

As mentioned in the chapter 5, the loads are modelled as negative active and reactive power sources, with a slight dependency on voltage. However, the ratio between active and reactive consumption is unknown, and therefore estimated based on a dated analysis from Elkraft Consult in 1992. The SCADA-measurements of the 60/10 kV-transformers and lines only consists of the current, and not of the phase angle. For this reason, the simulation will be set up to display the current through the transformers, and this value will be compared to the SCADA-measurements of the current. Several of the measurements from the SCADA-system, are either missing or cannot be considered reliable. For this reason, the comparison will be made using only parameters deemed reliable as input or output to the model.
As an example, all measurements from the substations in Rønne and Åkirkeby are missing due to respectively missing voltage/current transformers, and a recent fire. It should be noticed, that the direction of the current is not measured. For that reason, the comparison is only made of the amplitude of the currents. This should in most cases be of little importance since the current direction is fairly obvious, with all electric power production coming from either the interconnection or the power plant in Rønne.

6.1.1 Interconnected scenario

The least complex scenario is one where no windturbines or powerplants are operating, and Bornholm is only being supplied with electricity through the interconnection to Sweden. Such a scenario will only have the voltage in Hasle, the power transfer from Sweden, and the tap changer settings as input. A scenario fulfilling these requirements was identified on the 25th of June 2007 around 13:00. From Østkraft we were supplied with the screendumps from the SCADA-system enclosed in reference [30]. Based on these, a case was built with the interconnection transferring 36 MW of power, and the voltage in Hasle at 62.6 kV. The interconnection transfers 4 MVAR as well, but according to the operators in the Rønne powerplant, this number is only an approximation of the actual reactive power transfer. Since the interconnection was supplying the whole island at this point, the transfer of active power was used to scale the total load to 36 MW including transmission losses. As such the case was built around the active power transfer, the voltage in Hasle, the tap changer settings and the known grid configuration from the SCADA-system. The scenario, called a revision in Power Factory, can be found on the enclosed CD-ROM [34].

The simulation results compared with the SCADA-measurements, can be seen in table 6.1 and table 6.2.

The results shows, that there is clearly coherence between the simulation and the measurements. Studying the SCADA-system screen dumps in [30] closely, one will notice certain discrepancies in the current measurements. In some cases, the current deviates greatly when measured from each end of the same line, and a certain inaccuracy of the current measurements should be expected.
From the SCADA-system, it can also be concluded with certainty, that not all voltage measurements are functioning properly. In many cases, two or more voltage measurements made on different lines in the same substation, varies in the order of up 1 kV. This is of course incorrect, since the impedance between the different measurement points is close to zero. For this reason, the voltage measurements are somewhat hard to use for verification purposes. If more than three voltage measurements in the same substation are present, the two resembling each other the most, were used for the comparison. If only one voltage measurement is present, or all measurements deviates more than about 0.5 kV from eachother, the voltage measurements are not used for comparison purposes. In a few cases, a relatively large deviation in the current is observed. For instance, the substation in Nexø measures 103 A through the transformer, but the simulation calculates 242 A. The flows and voltages, mainly around the larger substations, are reasonably accurate, considering the obvious measurement errors that were observed. This deviation, and others, could be the result of several factors:

- The load model and distribution of active and reactive power is probably outdated in certain substations. A detailed analysis would be neccesary in order to clarify this.
- The wind turbines. Though the simulation is based on a scenario with no wind, a number of wind turbines not governed by Østkraft could be running, and thereby supply a part of the load in the substation.
- The measurements of the currents themselves. They have proved to be inaccurate to some extent.
- The grid model itself could be inaccurate due to incorrect data, if certain lines or transformers have parameters differing drastically from the model.

6.1.2 Isolated scenario

In order to ensure the validity of the model in an isolated scenario as well, one such must be identified. As described in chapter 3, Bornholm was disconnected from the swedish grid during week 37, and measurements were collected during this period. For this week, phasor measurement units, were set up to provide detailed

Line/Transformer	Measured current [A]	Simulated current [A]	Deviation +/- [A]
RSY-VÆR	27	33	6
RSY-VIA	56	67	11
RSY-ÅKI	66	86	20
RSY TRF1	114	93	21
POU-BOD	13	15	2
POU TRF1	67	87	20
NEX-SVA	20	18	2
NEX-BOD	21	29	8
NEX TRF1	138	242	104
SVA-DAL	47	21	26
SVA TRF1	103	86	17
ØST-GUD	14	15	1
ØST TRF1	78	106	28
GUD TRF1	61	82	21
ALL TRF2	129	117	12
HAS-SNO	46	50	4
HAS-RNO	167	167	0
HAS-OLS	74	92	18
HAS TRF2	218	162	56
RNO-VES	51	53	2
RNO-VIA	88	91	3
RNO TRF1	226	159	67
VES-VÆR	36	40	4
VES TRF1	113	88	25
SNO TRF1	181	169	12
VIA-VÆR	5	10	5
VIA TRF1	199	167	32
Interconnection	316	336	20

Table 6.1: Results of interconnected scenario. Comparison of currents.

Substation (60kV)	Measured voltage [kV]	Simulated voltage [kV]	Deviation +/- [kV]
VÆR	62.3	62.3	0
VIA	62.3	62.4	0.1
BOD	61.9	61.5	0.4
SVA	62.0	61.5	0.5
DAL	61.9	61.5	0.4
NEX	62.0	61.4	0.6
GUD	62.0	61.7	0.3
HAS	62.6	62.7	0.1
SNO	61.9	62.3	0.4
RNO	62.6	62.4	0.2
OLS	62.2	62.1	0.1
RSY	62.3	62.3	0

Table 6.2: Results of interconnected scenario. Comparison of voltages.

measurements from the powerplant units. Again, the scenario must be kept as simple as possible in order to keep the number of error sources to a minimum. Most wind turbines were disconnected for the majority of the period of isolated operation, and this makes finding such a scenario more simple. A scenario was identified on the 12th of September 2007 at 19:00. At this time both unit 5 and unit 6, were operating at respectively 11.5 MW and 19.5 MW. Furthermore, the Biogas units were producing approximately 2 MW in total. Since the powerplant was supplying the island on its own, the total load was scaled to 33 MW including losses. The magnetizing of the generators was set to obtain the voltage measured by the PMUs on the generators themselves. The scenario is enclosed as reference [34]. A comparison between the simulation and the measurements is seen in table 6.3

The conclusion and results of the isolated scenario, much resembles those of the interconnected scenario. The deviation observed is approximately the same, and the same obvious errors in the voltage and current measurements can be seen in the SCADA-system measurements. The substation in Nexø again displays a very large deviation between simulations and measurements. This station, among others, should be the target for future analysis in order to clarify the reason behind this deviation.

Line/Transformer	Measured current [A]	Simulated current [A]	Deviation +/- [A]
RSY-VÆR	49	53	4
RSY-VIA	28	37	9
RSY-ÅKI	62	76	14
RSY TRF1	106	77	29
POU-BOD	17	13	4
POU TRF1	90	92	2
NEX-SVA	14	18	4
NEX-BOD	27	30	3
NEX TRF1	136	223	87
SVA-DAL	29	16	13
SVA TRF1	99	79	20
ØST-GUD	16	14	2
ØST TRF1	76	97	21
GUD TRF1	70	75	5
ALL TRF2	137	102	35
HAS-SNO	17	20	3
HAS-RNO	69	73	4
HAS-OLS	63	69	6
HAS TRF2	148	149	1
RNO-VES	57	53	4
RNO-VIA	49	43	6
RNO TRF1	201	127	74
VES-VÆR	71	65	6
VES TRF1	98	81	17
SNO TRF1	103	140	37
VIA-VÆR	105	99	6
VIA TRF1	152	154	2
Interconnection	0	0	0

Table 6.3: Results of isolated scenario. Comparison of currents.

6.2 Verification of dynamic model

It is required for the model to be relatively accurate in steady-state, before it is possible to make any kind of dynamic validation. The verification of the dynamic model, is done in much the same way as the steady state validation; by comparing measurements with simulations. The dynamics though, are much more complex and sensitive to inaccuracies in the model.

As described in this chapter, these measurements are not only used to validate the models, but also to adjust them as to resemble the actual controllers. These controllers are complex electronic systems, that requires a lot of parameters to accurately represent. The two basic controllers governing the Bornholm electric grid, during isolated operation, are the turbine governors and excitation systems on the power plant units. The turbine governor controls the flow of steam passing through the turbines, thereby controlling the speed of the turbine shaft keeping it at a constant speed. Any imbalance between production and consumption will lead to a deviation in frequency, and the turbine governor will increase or decrease the steam flow to obtain a new equilibrium. The power plant operators are then expected to manually adjust the active power setpoint to return the system frequency to 50 Hz.

The exciter controls the magnetizing current of the rotor windings, thereby controlling reactive flow and terminal voltage. When operating automatically, the exciter is given a voltage set point, and will aim to keep the terminal voltage at this set point. A voltage disturbance in the grid will thus be reduced by the exciters.

In order to adjust and verify the models, used for representing the turbine governors and excitation systems, scenarios should be identified in which these control systems act automatically. If simulating, for example, a loss of production, an interconnection to Sweden, would supply most of the deficit active power, and thereby reduce the frequency deviation and the governor response. When using an isolated operation scenario, it can be assured that, the response of the control system in question, without influence from a large interconnected grid, is observed in the measurements. As described in chapter 4, a dynamic model should be verified with both large signal and small signal disturbances, in order to exhibit the non-linear behavior of the control systems. Phasor measurement units were operating, for the entire week of isolated operation, and from these measurements, we had hoped to identify a number of useful scenarios. In order not to endanger the security of the system, we were as mentioned unable to perform staged tests, and had to rely on analyzing the data for any useful disturbances.

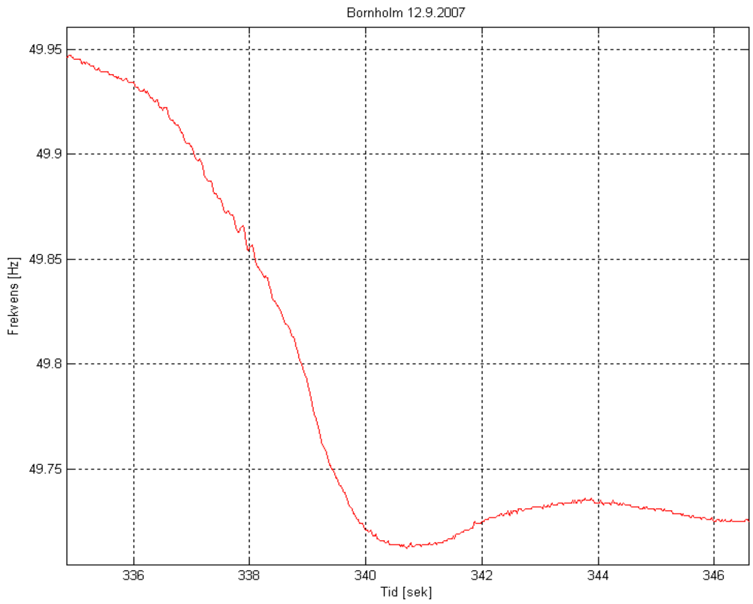
6.2.1 Turbine governors

As described in chapter 5, both unit 5 and 6 are fitted with turbine governors. However, during isolated operation, unit 6 supplies constant power without the use of its turbine governor. Unit 5 alone is responsible for counteracting fluctuations in demand as well as failures. During a frequency disturbance, the system frequency will drop approximately linearily with the gradient of the first part of the transition being dependant only on the size of the imbalance, and the total power system inertia. This will shortly be used to estimate the missing inertia time constant, of the combined turbine and generator on unit 6. The consequence of this, is that we have no measurements that can be used for validating the unused turbine governor on unit 6. The same goes for the speed governor on the diesel units, since they were not running at all during the week of isolated operation.

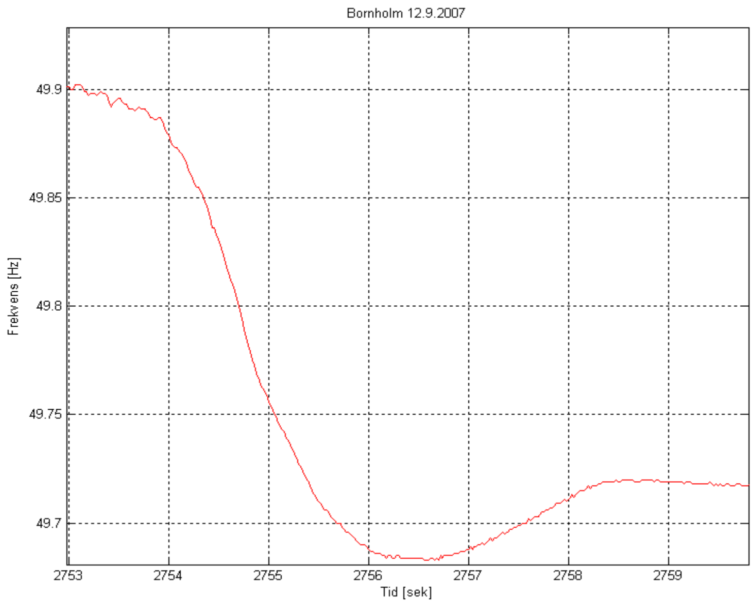
Shortly after the steady state scenario used in section 6.1.2, at about 19:05, a frequency disturbance occured in the Bornholm grid. The Biogas units failed, and caused an instant loss of 2.1 MW production. This resulted in a frequency drop to 49.68 Hz, and caused the turbine governor on unit 5 to increase production automatically, and thereby produce a response, useful for adjusting and validating the model. This event reoccured about 40 minutes later at 19:45, when the Biogas-units again disconnected with about 1.9 MW of active power production. In figure 6.1 can be seen the frequency response measured by the PMUs during these events.

The frequency can be seen decreasing until the point where the turbine governor on unit 5 begins counteracting the disturbance, and stabilizing the frequency at a new equilibrium. The gradient of both frequency disturbances in figure 6.1, is the result of the imbalance and the system inertia. However, a sudden change of the gradient in figure 6.1 (a), could indicate that the biogas units did not disconnect at exactly the same time. This is not the case to the same extent in figure 6.1 (b), and it is therefore better suited for estimating the total system inertia, and thus the missing inertia time constant on unit 6.
The gradient in the measurements can be estimated to approximately 0.14 Hz/s. A simulation is run where the same disturbance is simulated, but the turbine governor is disabled. The inertia time constant on unit 6 is adjusted to make the simulated gradient the same as the measured. The simulated frequency response can be seen in figure 6.2.

Besides being used for verifying and adjusting the inertia time constant, the simulation in figure 6.2 can also be used to verify the operation of the under-frequency relays. With no governor to counteract, the frequency decreases steadily until about 48.3Hz where the first 5 substations disconnects the consumers, as part



(a)



(b)

Figure 6.1: Measured frequency response of Biogas malfunction 12/9-2007 (a) 19:05 and (b) 19:45.

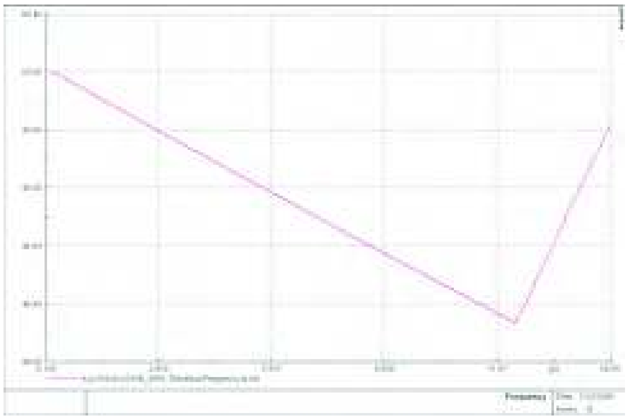


Figure 6.2: Simulated frequency response of 2MW disturbance without turbine governor.

of the load-shedding schedule described in chapter 5.

Turbine governor parameters

The parameters controlling the dynamic response of the turbine governor are, as mentioned, estimated from measurements of an actual disturbance. The only useful disturbance of the frequency,that was registered during the week of isolated operation, was the aforementioned loss of approximately 2 MW from the Biogas units. The adjusted parameters and the way they influence the response are as follows.

- Controller gain, K_1. This is the gain of the feedback loop in the governor, controlling the amplitude of the oscillations after a disturbance, and the stationary error of the frequency. In figure 6.3 can be seen frequency responses for different values of the controller gain.
- Governor time constant, T_1. This is the primary time constant of the governor, defining how fast the governor will react to disturbances. If the governor responds very fast, it will in some cases also cause oscillations to diminish. Certain combinations of time constants and gain could cause instability. The influence of the governor time constant can be seen in figure 6.4.
- Governor derivative time constant, T_2. According to reference [3] this parameters is used in the modelling of hydro power governors. For fossil fuel steam turbines, it should be set to zero.

- Servo time constant, T_3. The time constant defining the time it takes for the servos to operate the valve, increasing or decreasing the steam flow. This has much the same effect as the governor time constant as indicated by figure 6.5.

- Maximum and minimum gate limit, P_{MAX} and P_{MIN}. These parameters act as limits, to the interval of active power in which the turbine governor can operate. These have no implications on the dynamic simulations, unless the turbine is operating close to the limits when the disturbance occurs, and attempts to operate outside the limits.

- Steam chest time constant, T_4. This is the time constant defining the thermodynamic reaction time of the steam flow, to a change in the valve opening. This is dependant on the volume of the piping leading to the control valve, and reference [3] has recommendations on the size of this parameter depending on the MVA rating of the units.

- Reheater time constant, T_5. Reheating is the process of leading exhaust steam from the high pressure turbine back to the boiler, before leading it to the intermediate or low pressure turbine. Unit 5 only consists of a high pressure turbine, and the parameter is therefore set to zero. Unit 6 is not fitted with a reheating system.

- High pressure to low pressure ratio and time constant, K_3 and T_6. This parameter is used to define the percentage of rated power coming from the high pressure, intermediate and low pressure turbines. Unit 5 consists of 100% high pressure and unit 6 is approximately 80% high and 20% low pressure.

Having selected the IEESGO turbine governor model, and identified the neccesary parameters, a scenario is now built around the malfunction of the two biogas units at about 19:45, 12th of September 2007. The simulation is configured for steady-state conditions, using measurements from the SCADA-system to ensure authenticity of the scenario. The parameters of unit 5, that are not defined by physical factors, are now adjusted to produce the same frequency response as measured by the PMUs and displayed as figure 6.1 (b). The parameters of unit 6 are set to values recommended by reference [3]. The resulting parameter values are displayed in table 6.4.

A comparison between frequency response simulations and measurements, of the 19:45 scenario is displayed in figure 6.6. It should be noted that the steady state frequency of the measured scenario was not 50 Hz, but rather about 49.9 Hz. To make the simulation, which has a steady state frequency of 50 Hz, start at the

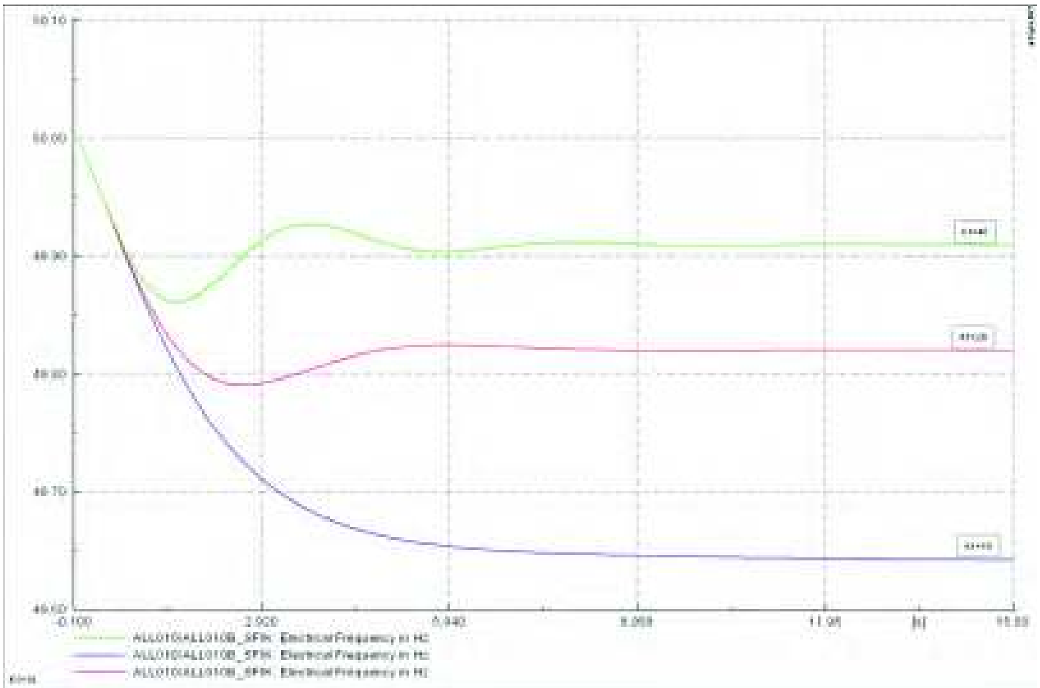


Figure 6.3: Frequency response variation when varying the controller gain.

Parameter	Value
K_1	20
T_1	0.42
T_2	0.0
T_3	0.3
P_{max}	1.0
P_{min}	0.0
T_4	0.4
K_2	1.0
T_5	0
K_3	0
T_6	0.45

Table 6.4: IEESGO parameter values for turbine governor on unit 5.

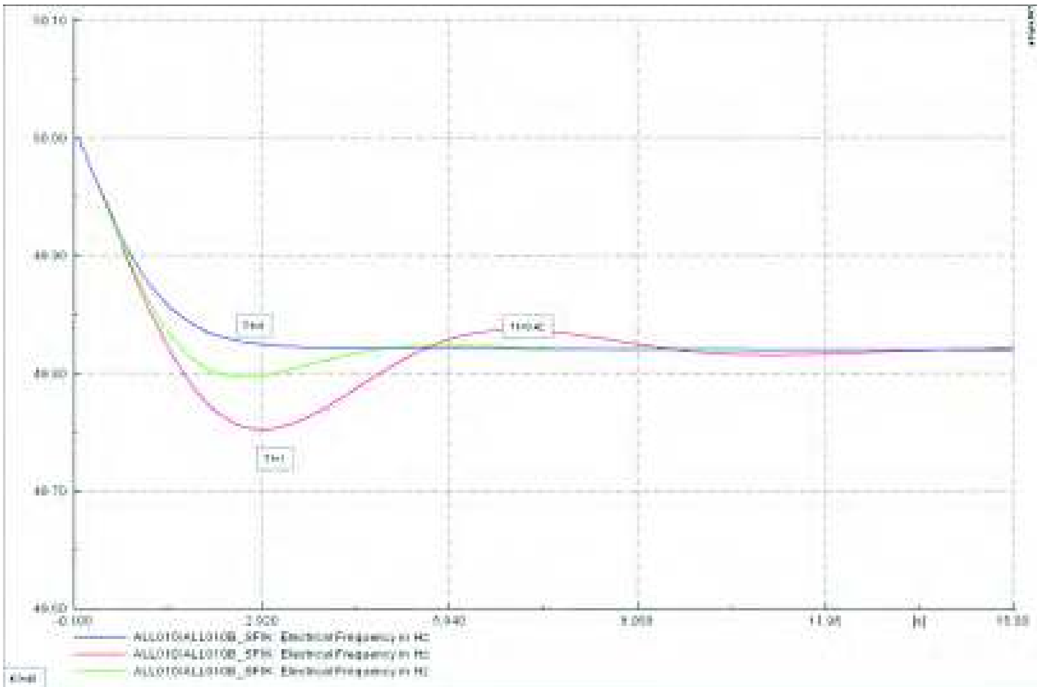


Figure 6.4: Frequency response variation when varying the governor time constant.

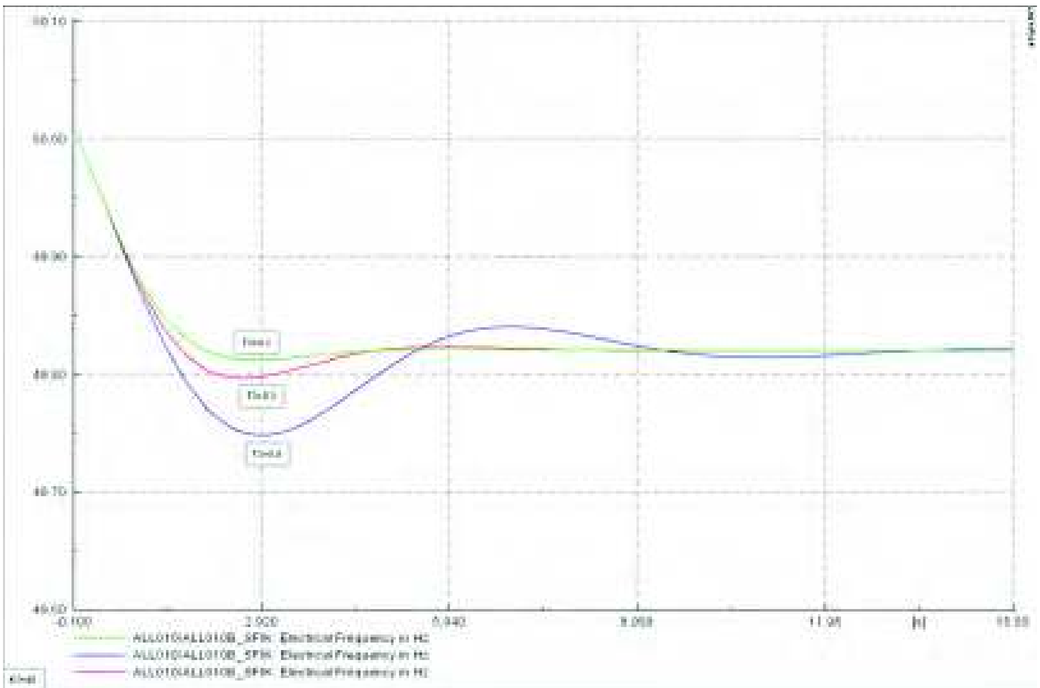


Figure 6.5: Frequency response variation when varying the servo time constant.

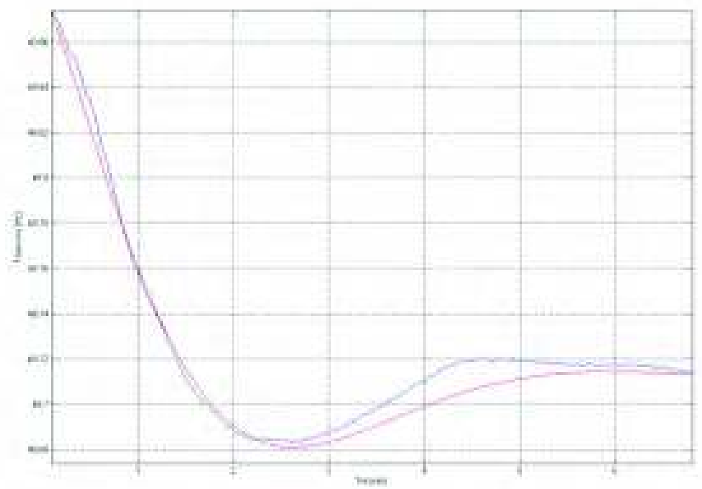


Figure 6.6: Comparison between frequency response measurements and simulations. Biogas failure, 12/9-2007 19:45.

same initial frequency, the frequency deviation from 50 Hz was subtracted from the simulated values. Due to the fact, that the steady state frequency initially is only 49.9 Hz, the governor must already have acted to some extent. This could have influence if the 19:45 disturbance causes the governor to hit non-linearities, where the simulation would not, since it started at a higher frequency. The same comparison is displayed in figure 6.7 for the biogas failure at 19:05.
As mentioned earlier, from the frequency response, it would appear that the gradient suddenly lowers distinctly during the initial drop in frequency. This could perhaps be explained by both biogas units, not failing at exactly the same time. This was attempted reproduced in the simulation by making one generator fail two seconds later than the other.

Displayed in figure 6.8 and figure 6.9 is the comparison between simulations and measurements of the active power, during the 19:45 event from both unit 5 and unit 6. It can be observed how the turbine governor on unit 5 increases power to stabilize the frequency. Unit 6 operates with a fixed production, and returns to this value after the initial excursions caused by the fault. The reason for these excursions is that, in the first instance after the fault, the system load stays the same, and the additional power is taken from the unit's inertia. Small oscillations caused by dynamic differences between the two units can clearly be observed afterwards.

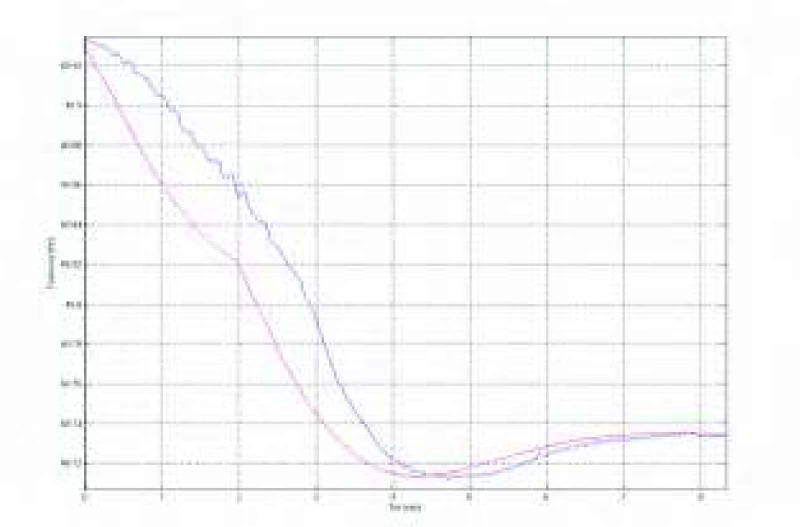


Figure 6.7: Comparison between frequency measurements and simulations. Biogas failure, 12/9-2007 19:05.

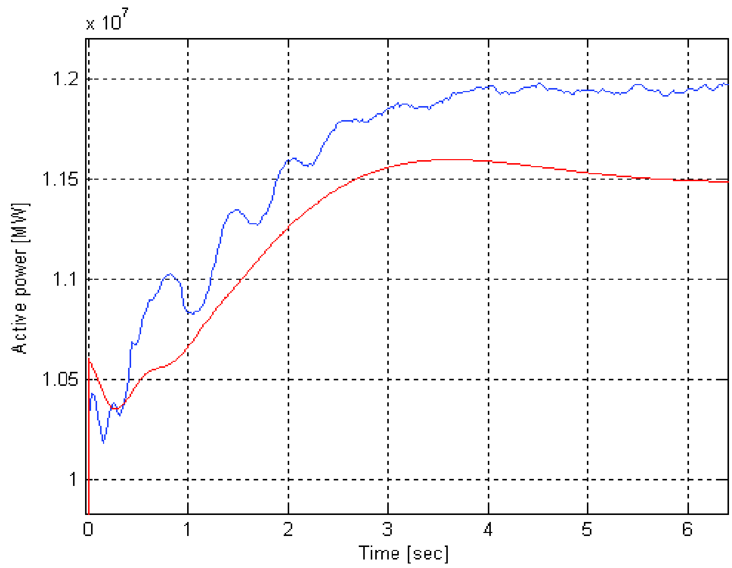


Figure 6.8: Comparison between active power measurements and simulations (Unit 5). Biogas failure, 12/9-2007 19:45

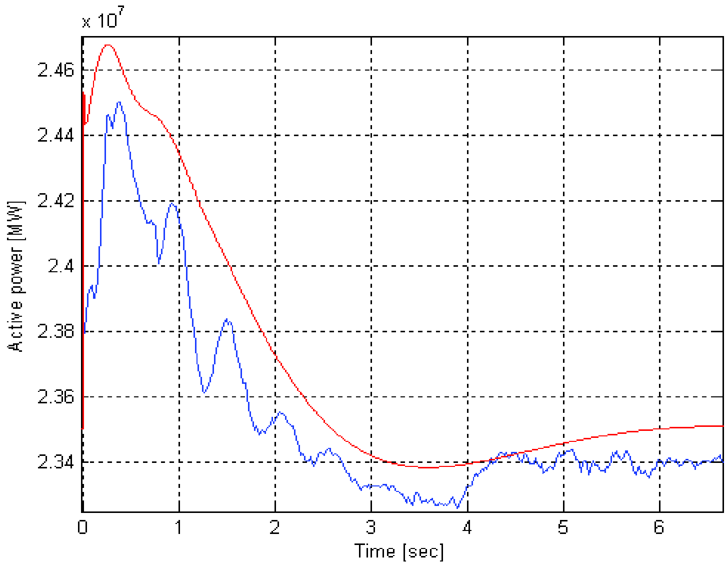


Figure 6.9: Comparison between active power measurements and simulations (Unit 6). Biogas failure, 12/9-2007 19:05

6.2.2 Excitation systems

As mentioned, we have no measurements of major voltage fluctuations during the period of isolated operation. For that reason we have no way of reproducing any event, that would make the excitation systems exhibit their response to a voltage disturbance, and use the same approach as with the turbine governor to validate and determine parameter settings.
The voltage fluctuations caused by the malfunction of the biogas units, are only in the range of approximately 40 V, and not sufficient to produce any reasonable exciter response. Instead we have used the recommended parameter values from reference [18] as described in chapter 5. The comparison between simulated and measured voltage on both units during the 19:45 event is shown on figure 6.10 and figure 6.11. As can be seen, the match between the simulation and the measurements is not impressive. This could indicate that the model is not realistic, at least for a small signal disturbance. The disturbance being compared with is not pronounced enough to reliably be used for adjusting the model parameters. Unfortunately, this disturbance was the only one measured throughout the week of isolated operation that could be reasonable explained, and imitated in PowerFactory.

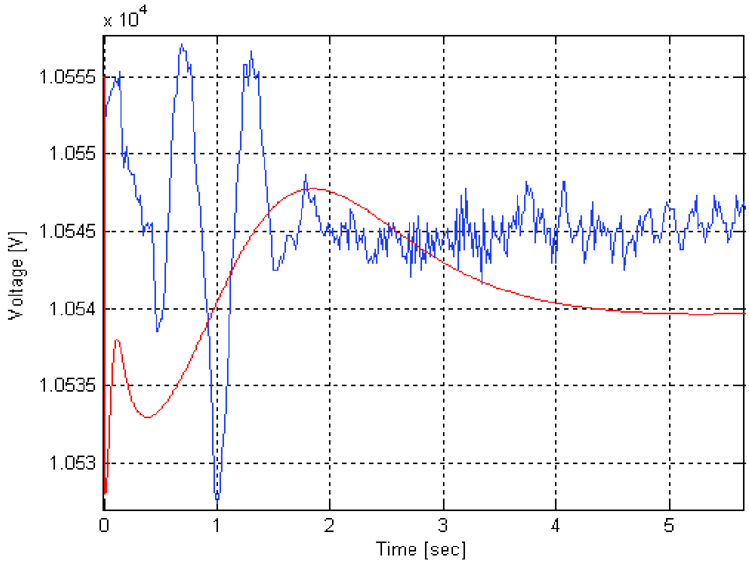


Figure 6.10: Comparison between voltage measurements and simulations on unit 5. Biogas failure, 12/9-2007 19:45.

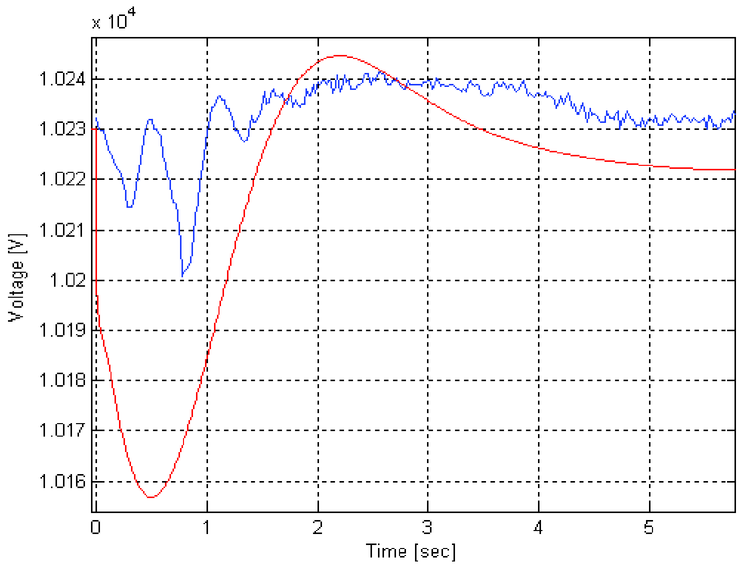


Figure 6.11: Comparison between voltage measurements and simulations on unit 6. Biogas failure, 12/9-2007 19:45.

6.3 Evaluation of model

In general the steady-state model seems to reflect reality to an acceptable degree. The observed measurement errors, and the uncertainty of the load-modelling diminishes such a conclusion. Further studies should be made, to finally verify this part of the model. The frequency response is acceptable as well, considering the unknown factors with the exact timing of the observed faults on the biogas units. The lowest measured frequency corresponds to the simulated, and the time constants seems approximately correct for a disturbance of this magnitude. Nothing definitive can be said of disturbances of a different magnitude, since this would require further measurements of disturbances. In conclusion we believe that, it is probable that the dynamic model is fairly well representative of the real world isolated power system on Bornholm, but further analyses are necessary to validate this. The resulting dynamic model is enclosed as reference [34].

Chapter 7

Discussion

Building a fully detailed dynamic model capable of performing any kind of simulation, is a huge undertaking, and often an impossible one. Simplifications will always have to be made, in order to reduce the complexity to within reasonable limits. Usually these simplifications are of little concern, as long as they are reasonable and kept in mind when utilizing the model - the output of a model is never better than the input.
Over the course of this project, we encountered a lot of difficulties. Some were expected, others were not. Identifying the neccesary data, and collecting it is time consuming, and not everything is available or even exists. It took numerous visits to the Østkraft offices in Rønne, as well as the power plant, to solve this puzzle, and to obtain an understanding of the way the Bornholm power system is operated. We got to personally know quite a few of the Østkraft staff, and this was immensely helpful when we had to find answers to a seemingly endless number of questions.

Through several visits to the Rønne powerplant, and numerous e-mails and telephone conversations, we discussed the possibility of making high resolution measurements with the power plant staff. They naturally had their reservations about installing unknown devices on both their critical units, and especially with an upcoming week of intentional isolated operation. In the end, we reached an agreement on how this could be done safely, with the use of current transformers, galvanic seperating the PMUs from the power plant systems. The PMUs were succesfully installed the week before the islanding, and in cooperation with the IT-department at Østkraft, the remote connections to the PMUs were established as well.

A lot of options for expanding and enhancing the model exists. In the future, having additional measurements would prove invaluable for a lot of different purposes. The model could be verified and adjusted further. Having, for exam-

ple, high resolution measurements of the transfer in the Swedish interconnection, would enable us validate frequency reponses in interconnected mode, and improve the reliability of the model in this case. Further 3-phase current measurements, could make us capable of validating the model during unbalanced faults, if a such could be recorded at some point. The voltage fluctuations during a fault, could also be suitable for enhancing the excitation system models further. As it is now, we have insufficient measurements to properly determine the capabilities of the excitation systems. As they are modelled, it is only a guess based on the known type of the excitation systems.
Many of these additional measurements are relatively simple to perform. Most substations are already fitted with voltage and current transformers, and further PMUs could easily be installed given the opportunity. If an IP-connection is not available at the site, the PMU can operate independently, and is capable of logging the measurements for several months. Should any useful event occur, the PMU measurements could be retrieved manually. PMU-measurements from substations could also be used to validate or calibrate the existing SCADA-system measurements, and pave the way for further adjustment of the steady state model.

We had originally hoped to be able to obtain further detailed measurements of signals from within the generator control systems. For different reasons, including the physical layout, the equipment used and others, this proved to be beyond the time frame of this project. Furthermore, knowing that it would be difficult, we had hoped to be able to perform the staged disturbances of voltage and frequency described in chapter 4. Out of concern for the security of supply, this proved to be impossible. For that reason, we had to rely on analyzing random events occurring during isolated operation. Staged tests, both online and offline, would have given us better grounds for applying different methods for determination of steady-state parameters, transient parameters and control systems.

As is, it can only be concluded that it is somewhat probable, that the model is an acceptable representation of the real system under balanced conditions. Only a small amount of additional data is necessary, in order to make the model capable of handling unbalanced grids as well. Under steady-state conditions, it seems the model is fairly realistic, but considering the quality and availability of measurements, a lot of improvements could be made in this field. The composition and behavior of the loads should be analyzed further, and better wind turbine models should be obtained. We have simply tried to model the Bornholm power system as detailed as possible, given the data available.
Regarding the dynamics, the model would benefit immensely from the above mentioned measurements of staged tests, and further analysis of the controllers' behavior. Again, the controllers of the newer wind turbines should also be implemented, should such information become available. Without these, the model can only be

used dynamically for scenarios without wind turbines operating. With a more detailed wind turbine implementation, studies could be made that could potentially improve the Bornholm power grids' capability of handling an even greater integration of wind power. A simplified dynamic representation of the Nordic grid, could be used to replace the fixed voltage source, creating the possibility of making dynamic simulations in interconnected mode. Such a representation could probably be obtained from the Swedish or Danish TSO.

Bornholm as a test site for the power system of the future, could potentially pave the way for the integration of unique technologies world wide, and maintain the Danish reputation as one of the world's leading nations regarding power system innovations. We hope that the work done on this model, could become a single brick in this puzzle.

7.1 Future use of the dynamic model

The dynamic model of the power system on Bornholm, is constructed in preparation for future research projects, using Bornholm as the test site, for later full scale implementation of the technologies. Even though Bornholm is a small island with a low population, the composition of the demand and the structure of the power system itself, makes Bornholm representative of a much larger power system [8].

The activity PowerLab*DK will benefit from the dynamic model. The research project is working on turning the Bornholm power grid into a power laboratory, for testing new technologies. The goal of the project, is to develop a way of combining low emission power production, with high security of supply. One research project at CET has already benefitted from a preliminary version of the model. This project explores the possibility of using the demand response as a way of controlling frequency. By intelligently switching on or off the electrical heating, depending on the system frequency, the demand can help support the frequency stability. This is done autonomously on each heating system, and with a sufficient number of controlled devices in the demand, the impact is significant.

The dynamic model of Bornholm could also be useful in the ongoing cell-projects. The aim of these projects, is to explore the possibilites of sectioning the distribution grids dynamically, and having a large integration of distributed production. Several projects are involved with this topic, and are described in reference [19].

Several other projects are to some extent involved with Bornholm, and many of these would benefit from a realistic model of the Bornholm power grid. With relatively few resources, this model could be upgraded to meet the demands of many of these projects.

Further information on the ongoing research projects, can be obtained on the CET homepage [13].

Chapter 8

Conclusion

In order to build a dynamic model of the power system on Bornholm, detailed knowledge of the characteristics was obtained. To gather this information, we have been through a long process of collecting data, to the extent it was possible within the time frame. Data that could not be obtained, was either estimated through measurements, or typical values were used for the component in question.
Of equal importance when modelling, is to be aware of the expected use of the model. Considerations were done of the ongoing research activities on Bornholm, and the priority was placed on a 3-phase dynamic representation, valid for simulations of frequency and voltage fluctuations.

When using measurements for modelling purposes, it is essential that they are reliable, and for dynamic purposes they must be of a high resolution. Measured dynamic responses are the basis for the determination of the dynamic parameters, controlling the turbine governor and excitation system models.

A theoretical method for determining or validating parameters was found, and became the inspiration for our method. The theoretical method is based on series of both offline and online steady state tests, and a series of dynamic tests. The steady state tests are performed for the determination of the synchronous reactances and the saturation parameters. The dynamic tests would result in estimations of the transient and subtransient reactances and time constants. The exact setup of the tests, is dependant on the type of the components in question.

The actual parameters and models used for the modelling of the thermal units on Bornholm, was determined from measurements done during island operation. Using the islanding scenario increases the probability that the observed dynamic

responses, are the result of the power plant control systems, and not the Nordic grid. The fact that no staged test could be done out of concern for security of supply, made the basis for adjusting and validating models limited.
The model as of now, consists of the following:

- 3-phase representation of the electrical power grid down to, and including, the 60/10 kV substations and loads.
- 1-phase representation of most components, though some parameters are missing.
- Steady state and dynamic generator parameters for four diesels units and the thermal units.
- Dynamic model of the excitation systems, and turbine governors on thermal units and diesels.
- Electrical interconnection between Sweden and Bornholm.
- The Nordic grid represented by an infinite voltage source.

Comparisons between the steady state model and SCADA-measurements displayed excellent coherence. Measurement errors were observed, and this leads us to the conclusion, that further studies are necessary in order to conclude that the model is realistic with certainty.
Validation of the dynamic model was done based on measurements, but no events suitable for validation of the excitation systems were registered. The resemblance between measurements and simulations of the voltage response was mediocre, but the amplitude of the measured voltage disturbance was too slight to produce a reasonable exciter response.
A frequency disturbance, with a known cause, was measured and was used for adjusting the turbine governor of the controlling unit. The resulting comparison between simulations and measurements displayed an excellent correlation, but the comparison could only be based on two almost similar events.

We think that the developed model will become a useful tool, in many of the research projects in progress in the Bornholm electric grid.

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[19] Østergaard, Jacob, *Research and Educational Activities within Electric Energy Systems using Bornholm as Full-scale Laboratory, 26th November.*, Ørsted•DTU - CET, 2007

8.1 References for modelling

The references listed below is included on the enclosed. This appendix contains data files, from which the parameters for the power network on Bornholm was derived.

[20] netsys_tabeller_CRA.xls

[21] 10 kV strækninger med kabeltyper og længder_CRA.xls

[22] 60kV liniedata.xls

[23] Info 60 kV net Bornholm.htm

[24] 60 slukkespoler.xls

[25] skematisk netoversigt med TR.pdf

[26] 10kv kondensatorbatterier.xls

[27] frekvensaflastningsplan.xls

[28] generator blok 5 data.tif and generatordata blok 6.pdf

[29] testreport_unit6

[30] screen dump.doc

[31] Bornholm_LF1

[32] Driftsinstruktion 60kV.doc

[33] liniedata Mvar udnersøgelse.tif, 1992.

[34] Bornholm_Final1.dz

Appendix A

The Power system on Bornholm

A.1 Wind turbines on Bornholm

Capacity [kW]	Manufacturer	Type	Locaktion
225	Vestas	Vestas V27	Rutsker
225	Vestas	Vestas V27	Rutsker
225	Vestas	Vestas V27	Rutsker
225	Vestas V29	V29/225/690/50/-/F/ R 9010	Bodilsker
225	Vestas V29	V29/225/690/50/-/F/ R 9010	Bodilsker
225	Vestas V29	V29/225/690/50/-/F/ R 9010	Bodilsker
55	Vestas Windmatic 15S	Unknown	Klemensker
30	Nordtank	NT 22/7,5 22kW	Bodilsker
130	Windmatic	WM 20S	Nyker
130	Windmatic	WM 20S	Nyker
18	Reymo DK	Reymo 18,5	Vestermarie
660	Vestas	V47/660	Rutsker
11	Gaia-møllen	Unknown	Østermarie
30	Vestas	Vestas HVK 10	Rutsker
660	Vestas	V47-660-2G	Olsker
900	NegMicon	NM 52/900	Bodilsker
900	NegMicon	NM 52/900	Bodilsker
900	NegMicon	NM 900/52	Bodilsker
800	Nordex	Nordex N50/800	Knudsker
800	Nordex	Nordex N50/800	Knudsker
800	Nordex	Nordex N50/800	Knudsker
1300	Nordex	Nordex N60/1300	Rutsker
1300	Nordex	Nordex N60/1300	Rutsker
1300	Nordex	Nordex N60/1300	Rutsker
1300	Nordex	Nordex N60/1300	Åker
1300	Nordex	Nordex N60/1300	Åker
1300	Nordex	Nordex N60/1300	Åker
1300	Nordex	Nordex N60/1300	Åker
1300	Nordex	Nordex N60/1300	Åker
1750	Vestas	Vestas V66-1,75 MW	Rutsker
1750	Vestas	Vestas V66-1,75 MW	Rutsker
1750	Vestas	Vestas V66-1,75 MW	Rutsker
2000	Vestas	Vestas V80-2.0 MW	Åker
2000	Vestas	Vestas V80-2.0 MW	Åker
2000	Vestas	Vestas V80-2.0 MW	Åker

Table A.1: Wind turbines on Bornholm, rated power, manufacturer, type and location[17].

Appendix B

Modelling

B.1 Saturation of generators

B.2 Step-up transformer nameplates

B.3 Excitation system, EEST1A, parameters

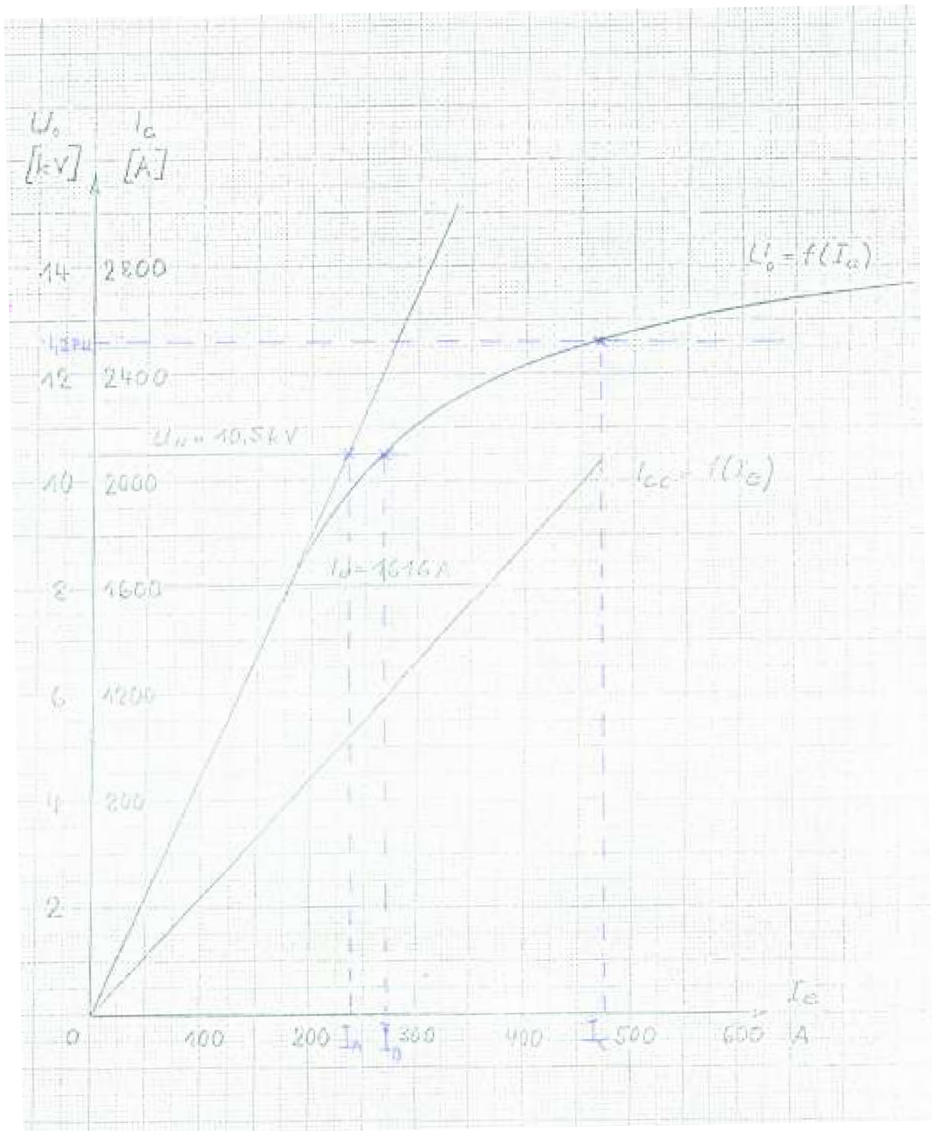

Figure B.1: Determination of saturation parameters for unit 5.

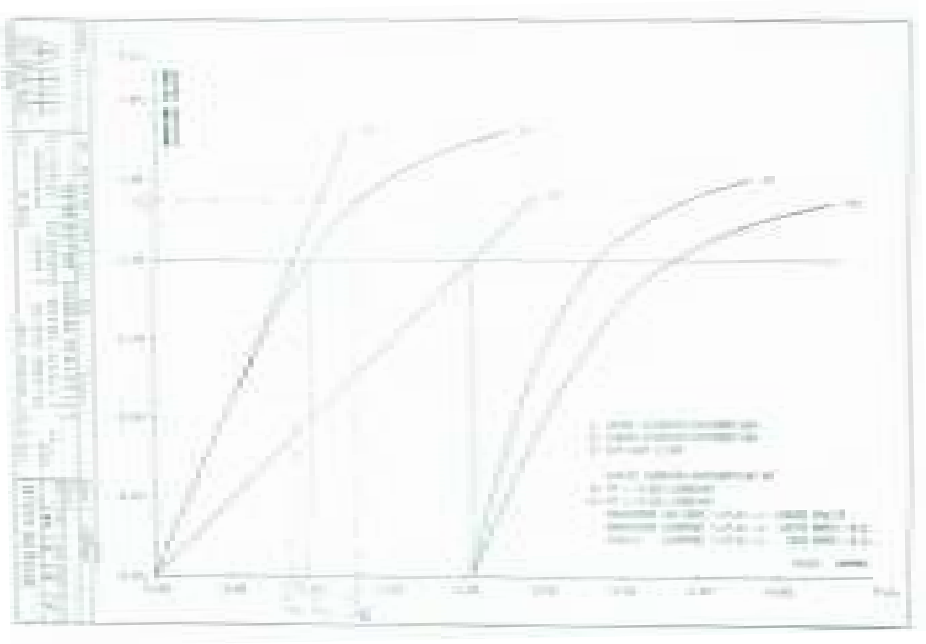

Figure B.2: Determination of saturation parameters for unit 6.

Parameter	Value	Description
K_A	210	Controller gain
T_A	0	Controller time constant #1
T_C	1.0	Controller time constant #2
T_{C1}	0	Filter delay time constant #1
T_{B1}	0	Filter delay time constant #2
V_{RMAX}	6.43	Controller maximum output
$VRMIN$	-6.0	Controller maximum input
K_C	0.038	Excitation current factor
K_F	0	Stabilization path gain
K_{LR}	4.5	Exciter output current limiter gain
I_{LR}	4.4	Exciter output current limit reference
T_R	0.02	Controller input filter time constant

Table B.1: Excitation system, EEST1A, parameters.

Figure B.3: Nameplate from step-up transformer in unit 5

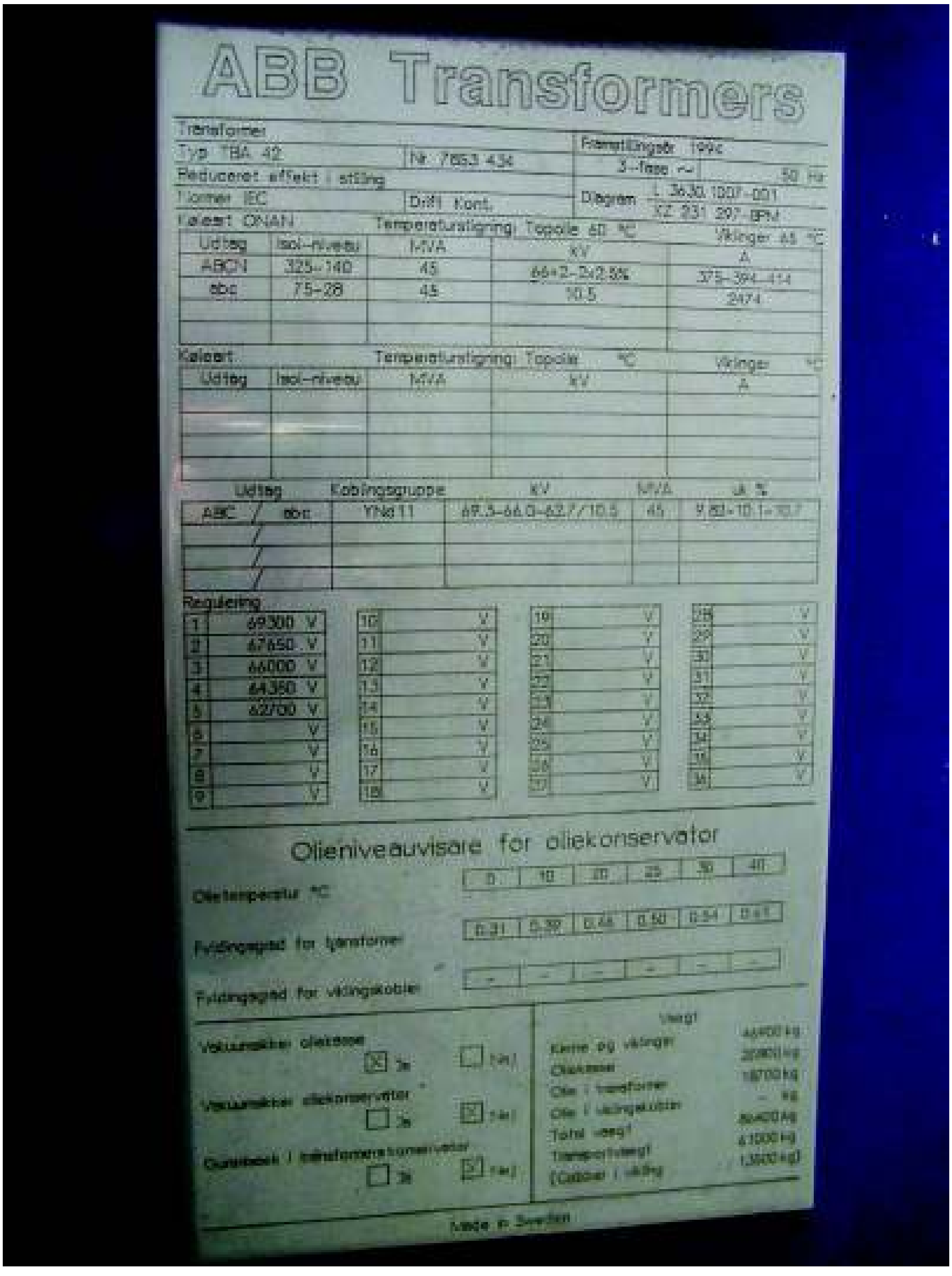

Figure B.4: Nameplate from step-up transformer in unit 6

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8. Island Operation 2007

Frequency Analysis for Planned Island Operation

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Frequency Analysis for Planned Islanding Operation in the Danish Distribution System – Bornholm

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***Abstract*-The power system in the Danish island Bornholm is a distribution system with a high penetration of wind generation, which is representative for expected future power systems. During the period from 11th to 14th September 2007, the Distribution System Operator (DSO) Østkraft in Bornholm conducted a planned islanding operation test. To evaluate the test and achieve useful experience for future similar operations in Bornholm or even in other similar systems, the frequency data before, during and after this period, were recorded by Phasor Measurement Units (PMUs), supplied by Centre for Electric Technology (CET), Technical University of Denmark (DTU). Statistical analysis of frequency data has been performed and the results reveal that the frequency quality during the islanding period was significantly decreased, indicating the need for enhancing frequency control of such systems in the future.**

I. Introduction

As shown in Fig. 1, Bornholm is a Danish island in the Baltic Sea, which is situated in the east of Denmark, the south of Sweden and the north of Poland. According to [1], the electric power system in Bornholm is a distribution network consisting of three voltage levels: 60 kV, 10 kV and 0.4 kV. At 60 kV level, the network has 18 nodes, 23 60/10 kV transformers with On-Load Tap Changer (OLTC), 22 cables and overhead lines. Besides, there is one 60 kV sea cable with 60 MW capacity [2], connecting the Bornholm system to the Swedish system. This cable makes Bornholm a part of the Nordic power system that covers Sweden, Finland, Norway and Eastern Denmark. The Bornholm system is normally inter-connected with the Nordic system.

The peak load in Bornholm is 63 MW while the minimum load is 13 MW in 2007. The generators include 14 Diesel (Oil) units with a total capacity of 35 MW, 1 steam plant (BLOK 5) with 25 MW capacity, 1 Combined Heat and Power plant (CHP) (BLOK 6) with 37 MW capacity, 35 Wind Turbines (WTs) with a total capacity of 30 MW and one 2 MW Biogas plant (BLOK 7) [1], [3]. Given so many wind turbines in Bornholm, the maximum penetration level of wind power with respect to minimum load can reach 231% in 2007, and 32.4% of electricity supply was already from wind energy, compared to 19.7% for the whole Denmark [4]. This percentage will be even higher, in that "A Visionary Danish Energy Policy 2025", published by the Danish government on 19th, January 2007, has highlighted that at least 30% of total energy consumption in Denmark should be supplied by renewable resources [5]. To fulfill this goal, the new policy expects that 50% of total electricity demand should be supplied by wind power by 2025. Since Bornholm already has a high share of electricity supplied by renewable energy, particularly wind power, its system can be a representative of future systems, so as the challenges that have appeared in system operation and control.

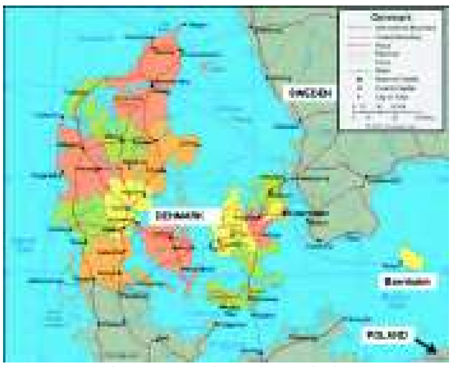

Fig. 1. Location of Bornholm

From time to time, the sea cable to Sweden was disrupted by the anchor of ships that passed around the island, which forced Bornholm system to run into islanding mode in periods of several weeks. During those periods, frequency control of the system became fairly difficult and the Distribution System Operator (DSO) Øskraft had to shut down most WTs. The experiences of those islanding operations in practice reveal that the existing technology failed to operate such system with high penetration of WTs. In order to achieve clear understanding of the challenge, the system performance during islanding operation periods should be analyzed carefully, which is the main focus of this paper. Such analysis will provide useful insights into the nature of the problem and then facilitate the research and development of new technologies in need.

In this paper, the system performance analysis is based on the data from a planned islanding operation in Bornholm, since it has not been possible to collect all needed data during previous islanding accidents. Those system data, including frequency, voltage, current, power, phase angle, etc., were collected by three measurement systems: the SCADA system for monitoring and operation [6], SonWin system for business transactions [7] and two Phasor Measurement Units (PMUs) [8]. In addition, there is a measurement system for six Vestas WTs [9]. Details of these systems are presented in Table I.

TABLE I
MEASUREMENT SYSTEMS IN BORNHOLM

System	Supplier	Time resolution	Data items
Settlement system-SONWIN	SONLINC	15 minutes	Average Active Power (MW) and Reactive Power (Mvar)
SCADA system - Network Manager for 60 kV and 10 kV network	ABB	10 seconds 1 minute 1 hour	Current (A), Voltage (kV), Power Factor (Cos phi), Tap Position, Frequency (Hz, only in HASLE station), Active Power (MW) and Reactive Power (Mvar) in sea cable (only in HASLE station)
PMU system	CET, DTU	20 ms	UTC, Voltage (kV), Current (A), Phase Angles (degree) of Voltage and Current, Frequency (Hz), Change rate of Frequency (df/dt)
VestasOnline® Business SCADA system for 6 wind turbines	VESTAS	instant	Status, Power, Wind Speed, Voltage, Current, Temperatures and Alarms
		10-minute average	Mean Values, Standard Deviations, Minimum and Maximum Values

Since frequency control is the challenge in focus and the PMUs have high accuracy and fine time resolution (20ms) [10], we mainly analyzed the PMU frequency data. The measurement of PMUs is synchronous to Universal Time Coordinated system or UTC. (UTC is 2 hours later than Central European Summer Time, or CEST.) The data therefore can accurately reflect the system status at exactly the same moment. Section III explains the PMU frequency data in detail after Section II, which describes the planned islanding operation. In Section VI, relevant analysis results are presented. Finally, Section V draws several conclusions.

II. The Planned Islanding Operation

From 11th to 14th September 2007, DSO Østkraft conducted a planned islanding operation. The purposes are to test the system's capability to go into islanding operation mode and to accumulate operation experience. Centre for Electric Technology (CET) at Technical University of Denmark (DTU) was invited to participate and the task was to collect all measurement data and perform analysis subsequently.

The whole operation was conducted in three major stages. At the first stage, Bornholm system was operated under the grid-connection mode, where it was synchronized to the Nordic system and participated in Nord Pool, i.e., the Nordic electricity market. The demand was supplied mainly by the sea cable, WTs and BLOK6. Before disconnection, several planned operations have been conducted in sequence.
First, most WTs were shut down. This is because in previous islanding operations, BLOCK 6 was unable to follow up with the fluctuations of wind power if too much was integrated. Second, in order to replace the power supplied by the sea cable, the normally out-of-service BLOK5 was gradually started to produce power. This, together with other generators, limited the power flow in the cable to the least level, preparing for a smooth transition later on.

The second stage includes the disconnection operation and the following islanding operation mode. Once the sea cable was disconnected, Bornholm system was asynchronous to Nordic system and became a separated 60 kV Medium Voltage Microgrid [11]. It did not participate in Nord Pool any more; instead, the electricity was traded in a regulated way at a fixed or contracted price. After around one day, three large WTs with 6 MW capacity in total were started and continued produce power afterwards. At this stage, BLOK5 and BLOK6 supplied the most demand while the three WTs only supplied less than 4% of the total demand, which was much lower than the level under grid-connection mode.

Bornholm system was synchronized and returned to grid-connection mode by reconnecting the sea cable. Subsequently, the power from BLOK5 was gradually decreased to zero, and the power through the sea cable was increased to the normal level within around one hour after reconnection. Meanwhile, all WTs were in service and Bornholm system can participate in Nord Pool again. This is the last stage.

Those three stages have been summarized in Table II.

III. Frequency Data

A. *Extracting Data from PMUs*

The frequency in Bornholm was measured by the PMU - BORNH1, which is installed on the low voltage side of the machine transformer of BLOK5. The frequency data from PMU - HVE400, which is installed on the 400 kV high voltage side of a substation in Zealand (within Eastern Denmark), are used for comparison purpose, since they are the frequency of the Nordic system.

Due to a calibration problem of BORNH1, the frequency data are not complete for the whole islanding period, except phase angle data. Nevertheless, the missing frequency data f can be calculated from the phase angle difference $\Delta\theta$ using

$$f = 50 \cdot \frac{2\pi - \Delta\theta}{2\pi} \qquad (1)$$

TABLE II
STAGES OF THE ISLANDING OPERATION IN SEPTEMBER, 2007

Stage	Operation	Time (CEST)
Stage One	Nordic Grid-connection	Before 07:25, 11-09
Stage Two	Disconnection	At 07:25, 11-09
	Islanding operation	From 07:25, 11-09 to 13:00, 14-09
Stage Three	Reconnection	At 13:00, 14-09
	Nordic Grid-connection	After 13:00, 14-09

with acceptable approximation. Thus, the frequency data in Bornholm for analysis consist of two parts: one includes the frequency calculated from phase angle; the other is directly from BORNH1. Their availability within the islanding operation period is shown in Fig. 2.

Equation (1) approximates the frequency based on phase angle. To validate such approximation, we compared the calculated frequency data with PMU frequency data in the part with both angle and frequency data. The results showed that approximation by (1) would introduce additional noise into the resultant frequency data. Such noise, due to the difference between interpolation to frequency and interpolation to phase angle, has been analyzed. To smooth out the noise, one 4-sample moving average filter was applied to the data. The selected filtering algorithm can provide satisfactory performance. This will not be analyzed in detail herein, since it is not the focus of this paper. The filter used can be expressed as:

$$y(n) = \frac{1}{4}x(n) + \frac{1}{4}x(n-1) + \frac{1}{4}x(n-2) + \frac{1}{4}x(n-3) \qquad (2)$$

where x represents the data before being filtered and y is the resultant data.

B. Time Plots of the Frequency Data

The frequencies in Nordic system and Bornholm during the islanding operation period are shown together in Fig. 3, which corresponds to Fig. 2. Bornholm was disconnected from Sweden at 05:25, Sept. 11th and reconnected back at 11:00, Sept. 14th, 2007 UTC.

Compared with the Nordic system, the Bornholm frequency fluctuated much more and several severe high/low frequency spikes were observed. To attain clear pictures of the critical transition process, the 20 min time plots of frequency around both disconnection and reconnection moments have been presented in Fig. 4 and 5, respectively. At the moment of disconnection, there was some power exported to Nordic system since Bornholm frequency jumped from 49.90 Hz to around 50.18 Hz. Before the reconnection moment in Fig. 5, the power production in Bornholm was adjusted gradually to make the frequency as close to the Nordic system frequency as possible. Once reconnected, the Bornholm system was fully synchronous to the Nordic system, as shown in Fig. 6. However, due to the inrush current at the reconnection moment, the bus voltages in the relatively weak Bornholm system experienced fluctuations, resulting in less than 2s fluctuation of Bornholm frequency measured by BORNH1.

As summarized in Table III, 3 complete days' frequency data have been abstracted from the islanding period for comparison studies in section VI.

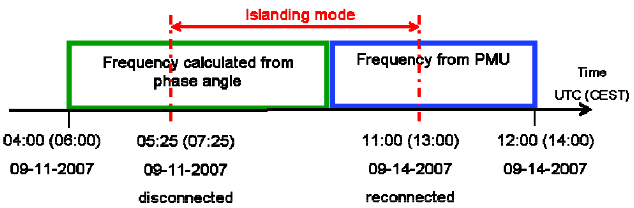

Fig. 2. Frequency Data Availability

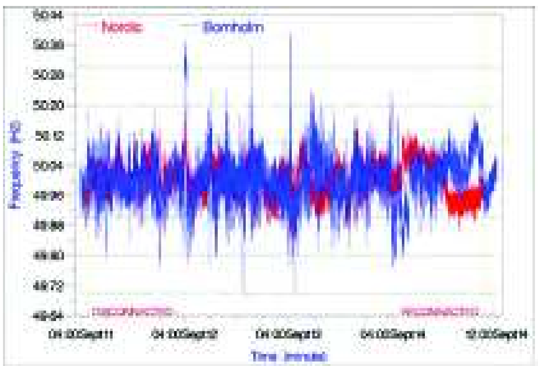

Fig. 3. Plot of Available Frequency Data

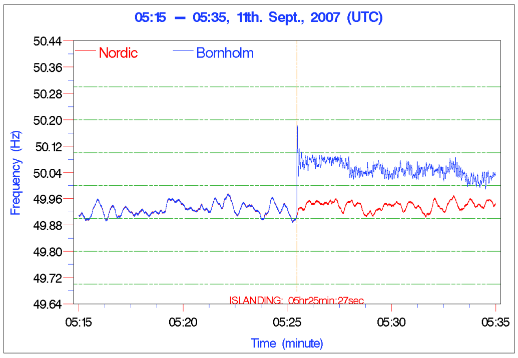

Fig. 4. Disconnection Moment

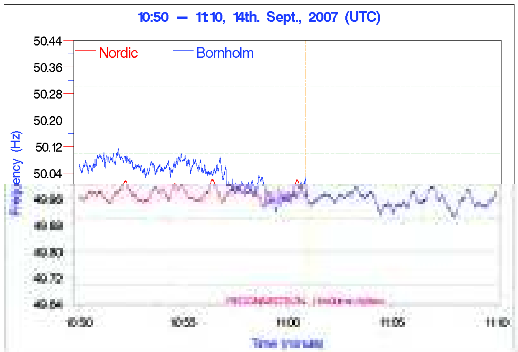

Fig. 5. Reconnection Moment

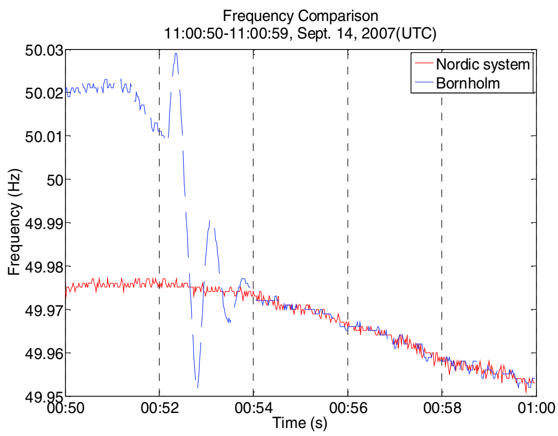

Fig. 6. Zoomed in Reconnection Moment

TABLE III
DEFINITION OF 3 DAYS

	FROM (UTC)	TO (UTC)
Day 1	10:00 11-09-2007	10:00 12-09-2007
Day 2	10:00 12-09-2007	10:00 13-09-2007
Day 3	10:00 13-09-2007	10:00 14-09-2007

IV. Statistical Analysis

The analysis has been performed using Statistical Analysis System or SAS software [12]. Maximal, minimal and mean frequency have been calculated and shown in Fig. 7 for each day, based on 4,320,000 data points per day. Besides, the histograms for both Nordic and Bornholm system during 3 days are compared in Fig. 8.

From Fig. 7 and 8, it is obvious that Bornholm had larger maximal and smaller minimal frequency for each day and the frequency deviated much more than its counterpart in Nordic system. This is understandable since the islanded Bornholm system had less inertia and less reserve for frequency control, resulting in higher vulnerability to small disturbances. According to Nordic Grid code 2007 [13], the normal frequency range should be within 49.90-50.10 Hz. During the 3-day's period, the frequency probability within that range in Bornholm is 91.29%, which is lower than 98.77% in the Nordic system. In addition, the goal for the duration of system operation outside 50±0.1 Hz in the Nordic system is suggested to be less than 1200min/year, or correspondingly

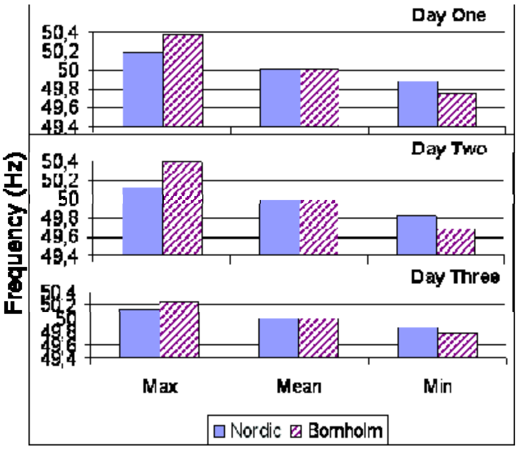

Fig. 7. Max/Mean/Min Value for Three Days

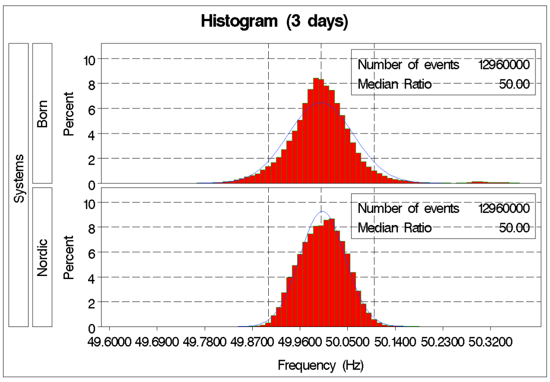

Fig. 8. Frequency Histograms of 3 Days

less than 0.228% in a one year period [14]. It is clear that the frequency quality in Bornholm was considerably decreased in Fig. 9, indicating that the Nordic Grid code can not be well fulfilled.

To further probe the feature of low/high frequency (f<49.90 Hz /f>50.10 Hz) events, we have plotted the durations of such events versus their counts in Fig. 10 and 11. As observed in both figures, Bornholm has more short and long events of both low and high frequency. This reconfirms the findings in previous figures that the frequency control under the islanding mode becomes more challenging due to insufficient inertia and reserve.

In addition, the probabilities of low frequency (f<49.90 Hz) have been plotted versus the minute of the hour in Fig. 12 and 13 for Bornholm and Nordic system, respectively. In the authors' previous work [15], strong correlation between time and low frequency probability has been proved due to the hourly market operation, based on a large amount of frequency data. However, the similar pattern could not be observed in Fig. 12 and 13. This is mainly due to insufficient data amounts for Nordic system.

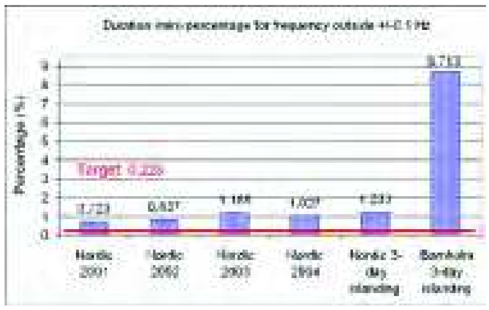

Fig. 9. Duration Percentage Comparison

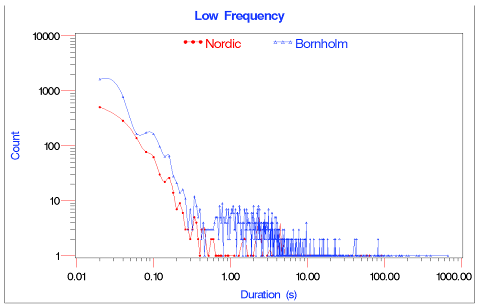

Fig. 10. Low Frequency Duration Analysis

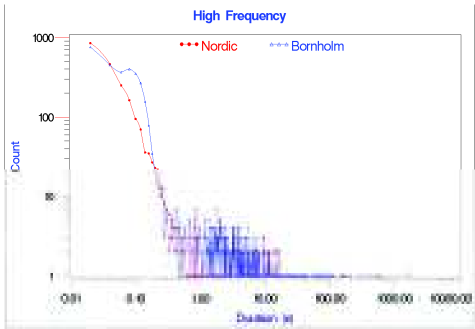

Fig. 11. High Frequency Duration Analysis

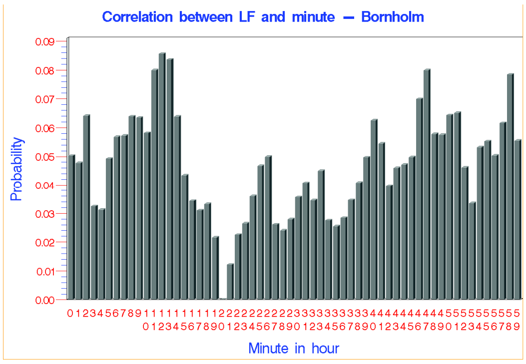

Fig. 12. Correlation for Low Frequency in Bornholm

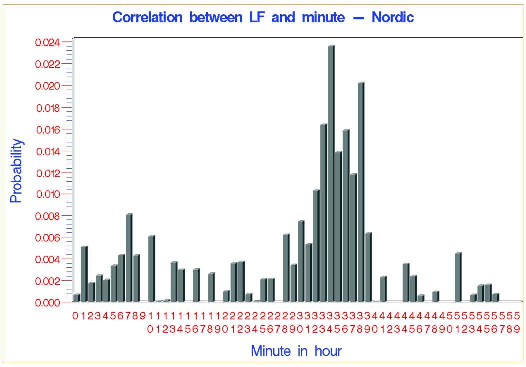

Fig. 13. Correlation for Low Frequency in Nordic System

For Bornholm, this is because it was no longer in the Nord Pool hour-by-hour market after being islanded. However, Fig. 12 and 13 demonstrate again that the Bornholm frequency deviated from the nominal 50 Hz more than that in the Nordic system.

V. Conclusion

With the planned islanding operation and the frequency analysis, some conclusions can be drawn:

First, the planned islanding operation in Bornholm is feasible, although well planned preparations are required beforehand, such as the adjustment of power through the sea cable, most WTs should be shut down and BLOK5 needs started. Those experience obtained can be beneficial to future similar operations.

Furthermore, the frequency analysis demonstrates that frequency deteriorated under islanding mode, even though wind power production only accounted for a small share of total electricity supply and the frequency control became difficult due to insufficient inertia and reserve.

Thirdly, the analysis makes it clear that new technologies need to be developed in order to secure the power supply of future systems with high penetration of intermittent Distributed Generations, like Bornholm. The new solutions should enable systems to perform flexible islanding operation during emergency, maintenance or even under the condition of poor power quality. This requires active utilization of all available resources including the electricity demand. As an effective attempt, the Demands as Frequency controlled Reserve (DFR) technology has been investigated with promising results achieved [16]. It has been found that many end-user demands, like refrigerators, freezers and electric heating, can be interrupted for short durations with little effects to customers. Therefore, the DFR is able to support frequency control under various conditions, including the islanding operation. Other technologies that can facilitate flexible islanding operations should also be investigated, including frequency control of WTs, storage devices, etc.

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9. Island Operation 2008

Model Setup and determination of operational regimes

Vladislav Akhmatov and John Eli Nielsen

WIND POWER SYSTEM OF THE DANISH ISLAND OF BORNHOLM: MODEL SET-UP AND DETERMINATION OF OPERATION REGIMES

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Summary

Bornholm is a Danish island situated south of Sweden, having the Oestkraft Company as the Distribution System Operator (DSO) and comprising 60 kV, 10 kV and 0.4 kV distribution systems with cables, overhead lines and transformers. Through a 60 kV submarine cable and a transformer, the island is connected to the 135 kV Swedish transmission system. The production capacity comprises thermal generation, being diesel and steam turbines, and on-land wind turbines. Wind power corresponds to 32% of the electric power load of the island having the maximum of 55 MW (in 2007). The power system of Bornholm reminds the Danish power system with a significant share of wind power. Regarding the area, population and electricity consumption, Bornholm corresponds to 1% of Denmark. The ability to go into planned island operation makes it suitable for research, education and demonstration of grid-integration, control and management of power systems with a significant share of wind power. Grid-connection of additional 70 to 100 MW offshore wind power is under consideration. This paper presents the determination of load-flow operational regimes with comparison to the measurements, i.e. state-estimation, being a necessary step for any other following research and demonstration activities including more wind power integration.

KEY WORDS: Distribution System, Island Power System, Load-flow Balancing, Model, Validation, Wind Power

1. INTRODUCTION

The Danish island of Bornholm is situated just south of Sweden, has the Oestkraft Company as the Distribution System Operator (DSO) and comprises 60 kV, 10 kV and 0.4 kV distribution systems with cables, overhead lines and transformers. The 60 kV system is operated as a meshed network and through a 60 kV submarine cable and a transformer connected to the 135 kV Swedish transmission system. The island production capacity comprises thermal generation, e.g. diesel and steam turbines, and on-land wind turbines. Wind power covers so far 32% of the electric power load of the island having the maximum of 55 MW [1]. Grid-integration of additional 70 to 100 MW offshore wind power into the island power system is under consideration.

The power system of Bornholm reminds in many regards the Danish power system characterized by a significant share of wind power [2], [3]. Regarding the area, population and electric power load, Bornholm corresponds to 1% of Denmark. The ability to go into planned island operation makes the island power system suitable for research, education and demonstration of grid-integration, control and management of power systems with a significant amount of wind power.

The island power system data collection and verification as well as determination of the system operation regimes using available measurements have been among the first steps towards preparation of the island power system model. This modeling work is carried out as cooperation between Centre for Electric Technology (CET), Technical University of Denmark, and Oestkraft.

This paper presents the island power system model implemented into the commercially available DIgSILENT PowerFactory simulation program. The model utilizes a DPL script developed by the CET for state-estimation of the load-flow including generation, load, active and reactive power exchange between the island and Swedish power systems. The applied algorithm is based on and validated using available voltage, current, power-factor, active and reactive power measurements.

Determination of the island power system operation regimes and validation of the model results have been a necessary stage before any other research, demonstration or wind power grid-integration study should take place.

The validation work has also resulted in recommendations for establishment of better measurements.

2. ISLAND POWER SYSTEM MODEL

The island power system model has been implemented at CET into the DIgSILENT Powerfactory simulation program. Fig. 2.1 shows the meshed 60 kV system graphics including the cable connection to Sweden, 60/10 kV distribution transformers and location of wind turbines, load and shunts in the 10 kV system.

2.1 Available Measurements

In the 60 kV system, voltage and current magnitude measurements have been available for this modeling work. In the cable connection to Sweden, voltage and current magnitude as well as active and reactive power measurements are available. Voltage magnitude, current magnitude and power-factor (with some restrictions) are available in all 60/10 kV substations. In addition, active and reactive power measurements have been available from a single 60/10 kV substation on 10 kV feeder levels. The accuracy, e.g. tolerance in %, of available measurements has not been provided.

2.2 State Estimation

A lack of complete and sufficiently accurate measurements, which are directly applicable for power system modeling and research, is a common challenge regarding modeling and analysis of distribution systems. The developed state-estimation procedure prioritizes the accuracy range of the available measurements as following starting with the highest priority: (1) voltage, current, active and reactive power measurement in the cable connection to Sweden; (2) voltage magnitude in the 60 kV island system; (3) voltage, current and power-factor in the 60/10 kV transformers in the substations determining load and generation, such as wind turbines, under each substation; (4) current magnitude in the 60 kV lines.

The applied priority range sets tolerances and manages iteration loops of the developed state-estimator to fit the load-flow solution to the available measurements in each instant of time. The applied priority range is selected because the power flow between the 60 kV meshed system and the 60/10 kV substations defines the load-flow, i.e. the line currents, of the 60 kV system and because it is expected that Oestkraft will improve measurements in the 60/10 kV substation in a near future.

2.3 How It Works

The developed state-estimator has been implemented into the DIgSILENT PowerFactory simulation program as a DPL script. The DPL script accesses the available measurements of a desired period and estimates the active and reactive power generation and load under each 60/10 kV substation, in each instant of time. Finally, the DPL script produces a load-flow solution for the entire meshed 60 kV system, with adjustments of the load-flow under the 60/10 kV substations, for a desired period and saves the load-flow results to a file for further validation, i.e. the measurements and simulation results can be directly compared for a whole desired period.

The DPL script can also be set to find a load-flow solution complying with the measurements for a given instant of time.

This option will be relevant for post-following dynamic simulations, comprising validations of historical records and new power system stability investigations.

3. RESULTS AND VALIDATION

In this modeling work, validation is applied as direct comparison between all the available measurements and load-flow simulation results during investigated periods.

3.1 Cable Connection to Sweden

The 60 kV voltage magnitude in and active and reactive power transport through the cable connection to Sweden are found identical between simulations and measurements in the investigated periods, whilst the 60 kV cable current deviates with an almost constant offset. This deviation is proven to be due to inaccuracy in the measurement. Fig. 3.1.1 shows the measured and simulated behavior of the voltage, current magnitude, active and reactive power in the Bornholm end of the submarine cable over a 24-hour period with 10-minute resolution.

3.2 60 kV System

The simulated voltage magnitudes in all 60 kV stations are in good agreement with the measurements; this is illustrated in Fig. 3.2.1 for a selected 60 kV station of the meshed power system for the same period as in Fig. 3.1.1. The measurement locations are given in the same figure.

In many 60 kV lines, the simulated current magnitudes are in sufficient agreement with the measurements, as illustrated in Fig. 3.2.1. However, simulations and measurements in some other lines may have deviations (offsets) which are, presumably, due to inaccuracy in the measurements in the 60/10 kV substations or suspect current measurements in the 60 kV lines.

The findings about suspect measurements have lead to suggestions for measurement enhancements.

3.3 60/10 kV Substations

The simulated voltage and current magnitudes in all 60/10 kV substations are in good agreement with the measurements, which is illustrated in Fig. 3.3.1 for a selected 60/10 kV substation for the same period as in Fig. 3.1.1.

This investigation has shown that the power-factor measurements in some 60/10 kV substations are suspect. A power-factor locked to the value of 0.5 is seen whilst an expected value should be in a range between 0.8 and 1.0 and vary with time. It is expected that suspect power-factor measurements will soon be improved by Oestkraft. Therefore, the state-estimator is prepared for this future improvement, i.e. it contains iteration loops to reach measured power-factor values. At the same time, the applied algorithm allows to deviate from the measured power-factor in order to comply with the measured voltage in the respective 60 kV station as well as with the measured voltage and current in the 60/10 kV substation.

The other challenge of the applied state-estimation has been evaluation of the active and reactive power flow directions, since the measured current is only available as magnitudes. In the 60/10 kV substations without any power generation, the active power flow is obviously directed from the 60 kV station to the 10 kV station. In the substations with wind turbines, the active power flow is determined knowing the current measurements of the 10 kV wind turbine feeders and the 10 kV load feeders of the substation. The reactive power flow and its direction are determined in order to comply with the measured voltage in the respective 60 kV station and voltage and current in the 10 kV station; this defines also the power-factor of the 60/10 kV substation.

In periods, the measured reactive power of wind turbine feeders in the 60/10 kV substation with available active and reactive power measurements deviate significantly from the expected value corresponding to the power-factor of unity. This requires further investigations.

4. SUBSTATIONS WITH WIND TURBINES

Fig. 4.1 compares the measured and simulated curves for a given 60/10 kV substation comprising wind turbines; the results are for the same period as in Fig. 3.1.1. The shown curves comprise the voltages in 60 kV station and 10 kV station, total current magnitude in the 10 kV side of the 60/10 kV transformer and current infeed from the local wind turbines. As the current infeed from the wind turbines increases, the total current magnitude in the substation transformer declines. This behavior is present because the wind turbines cover part of the local consumption and reduce the active power transport to this 10 kV station from the 60 kV system.

In periods with surplus of power generation in wind turbines, the active power flow may change direction so that the 10 kV station exports the power to the 60 kV system. However, this behavior cannot solely be evaluated from available current magnitude measurements due to missing information about the current flow direction.

The developed state-estimator provides this missing information. Fig. 4.2 shows the simulated active power load under 10 kV substations with wind turbines. Fig. 4.3 presents the active power transport between these 10 kV substations and 60 kV system. In periods with surplus of wind power, the stations with sufficient wind power shares export the active power into the 60 kV system. Similar behavior, e.g. active power export from the 60 kV distribution substations into the 150 kV transmission system, has also been observed in the continental Danish transmission system known for a significant share of distributed wind power [2]. Fig. 4.4 compares the measured and simulated (1) active power of wind turbines and (2) active power transport between the 60 kV and 10 kV systems in a given substation with available active power measurements. The simulated results are in good agreement with the measurements for this substation.

5. FURTHER WORK

5.1. Further Modeling Work

The Bornholm power system undergoes changes. For instance, underground cables substitute overhead lines [1]. This and other changes in the power system must be updated in the power system model regarding future studies. The island power system model should have stages corresponding to the power system stages.

5.2 Measurement Improvements

The developed state-estimator has been a useful tool in order to detect suspect measurements and recommend locations and types of new measurements. As example, the power-factor measurements in some 60/10 kV substations and some current measurements in 10 kV and 60 kV systems, with indication of the power flow direction, should be improved or established in order to model and analyze the island power system of Bornholm. The recommendations have been given to Oestkraft.

As the existing measurements get improved and new measurements get established, the state-estimation algorithm should be updated with subroutines corresponding to the stages of the measurements available in the island power system.

5.3 More Wind Power Integration

At present, establishment of 70 to 100 MW offshore wind power, presumably as one large offshore windfarm, connected to the Bornholm power system is under consideration. The impact of this additional offshore wind power onto the island power system operation, stability and reliability must be investigated.

Using the developed state-estimator, realistic, e.g. based on historical cases, operation regimes of the island power system can be superimposed with the offshore wind power regimes opening for the following investigations: (1) power flow contingencies in the present cable connection to Sweden; (2) needs of establishment of additional connections to Sweden; (3) impact on the load-flow, voltage profiles and needs of additional voltage compensation in the island power system; (4) needs of power generation reduction from and, perhaps, periods with shut-down of thermal units in favor of wind power generation in order to balance the island power system and avoid contingency in the cable connection to Sweden; (5) establishment of flexible demand, such as electrical vehicles, to balance wind energy.

5.4 Dynamic Modeling

At present, the dynamic model of the island power system is in work and validation. The state-estimator provides a validated load-flow solution for historical cases for post-following dynamic analyses. Among the relevant records are the scenarios where the island power system goes into planned island operation.

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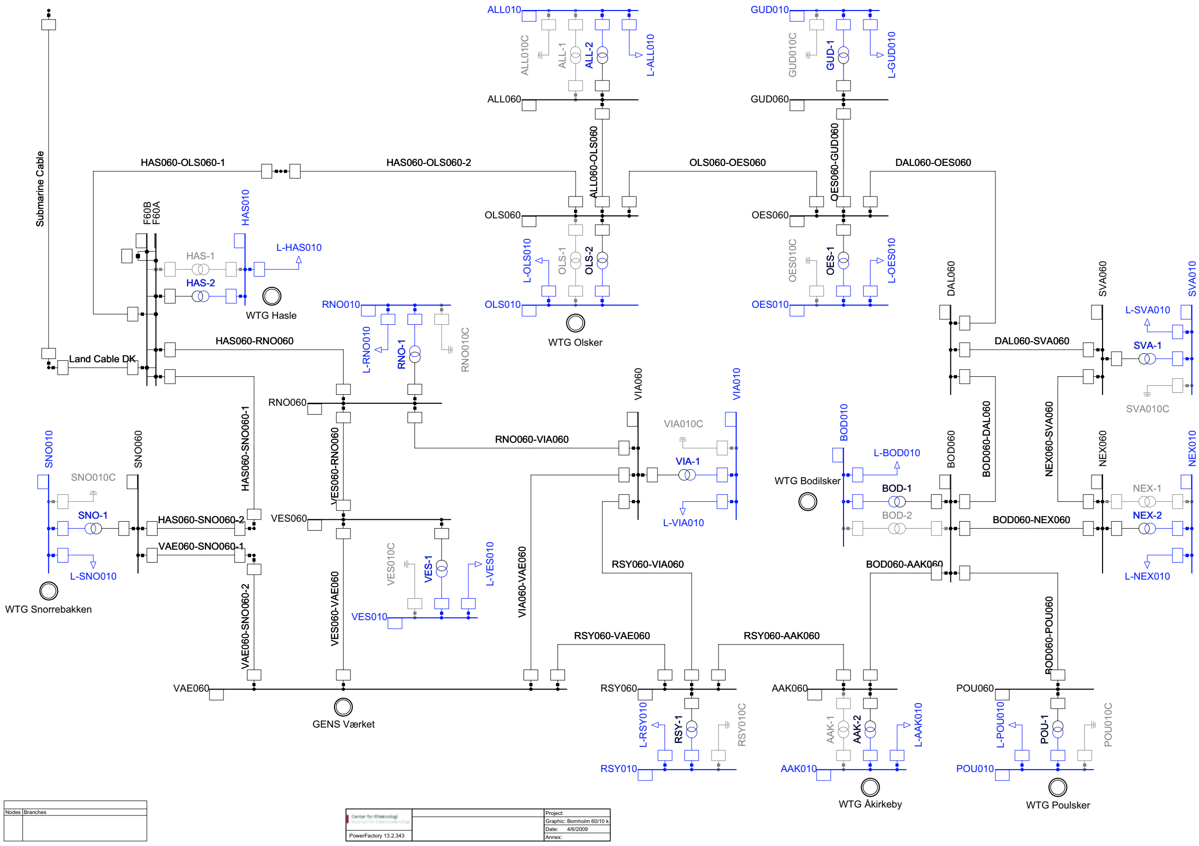

Fig. 2.1 Power System Model of Bornholm with a Cable Connection to Sweden

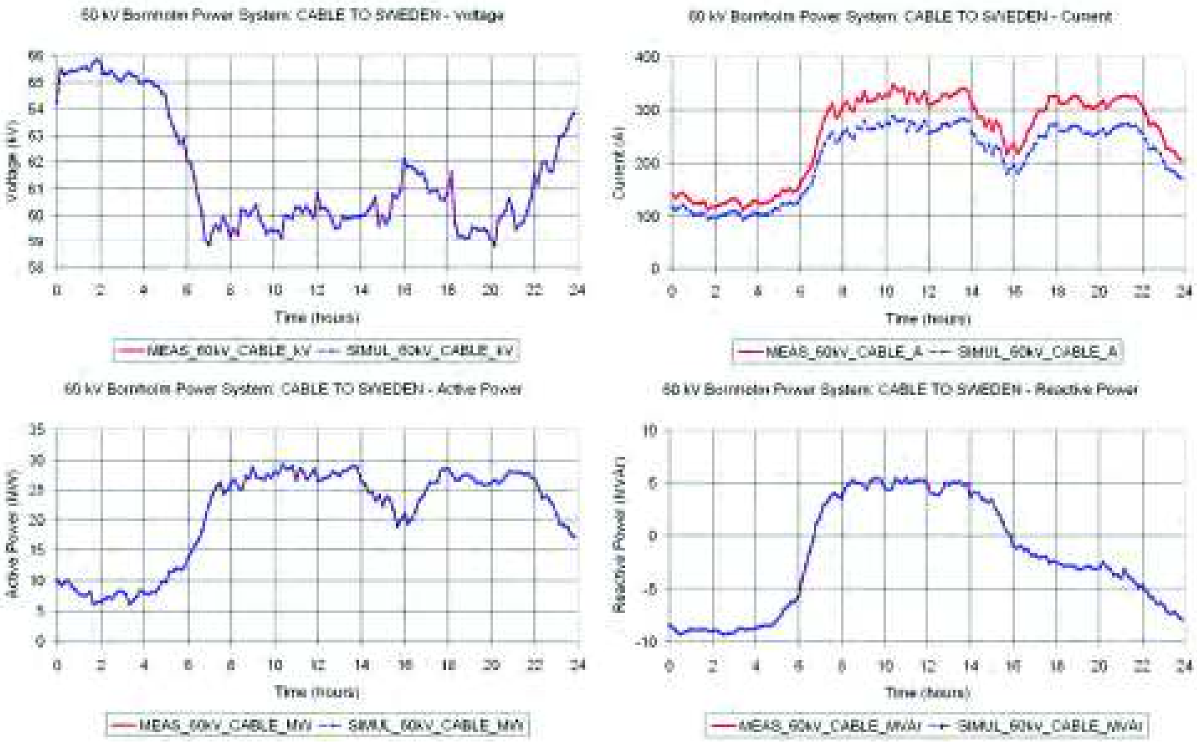

Fig. 3.1.1 Measured and Simulated Voltage, Current, Active and Reactive Power in the 60 kV Cable Connection to Sweden

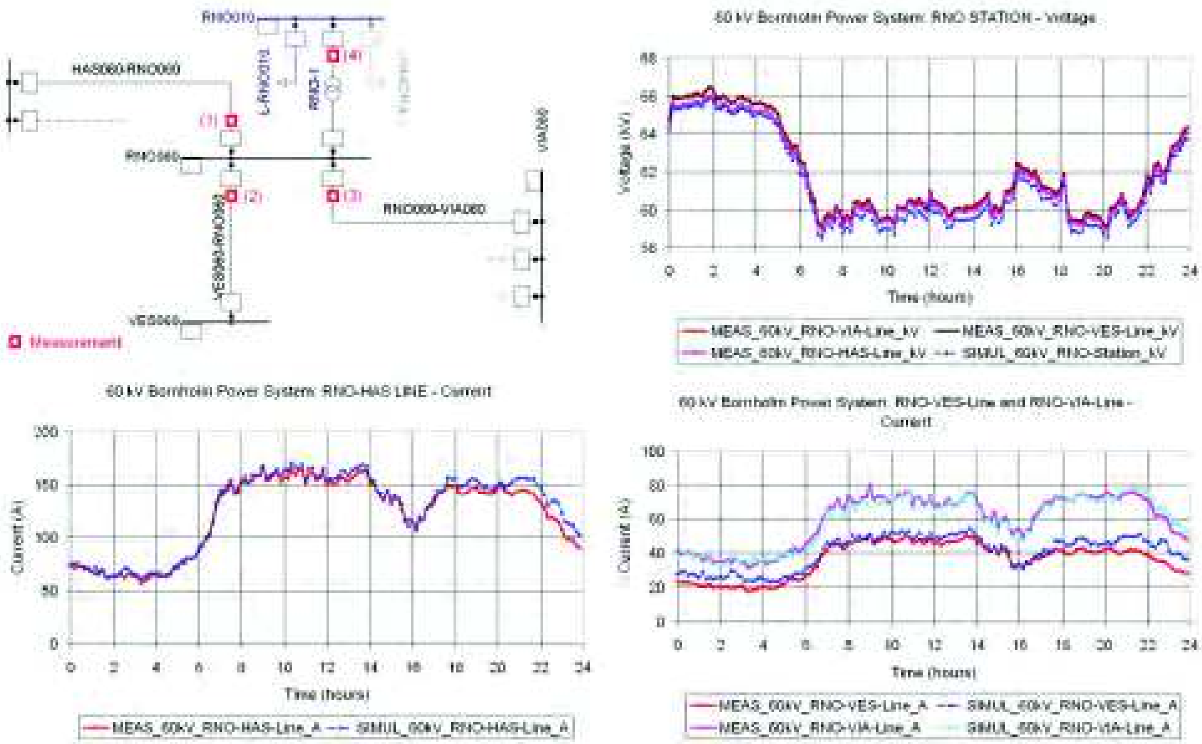

Fig. 3.2.1 Voltage and Current Measurements in the Selected 60 kV Station with

Respective Voltage and Current Measurements and Simulations

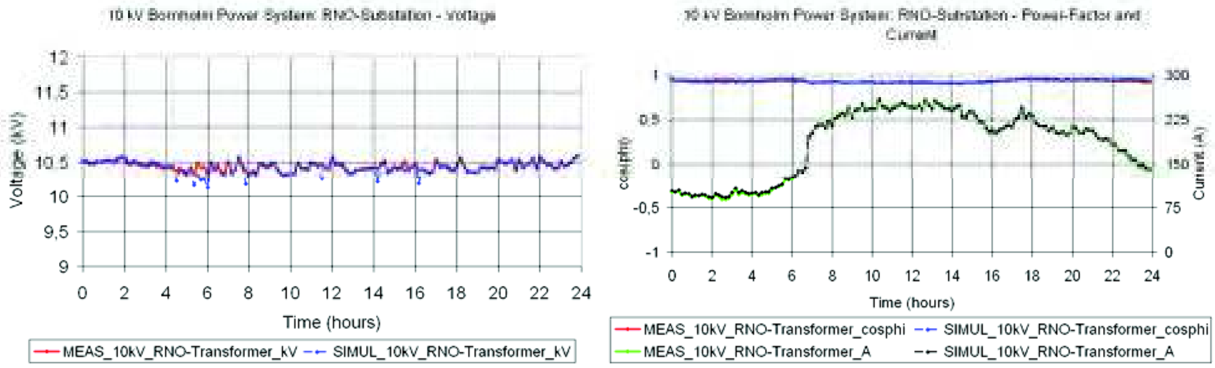

Fig. 3.3.1 Voltage, Power-Factor (Absolute Value) and Current Measurements and Simulations in the Selected 60/10 kV Substation, See Figure 3.2.1 for the Measurement Location

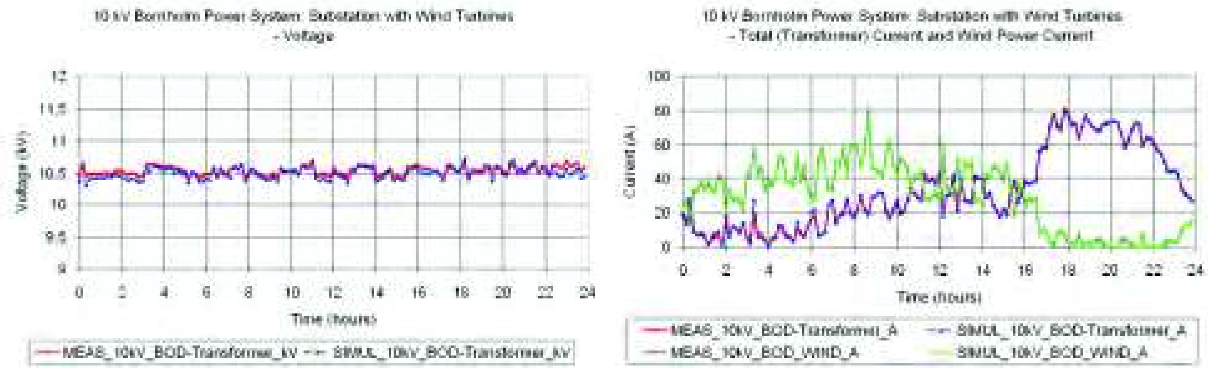

Fig. 4.1 Voltage, Total Current through the Substation Transformer and Wind Turbine Current Measurements and Simulations in a Substation with Wind Turbines

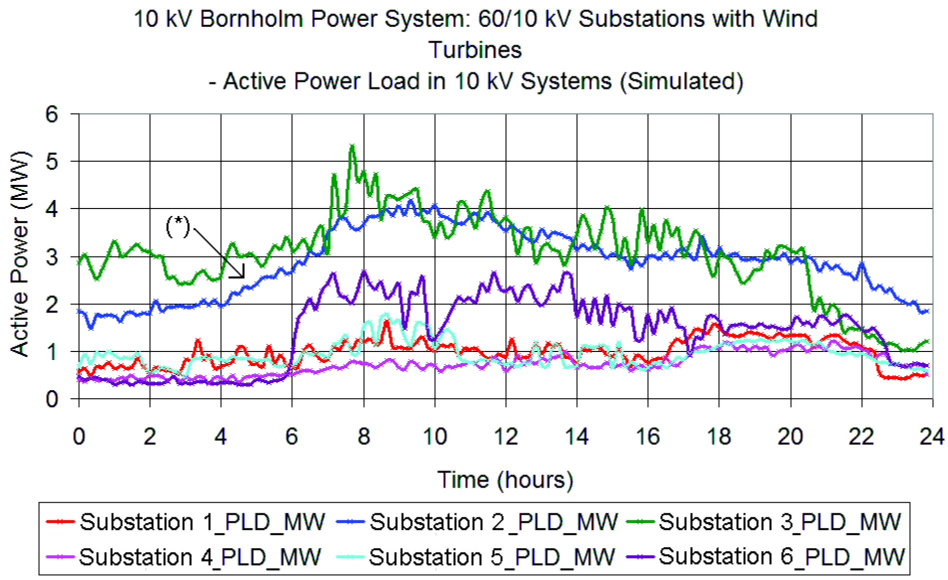

Fig. 4.2 Active Power Load (Simulation) in Substations with Wind Turbines; curve (*) is

compared to measurements in Fig. 4.4

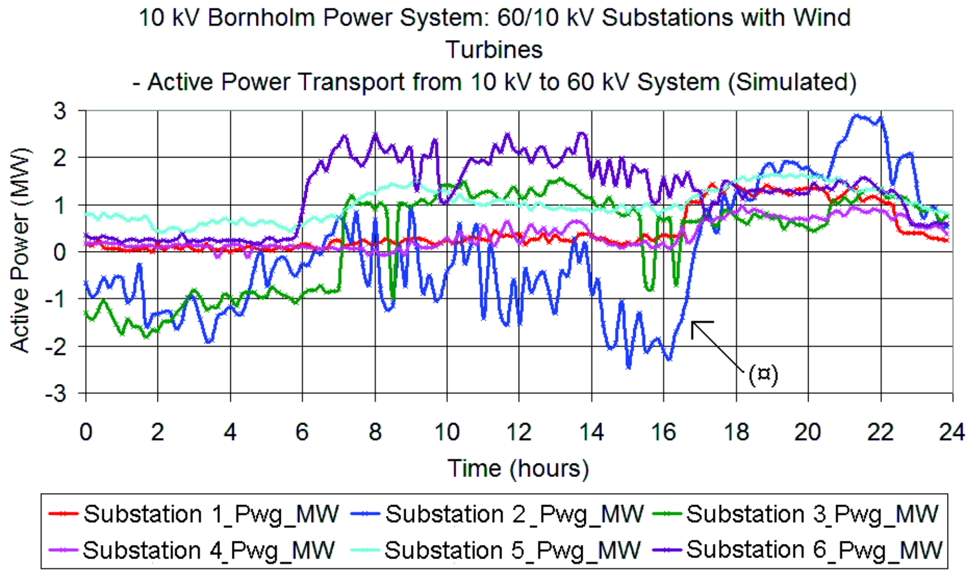

Fig. 4.3 Active Power Transport Between 60 kV and 10 kV Systems (Simulation) in Substations with Wind Turbines; Positive Means Import from and Negative Means Export to the 60 kV System; curve (¤) is compared to measurements in Fig. 4.4

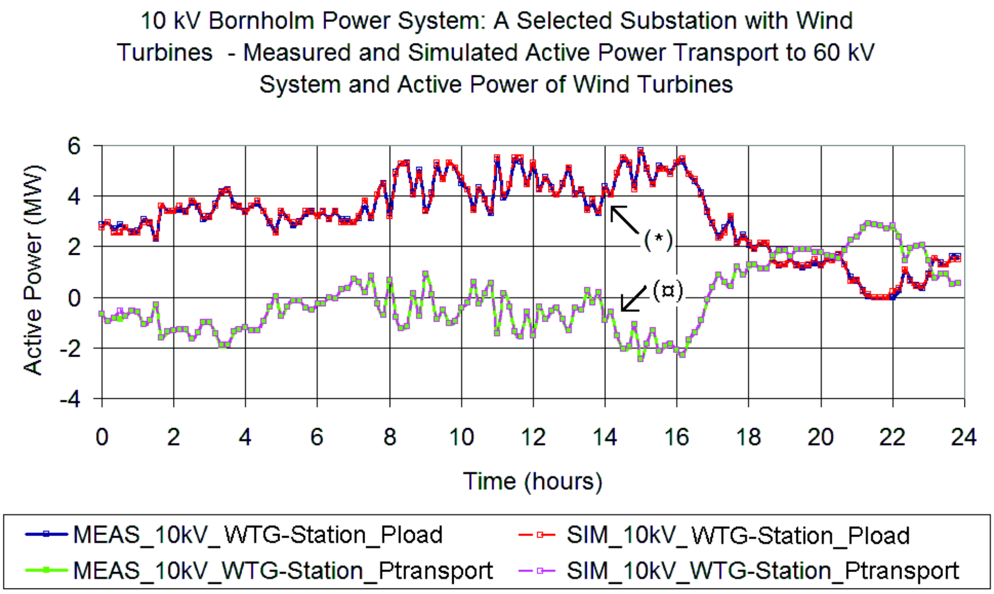

Fig. 4.4 Measured and Simulated Curves of (*) – Active Power of Wind Turbines and (¤) – Active Power Transport Between 60 kV and 10 kV Systems in a Selected 60/10 kV Substation with Wind Turbines

10. Island Operation 2008

State Estimation of Wind Power Systems

Vladislav Akhmatov and John Eli Nielsen

State-Estimation of Wind Power System of the Danish Island of Bornholm

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***Abstract*— The Danish island of Bornholm is situated just south of Sweden. The Bornholm power system comprises 60 kV, 10 kV and 0.4 kV grids with cables, overhead lines and transformers. The production capacity contains thermal and biogas power plants and wind power. At present, wind power covers about 30% of the electric energy consumption of the island and more commissioning of wind power is proposed. In many respects, the power system of Bornholm reminds the Danish power system known for a significant share of wind power. Regarding the area, population and power consumption, the island of Bornholm corresponds to 1% of Denmark. The Bornholm power system has kept the ability to go into planned island operation. All this makes the Bornholm power system suitable for research and demonstration projects of grid-integration of wind power.**

I. Introduction

The electric power system of Bornholm comprises a meshed 60 kV grid and radial 10 kV and 0.4 kV grids. The power system is owned and operated by the Oestkraft Company, the Distribution System Operator (DSO) of Bornholm. Through a 60 kV submarine cable and a 135/60 kV transformer the Bornholm power system is connected to the Swedish 135 kV transmission system.

The electric power generation contains thermal and biogas power plants and wind turbines. The wind turbines stay for about 30% of the electric energy consumption of Bornholm [1]. In relation to the area, population and electric energy consumption, the island of Bornholm comprises 1% of Denmark. The power system of Bornholm has many characteristics of the entire Danish system, with the exception of that the power system of Bornholm is able to go into planned island operation when, for instance, the submarine cable to Sweden is taken out of service.

Commissioning of additional 20 MW wind power in Bornholm would imply that about 50% of electric energy consumption is covered by wind power. This is the Danish governmental target for the year 2025 [2]. At present, commissioning of additional 70 to 100 MW (offshore) wind power is proposed.

All this makes the Bornholm power system relevant and interesting for research and demonstration projects with grid-integration of wind power and other renewable energy sources.

This paper presents the model set-up and experience with state-estimation, e.g. determination of load-flow regimes, of the Bornholm power system. The state-estimation applies available measurements in the Bornholm power system and utilizes a DIgSILENT Programming Language (DPL) script, e.g. a model code. The state-estimation provides a complete load-flow solution of the Bornholm power system, which is necessary to conduct before further investigations such as dynamic simulations and additional wind power grid-connection studies should take place.

II. Model

Conducting investigations of the power system operation (steady-state, load-flow) and stability (dynamic) with accurate and reliable results requires a sufficiently accurate and validated model of the Bornholm power system. In this connection, the model validation implies that the model has been compared to the available measurements and reproduces known and observed operation regimes within acceptable tolerances. Post-following investigations using such a validated model should clarify the consequences of additional commissioning of wind power in the Bornholm power system and contribute to maintaining stable and reliable power system operation.

In cooperation with the Oestkraft Company and ABB, the Centre for Electric Technology (CET) has developed and implemented the Bornholm power system model in the commercially available DIgSILENT PowerFactory simulation tool. The model comprises an electric representation, shown in Fig. 1, of the meshed 60 kV system with the cable connection to Sweden at the 135 kV level, 60/10 kV substations with distribution transformers, shunts, consumption and generation units. The developed model represents the wind turbines individually down to 0.4 kV connection terminals including their respective transformers, electromechanical generators and reactive compensation shunts; this is illustrated in Fig. 2.

Furthermore, the model comprises a state-estimation algorithm which is arranged as a DPL script setting up the load-flow of the Bornholm power system. The routine sets up the active and reactive power of the generation units, including the wind turbines, active and reactive load, e.g. consumption plus losses, under each 60/10 kV substation, voltages and currents in the meshed 60 kV system as well as in the cable connection to Sweden.

A. Measurements

Voltage magnitude, current magnitude (no direction) and power-factor (absolute values) measurements are available in almost each 60/10 kV substation. In a single 60/10 kV substation, the measurements of active and reactive power (with direction) are additionally available in the 10 kV feeders.

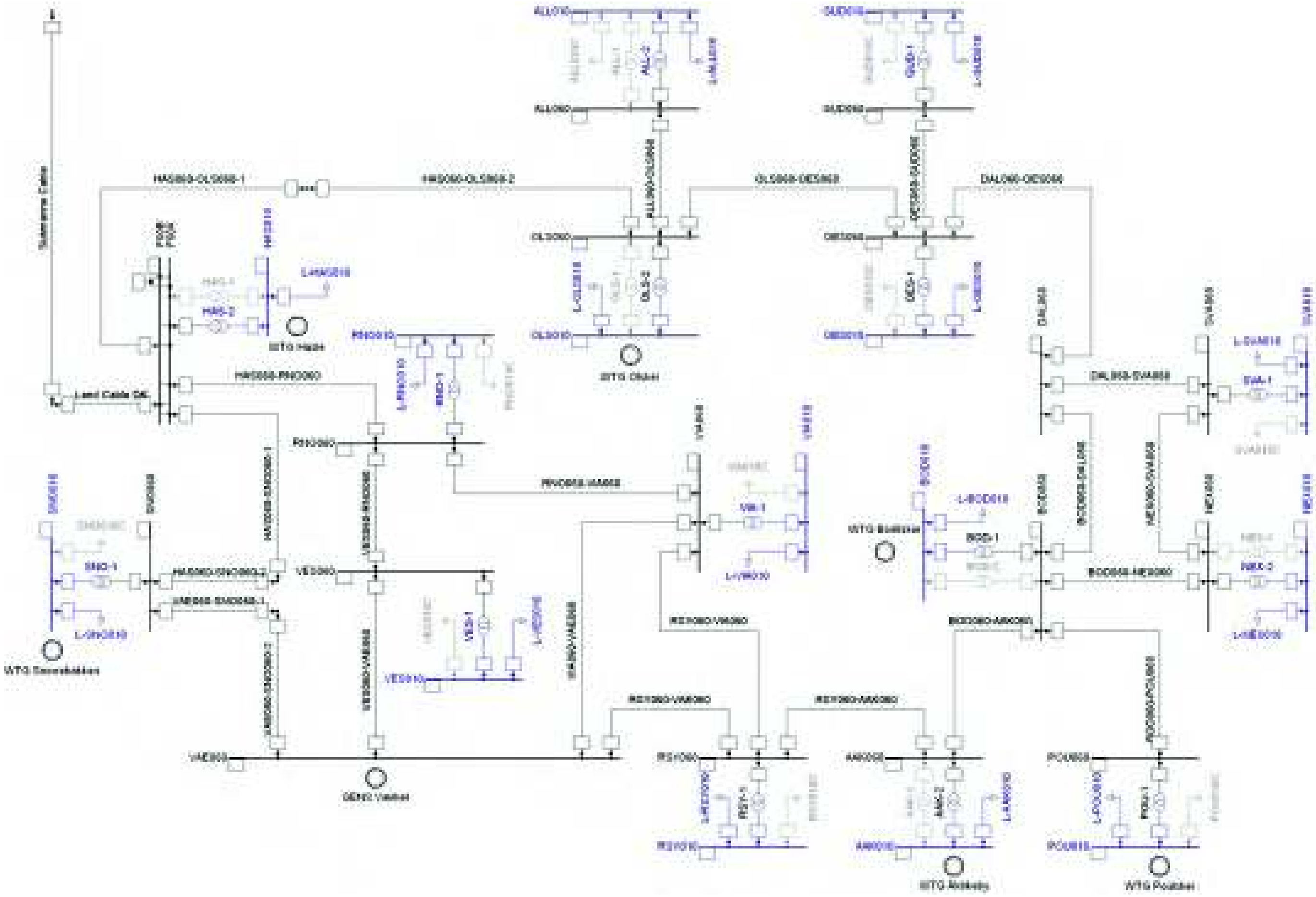

Fig. 1 Power system model of Bornholm with a cable connection to Sweden using the DIgSILENT PowerFactory simulation tool

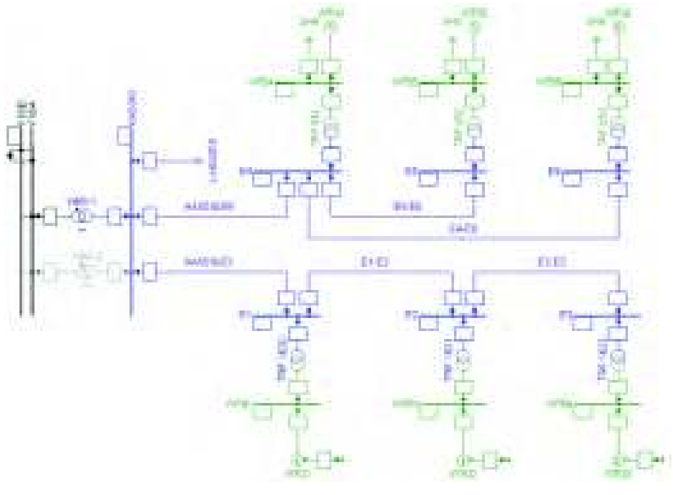

Fig. 2 A 60/10 kV substation model with wind turbines

Voltage magnitude measurements are available in the 60 kV stations as well as current magnitude measurements (no direction) are available in some 60 kV lines. The cable connection to Sweden has active and reactive power (with direction) and voltage and current magnitude measurements which are established and available at the Bornholm end of the submarine cable. The available measurement tolerances are not given.

The fact that power-factor measurements are not available in all four quadrants and the current measurements are only available as magnitudes with no direction introduces a challenge to define the active and reactive power values and directions from the available measurements. Some current and power-factor measurements are found suspect. Hence the available measurements are not directly applicable for modelling of the Bornholm power system.

B. *Algorithm*

The developed state-estimation algorithm reads the existing measurements of voltage, current and power-factor, sets priorities and chooses tolerances of the available measurements and simulated parameters. Using available information about the power system model and measurements, the algorithm simulates generation and load under each 60/10 kV substation, including individual power generation from the wind turbines.

First, the algorithm simulates the operation conditions and parameters related to the 60/10 kV substations such as active and reactive power with direction to match the measured voltage, current and power-factor, because the operation conditions under the 60/10 kV substations influence directly on the load-flow in the meshed 60 kV system.

Next, the algorithm finds the load-flow solution for the meshed 60 kV system including the power transport through the 60 kV submarine cable to Sweden and, when necessary, adjusts the operation conditions under relevant 60/10 kV substations. In absent or suspect measurements, the algorithm provides a correction of the load-flow solution. Enhancement of measurements in some areas of the power system is needed for better power system modelling.

III. Island Operation

The ability of the Bornholm power system to go into planned island operation is difficult to underestimate regarding research and demonstration projects of power systems with a significant share of wind power. The power system model and its state-estimation algorithm are prepared to represent such island operation regimes.

The following example shows the model simulation results and validation, e.g. direct comparison to the measurements, of an operation regime where the Bornholm power system starts in normal operation, goes into and stays in island operation for a period of several hours and then returns to normal operation. The simulation results comprise a series of continuous load-flow simulations over two days with a resolution of 15 minutes.

A. Cable Connection to Sweden

The simulated and measured voltage magnitude in the Hasle 60 kV station which is closest to the Bornholm end of the cable connection, the current magnitude, active and reactive power in the cable connection to Sweden are compared in Fig. 3. The simulated and measured parameters are in good agreement, with a notification that the current discrepancy needs to be clarified.

B. 60 kV System and 60/10 kV Substations

The simulated and measured (in the marked 60 kV line ends) voltage magnitude in the 60 kV station near the biggest consumption centre of Rønne is shown in Fig. 4. The simulated and measured parameters of the present 60/10 kV distribution transformer are compared in Fig. 5 representing the operation conditions in the 10 kV system under this 60/10 kV substation. The simulated and measured parameters are in good agreement.

C. Wind Power

During periods of island operation, wind turbines are normally stopped. The thermal units maintain the frequency and power system balancing of Bornholm. This regime is illustrated in Fig. 6. The simulated and measured wind turbine current magnitudes are in good agreement. As can be seen, the wind turbines under the shown 60/10 kV substation have been stopped during the island operation period except of a few hours.

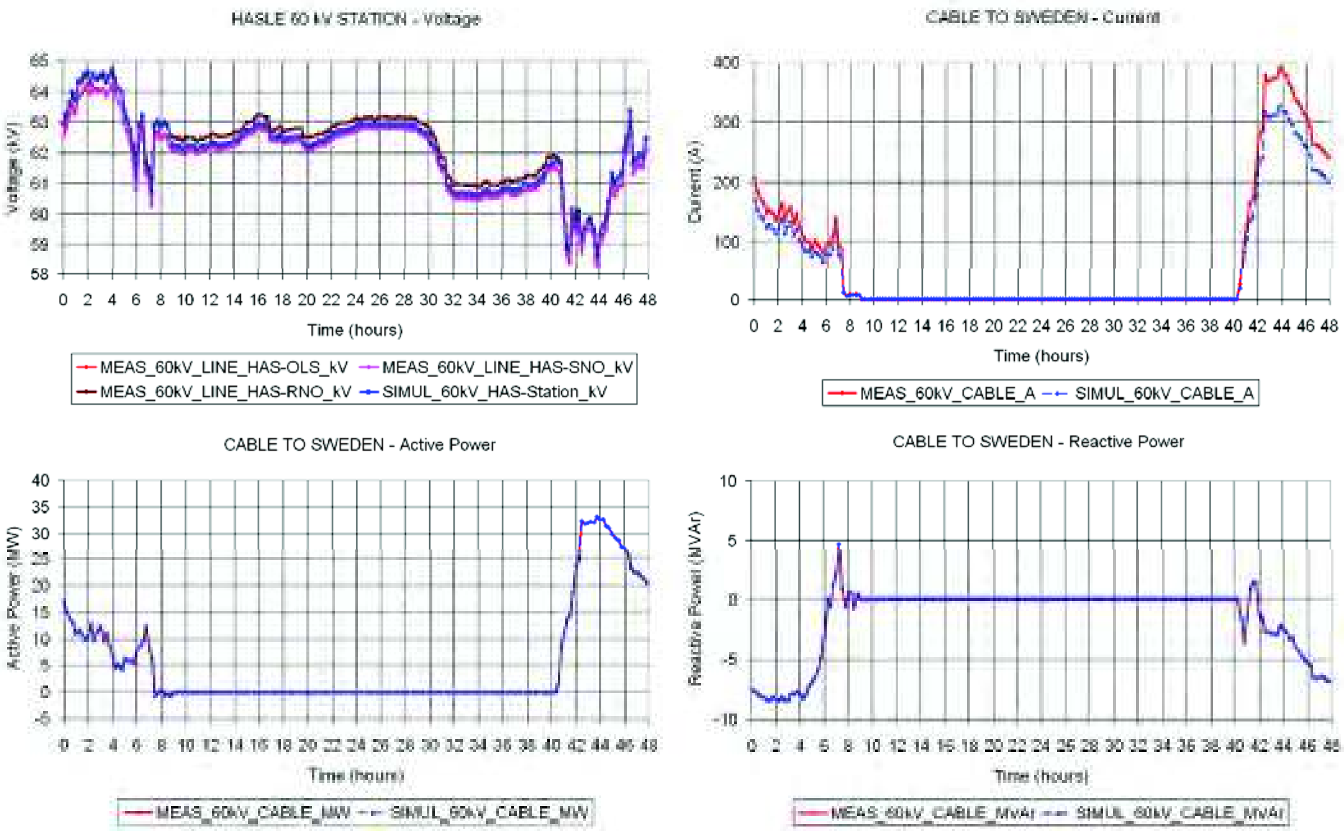

Fig. 3 Measured and simulated voltage, current, active and reactive power in the cable connection to Sweden during a island operation regime

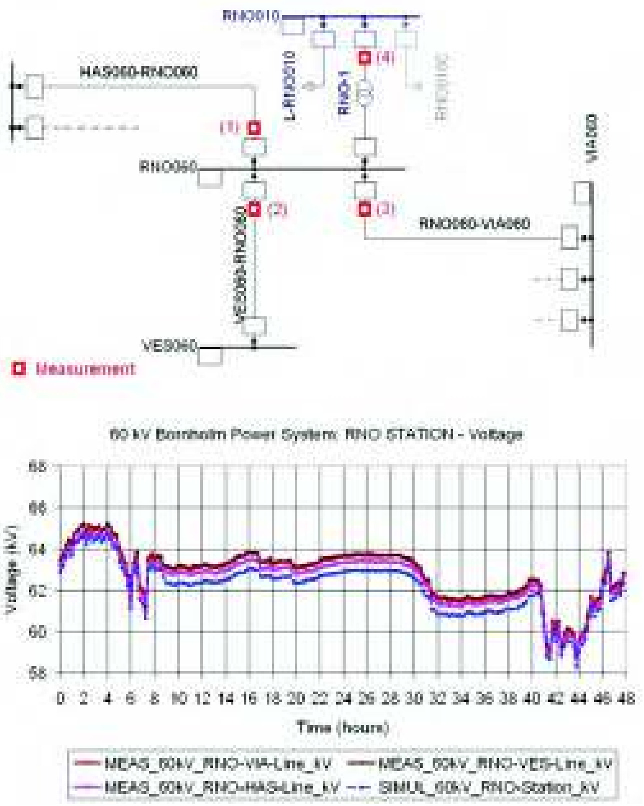

Fig. 4 Measured and simulated voltage in the 60 kV system near Rønne

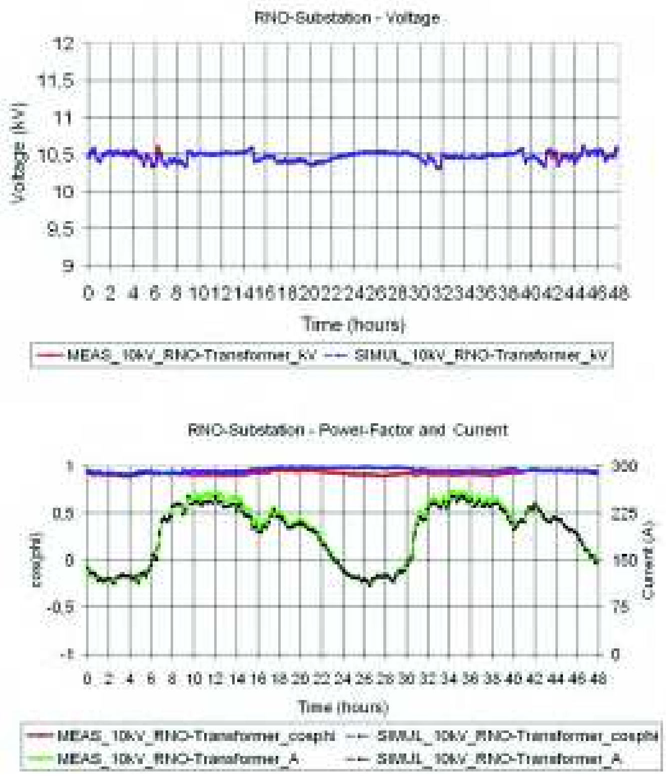

Fig. 5 Measured and simulated voltage and current magnitudes and power-factor (absolute value) in the 60/10 kV substation near Rønne

Fig. 6 Measured and simulated wind turbine current (total magnitude) under a 60/10 kV substation during the island operation period

Since the wind power share increases, the wind turbines, at least those with suitable power-frequency control options, should participate in the frequency and power system balancing, including island operation regimes.

IV. Wind Power Regimes

The Bornholm power system comprises a significant share of on-land wind power. Under some 60/10 kV substations, the wind power share is already now so significant that the active power flow between the 60 kV and 10 kV systems can have both signs [4]. This implies that in poor wind conditions, the power is sent from the 60 kV down to the 10 kV system. However, in strong wind conditions, the active power is sent from the 10 kV up to the 60 kV system.

In Fig. 7 the simulated and measured voltage and current magnitudes under a 60/10 kV substation with wind turbines are shown. The shown results are for a day period with normal wind conditions and established connection to Sweden. As can be seen, the total current exchanged between the 60 kV and 10 kV systems varies oppositely to the wind turbine current. This pattern is present because the wind turbine current partly or, in periods, fully covers the active power demand of the substation. When the active power demand is fully covered by the wind turbines, the total current is zero.

The active power direction between the 60 kV and 10 kV systems is not possible to define alone from the current magnitude behaviour since the current direction is not present in the available measurements. In such cases, the state-estimation algorithm becomes useful to define the active power direction.

The simulated active load under each 60/10 kV substation comprising wind turbines is shown in Fig. 8. The simulated active power flow between the 60 kV and 10 kV systems of these substations is present in Fig. 9. The simulations show that there are periods where the 10 kV systems send the active power into the 60 kV systems (despite of high active load).

It must be noticed that a similar pattern regarding the active power flow is also present in the Danish transmission system (Jutland and Fyn) where the active power is, in periods, sent from the 60 kV distribution system up to the 150 kV transmission system [2], [3].

For the 60/10 kV substation with available active power measurements, the simulated and measured active power flows are compared in Fig. 10. The simulated and measured results are in good agreement. This comparison is present to prove that the developed state-estimation algorithm is sufficiently accurate to simulate the load-flow under right conditions.

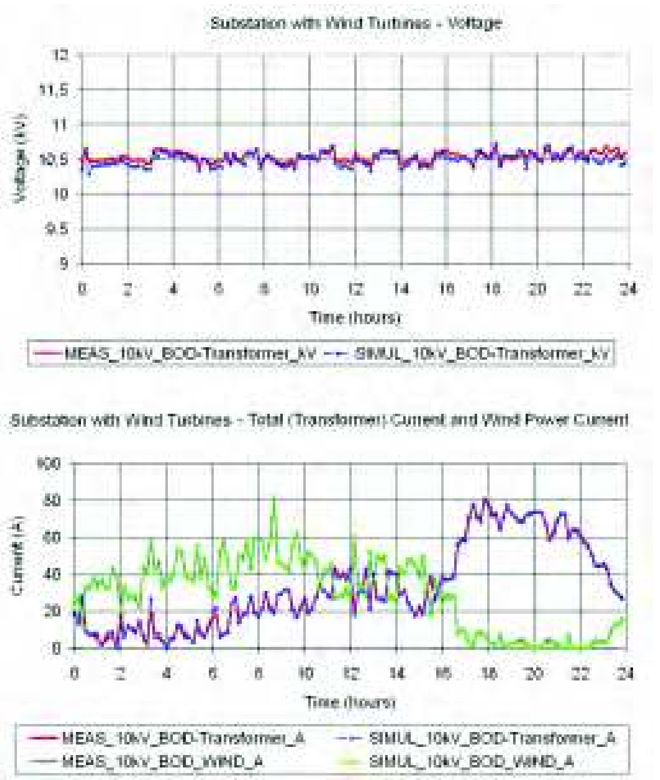

Fig. 7 Measured and simulated 10 kV voltage magnitude, total 60/10 kV substation current and wind turbine current magnitude

Fig. 8 Simulated active power load under 60/10 kV substations comprising wind turbines. The simulated curve (*) is compared to the measured curve in Figure 10.

V. Further Work

Further work contains the power system model update, measurement enhancement and proposed investigations.

A. *System Stages*

In Bornholm, the cables substitute the overhead lines and new cable connections get established [1]. This development implies that the electrical parameters of the power system change requiring similar updates in the power system model. Such updates should be arranged as the system stages so that historical, present and future scenarios could be investigated.

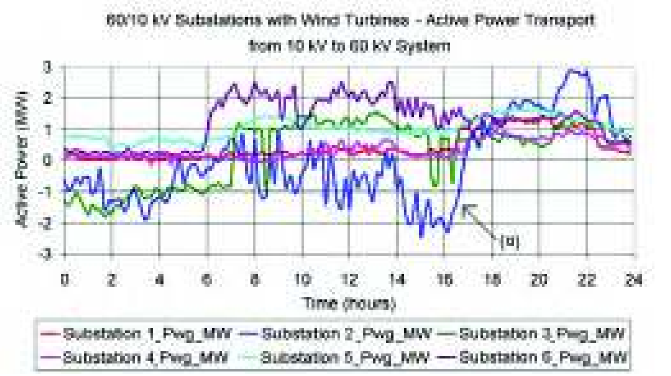

Fig. 9 Simulated active power exchange in the 60/10 kV substations comprising wind turbines. Positive sign means import from and negative sign means export of the active power to the 60 kV system. The simulated curve (¤) is compared to the measured curve in Fig. 10.

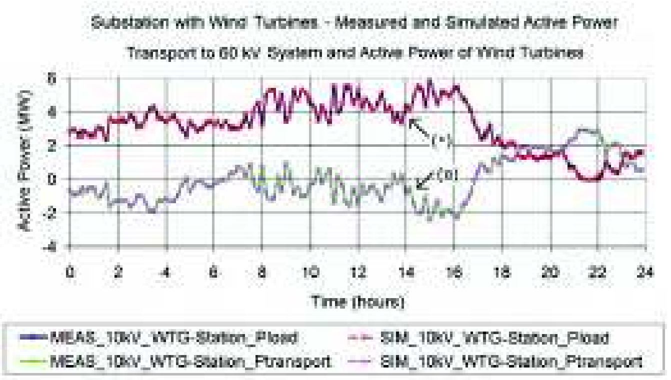

Fig. 10 Measured and simulated curves: (*) - active power of the wind turbines and (¤) – active power exchange in the 60/10 kV substation with available active power measurements in the 10 kV feeders.

B. *Dynamic Model*

A dynamic model comprising the controllers of the power plants and wind turbines and dynamic generator models should be added to the described power system model with the state-estimation algorithm. This work takes place at the CET. The developed state-estimation algorithm will be applied for validation of the dynamic system model starting the validation scenarios from accurate operation conditions.

The scenarios with island operation regimes and significant wind power generation are among the most important cases to be used for the static and dynamic model validation.

C. *Measurement Enhancement*

The developed state-estimation algorithm is applied to trace suspect measurements. Suggestions for measurement enhancement, e.g. accuracy improvement of specific measurements and proposals for new measurements, are discussed with the Oestkraft Company.

D. *Wind Power Integration*

Establishment of additional 70 to 100 MW offshore wind power is proposed. The impact of this additional wind power on the Bornholm power system operation, balancing and stability should be investigated.

By superimposing known operation scenarios and power generation forecasts from the proposed offshore wind power, the developed system model could be applied to investigate:

- needs of additional cable connections to Sweden,
- contingencies in the Bornholm power system and needs of the power system expansion,
- operation regimes with maintaining required voltage and frequency quality, voltage profiles and needs of additional reactive power compensation,
- power balancing, especially in island operation regimes with needs of reducing the power generation from the thermal power plants and wind turbines,
- activation of active demand, introducing electric vehicles for better power balancing of the wind turbines.

VI. Conclusion

A model of the power system of the Danish island of Bornholm comprising a meshed 60 kV system and radial 10 kV and 0.4 kV systems and a significant share of wind turbines has been implemented into the commercially available DIgSILENT PowerFactory. The model has been successfully validated using available measurements.

The model has been applied for determination of the load-flow operation regimes and state-estimation of the generation units and consumption, including scenarios with strong wind as well as scenarios with islanded operation of the Bornholm power system. The state-estimation has confirmed that in strong wind scenarios, the active power is delivered from the 10 kV system into the 60 kV system, corresponding to the opposite power flow direction in the grid.

The further work proposes the power system model updating, introducing the power system stages due to gradual cabling of the Bornholm power system, verification of the power system component data, measurement enhancement, developing of the dynamic power system model as well as investigations, based on load-flow time-sequences or dynamic simulations, dealing with further grid-connection of wind power. Specifically, the power system model and state-estimation algorithm should be applicable for investigations regarding further wind power integration by superimposing known operation regimes and the power infeed from future wind turbines as well as activation of active demand and utilization of electric vehicles. Moreover, the state-estimation algorithm should provide a right start, e.g. a right load-flow solution, to the post-following dynamic simulations in conduction to the dynamic model validation.

Acknowledgment

The authors are thankful to the Oestkraft Company and ABB for useful contribution to this work.

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11. Island Operation 2009

Study on Wind Turbines impact on the power system Frequency

German Tanowski and John Eli Nielsen

THE BORNHOLM POWER SYSTEM
Study on Wind Turbines impact on the power system Frequency

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ABSTRACT:

More wind power generation in the power system will demand modifications in the grid frequency control strategies, especially in power systems with high wind power penetration or island operation. In this work the capability of Variable Speed Wind Turbines (VSWT) with Doubly-Fed Induction Generators (DFIG) to provide active power support during grid frequency drops is investigated. The stored kinetic energy in rotating masses and the available wind power are the two active power sources which support (and limit) the wind turbine capability for frequency response. In this work, the way of assessing is by measuring the impact of changes in the windpower production on the power system frequency.

Keywords: Wind power integration, frequency control, frequency response, variable speed wind turbines, doubly fed induction generators, active power, power curtailment, inertia.

Abbreviations:

PMU	Phase Measuring Unit
VSWT	Variable Speed Wind Turbines
DFIG	Double-Fed Induction Generators
AVR	Automatic Voltage Regulator
CT	Current transformer
VT	Voltage Transformer
PCC	Point of common coupling
NI	National Instruments DAQ device DC value, 3ms sampling
Sweden connection	the generator was normally operated with Bornholm's power system connected to Sweden.
Ramp up/down	Changes on set points of governor and excitation were carried out
Island operation	The generator was normally operated with Bornholm's power systems disconnected from Sweden.
AVR special tests	special short tests carried out for AV performance.
Elspec	AC Waveform. Instantaneous values (1028 points per cycle)
Hioki	AC or DC Amplitude. 10ms sampling
Missed records	Measurements were carried out but due to instrument setting the memory was overwritten later with empty measure ments.

I. INTRODUCTION

Wind power generation is an important source of electricity. As the power system dependency on wind power in creases, wind power generation has to contribute with services that are normally delivered by conventional power plants.

Today VSWTs do not contribute to the power system inertia and do not participate in grid frequency control. In power systems with high wind power penetration, wind power generation will have to provide frequency response to support the grid and decrease cost of reserve power. Studying the operation of small isolated power systems as found in islands, frequency reserves can be more valuable to the system than maximizing the wind power generation yield.

The rotational speed of VSWT is decoupled from the grid frequency by the DFIG configuration. Therefore variations in grid frequency are not seen by the generator rotor and the power system apparent inertia decreases with increasing wind power penetration. VSWT has flexibility for very fast control of generated active and reactive powers.

Several recent works that have studied VSWT inertia response and frequency control can be found in the literature. But still studies on VSWT's power system integration and capabilities for frequency response are necessary for making the power system more reliable. *Frequency response* of VSWT is considered as a change in the VSWT electric power output due to a change in the grid frequency, including both *inertia response* (power released from stored kinetic energy) and *primary control* (power from reserve).

For inertia response it is possible for a short time to contribute with a temporary active power overproduction, which depends on rotational speed variations, VSWT inertia, and wind speed conditions. For primary control contribution it is necessary to operate the wind farm below the available wind power (curtailment).

This work contributes with the study of the impact of changes in the wind power production on the power system frequency.

II. TEST SETUP

In order to evaluate the impact of wind power production on the power system frequency, high resolution measuring systems was placed on the stator of the following production units:

- Blok 5 PMU1 ELSPEC1
- Blok 6 PMU2 ELSPEC2
- Diesel PCC PMU 3 ELSPEC3

High resolution measuring devices was also placed at 4 wind turbines.

- Wind turbine 1 VESTAS PC
- Wind turbine 2 VESTAS PC
- Wind turbine 3 VESTAS PC
- Wind turbine 4 VESTAS PC

The Bornholm power system was in planned islanding operation in 3 periods in 2009.

Period	From	To
1	2009-08-06 11:37	2009-08-06 16:27
2	2009-08-17 10:27	2009-08-17 13:36
3	2009-09-07 07:00	2009-09-08 16:07

In period 2 and 3, the wind power production was limited by the control system. By changes the setpoints of the wind farms it was possible to "release" wind power in small steps. The result was a lower production coming from the two generating units Blok5 and Blok6, and an increasing fluctuation in the power system frequency.

In appendix 3 and 4 are given the production from the generating unit Blok5 and the power system frequency

III. CONCLUSION

This study of Wind turbines impact on the system frequency was successful, even we experienced a lot of measuring problems. Unfortunately the amount of data measured during this test prohibits us to publish this paper in 2009. It will be published in 2010.

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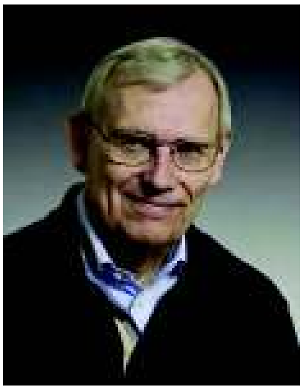
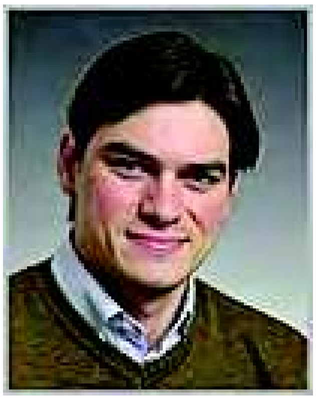
V. BIOGRAPHIES



John Eli Nielsen was born in Denmark 1944. He received his M.Sc.EE. degree in electrical engineering from The Technical University of Denmark in 1974 and his Industrial PhD degree in 1976. He has been working for the Distribution System Operator NVE for 7 years and the Transmission System Operator El-sam/Eltra/Energinet.dk for 25 years. Currently, he is working for The Technical University of Denmark as an associate professor. His experience lies in the area of planning and operation of power systems. He is a member of IEEE and has for many years been the Danish representative in CIGRE Study Committee 39 – *Power System and Control*. jen@elektro.dtu.dk



German Tanowski was born in Argentina. He has since 2007 been working on his Industrial PhD degree'Coordinated frequence control of Wind turbines in Power Systems with a high windpower penetration'. This PhD project is a cooperation between Vestas and the Technical University of Denmark DTU gct@elektro.dtu.dk

APPENDIX 1
Planned islanding periods 2009

Period	From	To	Blok5	Blok6	Blok7	Diesel
1	2009-08-06 11:37	2009-08-06 16:27				
2	2009-08-17 10:27	2009-08-17 13:36	Yes			
3	2009-09-07 07:00	2009-09-08 16:07	Yes	Yes		(Yes)

PMU Measuring devices in operation

Period	Blok 5	Blok 6	Blok 7	Diesel PCC
1				
2				
3	Yes	Yes		Yes

ELSPEC Measuring devices in operation

Period	Blok 5	Blok 6	Blok 7	Diesel PCC
1				
2	Yes			
3	Yes	(Yes)		

Measurements from NETWORK MANAGER

Period	Blok 5	Blok 6	Blok 7	Diesel PCC
1	Yes (MW)	Yes (MW)	Yes (MW+Mvar)	Yes (MW)
2	Yes (MW)	Yes (MW)	Yes (MW+Mvar)	Yes (MW)
3	Yes (MW)	Yes (MW)	Yes (MW+Mvar)	Yes (MW)

APPENDIX 2
Measured signals period 31/8 to 09/09 2009

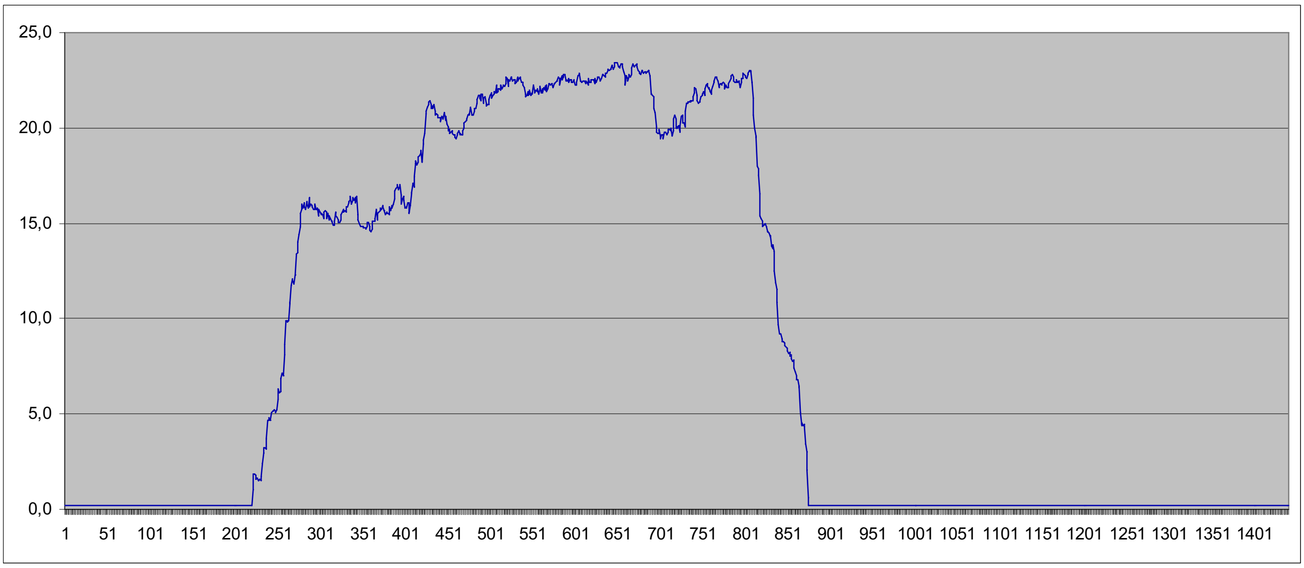
Measured Signals BLOK5	Device	Registered Events	Comments
STATOR - 3 phase currents - 3 phase line-to-line voltages - 1 phase currents - 3 phase line-to-line voltages	VESTAS Elspec MOBILE CT&VT interfaced DTU PMU BLOK5 CT&VT interfaced	- Sweden connection: - Ramp up/down - Island operation - AVR special tests	Missed records
AVR - Compound power supply current - Compound power supply voltage - Saturable reactor output voltage	VESTAS Elspec STATIONARY	- Sweden connection: - Ramp up/down - Island operation - AVR special tests	
AVR - Set point - Field current Steam turbine - Steam valve control oil pressure	DTU NI 1/ 2 Transmitter interfaced	- Sweden connection: - Ramp up/down - Island operation - AVR special tests	
AVR - Field current - Set point - Terminal voltage (sensor)	ØSTKRAFT Hioki	- AVR special tests	

Measured Signals BLOK6	Device	Registered Events	Comments
STATOR - 3 phase currents - 3 phase line-to-line voltages - 1 phase currents - 3 phase line-to-line voltages	VESTAS Elspec STATIONARY CT&VT interfaced DTUPMU BLOK6	- Sweden connection - Island operation	Missed records. Only few hr. on island operation available.
AVR - Compound power supply current - Compound power supply voltage - Saturable reactor output voltage	VESTAS Elspec STATIONARY	- AVR special tests	

Measured Signals DIESEL 1	Device	Registered Events	Comments
AVR - Compound power supply current - Compound power supply voltage (stator voltage) - Set point - Gain voltage drop	DTU Elspec STATIONARY	- Sweden connection - Island operation	Missed records. Only few minutes on Sweden connection available
AVR - Stator current signal for voltage compensation (stator current)	VESTAS Elspec STATIONARY	- Sweden connection - Island operation	Missed records.
AVR - Field voltage	DTU NI 2 1 transmitter interfaced	- Sweden connection - Island operation	

Measured Signals DIESEL PCC	Device	Registered Events	Comments
PCC - 3 phase currents - 3 phase line-to-line voltages - 1 phase currents - 3 phase line-to-line voltages	VESTAS Elspec CT&VT interfaced DTU PMU DIESEL CT&VT interfaced	- Sweden connection - Island operation	Missed records. Missed records.

APPENDIX 3
Blok5 production 2009-08-17



APPENDIX 4
Power System Frequency 2009-08-17