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

Vladislav Akhmatov, John Eli Nielsen, Jacob Østergaard, Arne Hejde Nielsen

Centre for Electric Technology, Technical University of Denmark, Elektrovej 325, DK-2800 Kgs. Lyngby, Denmark

va@elektro.dtu.dk; jen@elektro.dtu.dk; joe@elektro.dtu.dk; ahn@elektro.dtu.dk

***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.

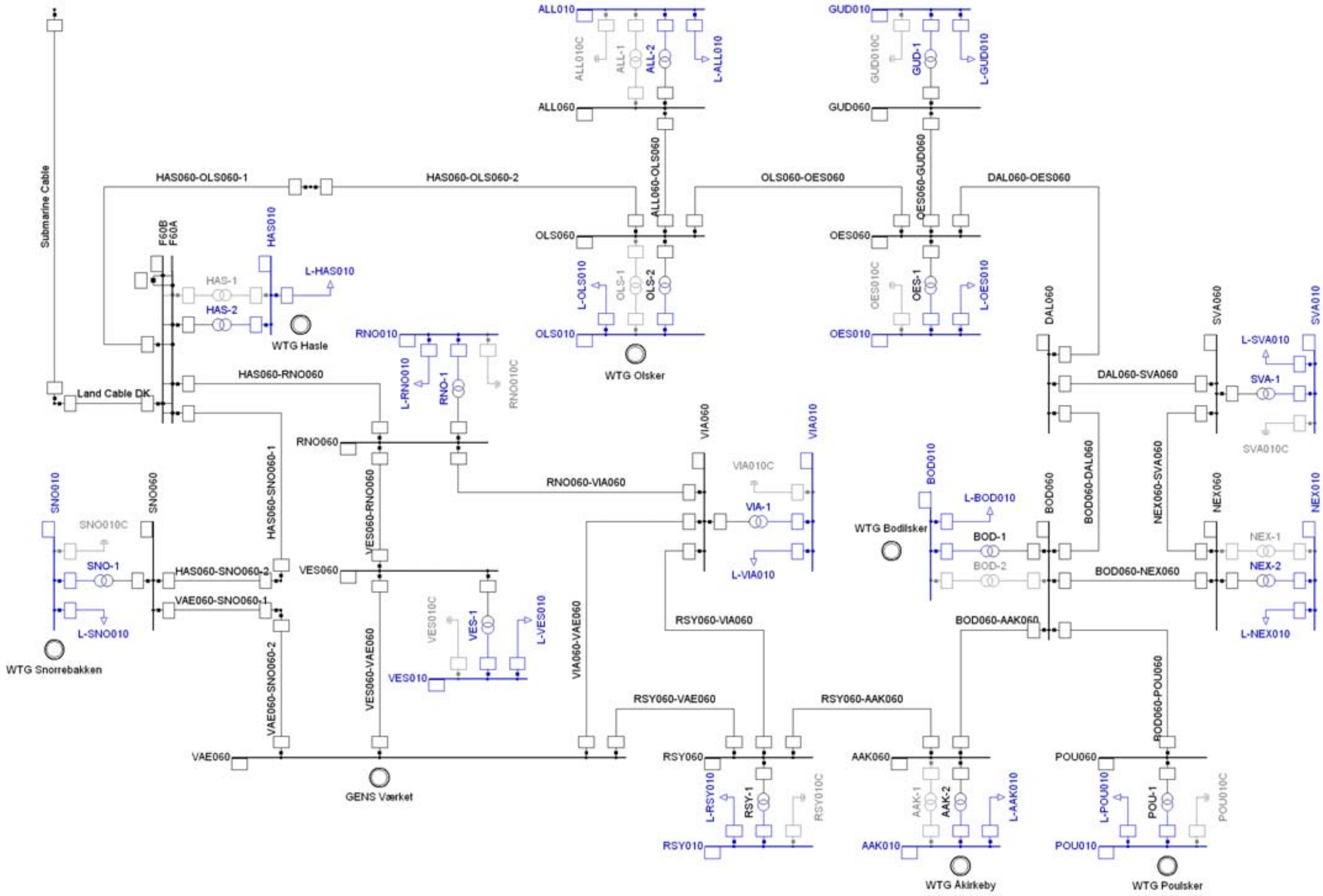


Fig. 1 Power system model of Bornholm with a cable connection to Sweden using the DIgSILENT PowerFactory simulation tool

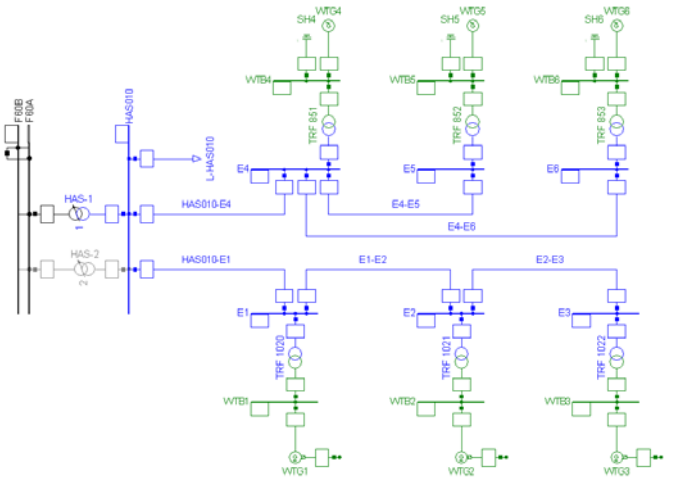


Fig. 2 A 60/10 kV substation model with wind turbines

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.

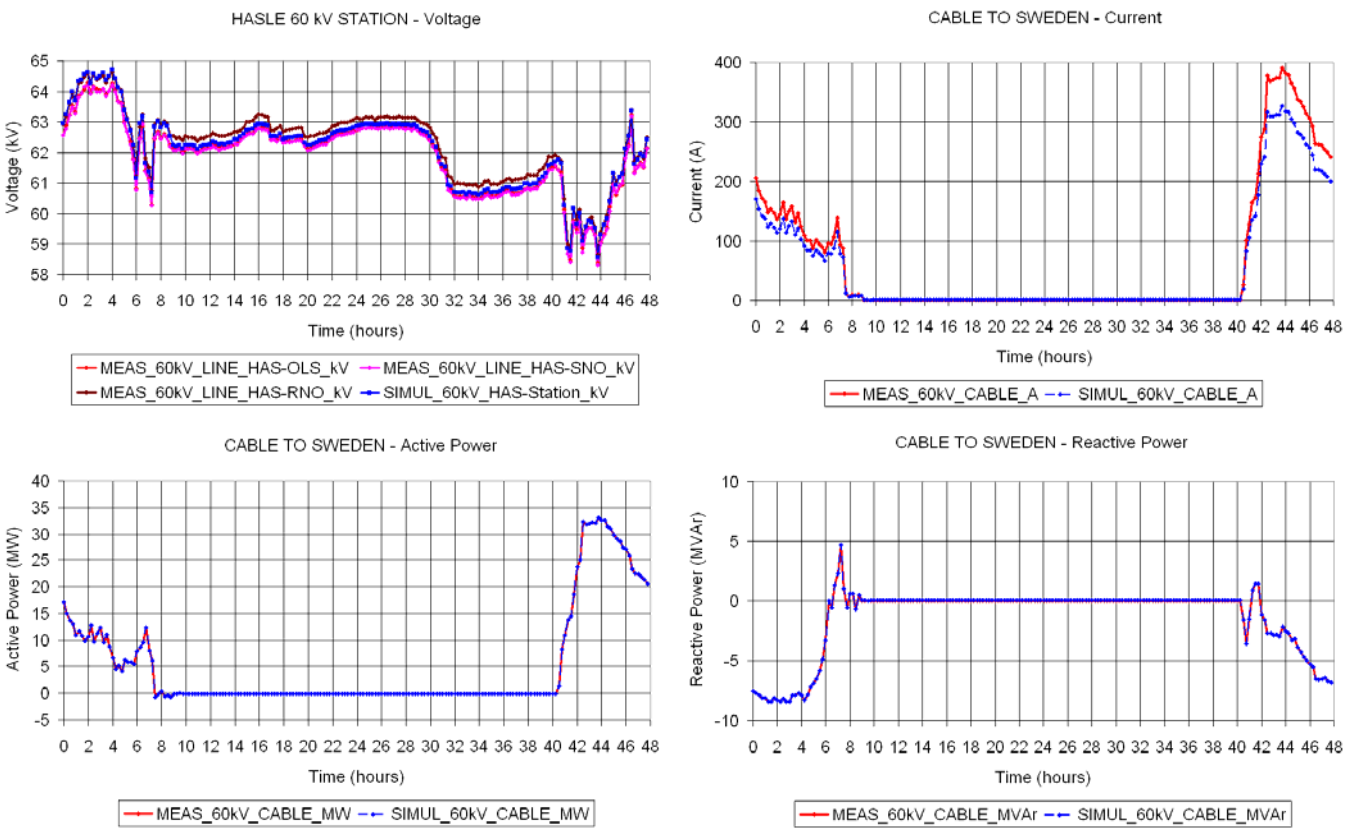
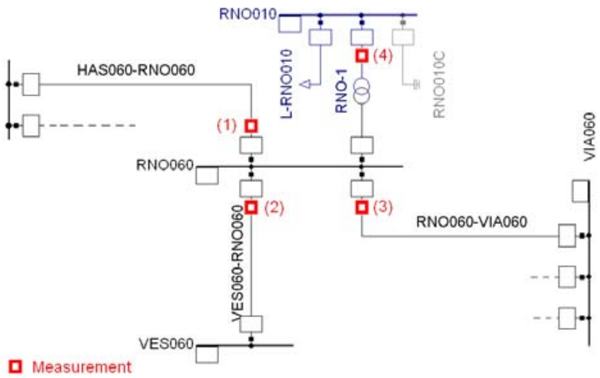


Fig. 3 Measured and simulated voltage, current, active and reactive power in the cable connection to Sweden during a island operation regime



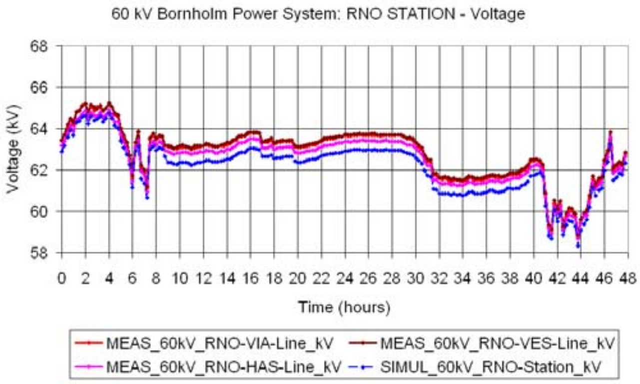


Fig. 4 Measured and simulated voltage in the 60 kV system near Rønne

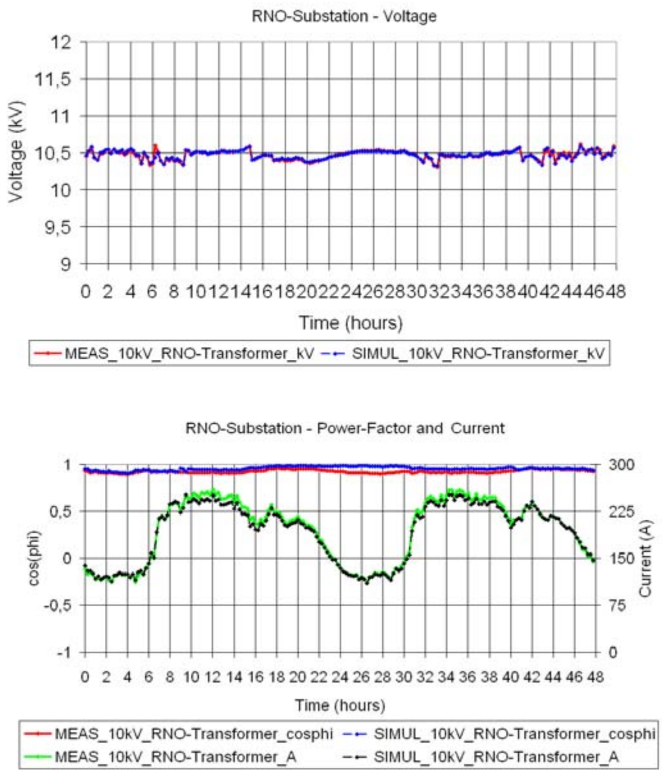


Fig. 5 Measured and simulated voltage and current magnitudes and power-factor (absolute value) in the 60/10 kV substation near Rønne

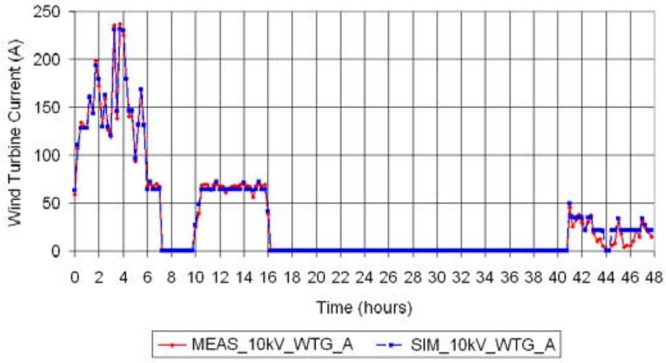


Fig. 6 Measured and simulated wind turbine current (total magnitude) under a 60/10 kV substation during the island operation period

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.

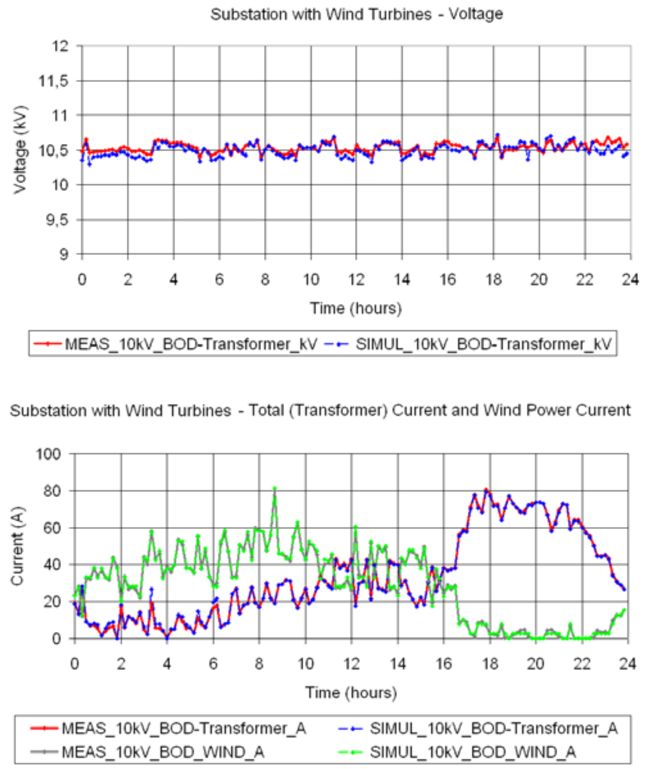


Fig. 7 Measured and simulated 10 kV voltage magnitude, total 60/10 kV substation current and wind turbine current magnitude

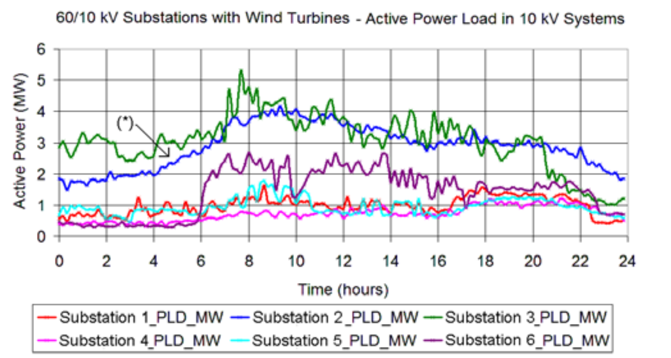


Fig. 8 Simulated active power load under 60/10 kV substations comprising wind turbines. The simulated curve (*) is compared to the measured curve in Figure 10.

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.

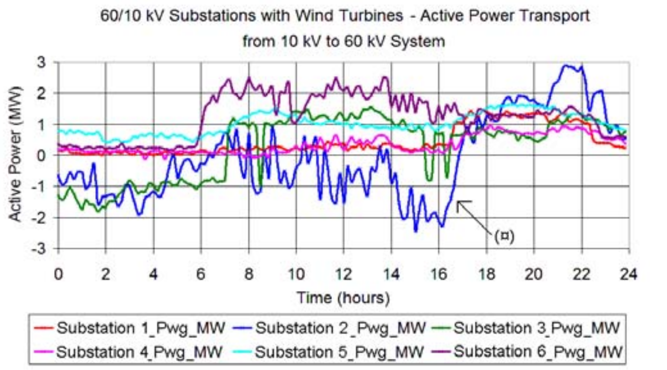


Fig. 9 Simulated active power exchange in the 60/10 kV substations comprising wind turbines. Positive sign means import from and negative sign means export of the active power to the 60 kV system. The simulated curve (¤) is compared to the measured curve in Fig. 10.

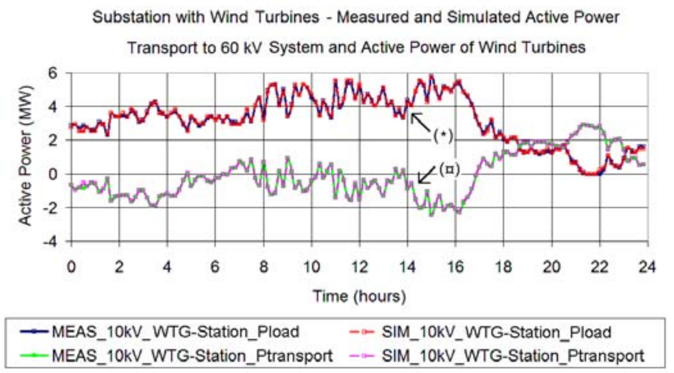


Fig. 10 Measured and simulated curves: (*) - active power of the wind turbines and (¤) – active power exchange in the 60/10 kV substation with available active power measurements in the 10 kV feeders.

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.

References

[1] Oestkraft Net A/S Annual Report 2007, Oestkraft Net A/S, Rønne, Bornholm, Denmark, 2008, 36 p, available on www.oestkraft.dk.

[2] P. B. Eriksen, A. G. Orths, "The Challenge and Solutions of Increasing from 20 to 50 Percent of Wind Energy Coverage in the Danish Power System until 2025", *7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms*, 26-28 May 2008, Madrid, Spain, 7 p.

[3] J. K. Jensen, "A balancing act. What demands does wind power make on a grid?", *Renewable Energy World*, Sept.-Oct. 2002, pp. 57-66.

[4] V. Akhmatov, J. E. Nielsen, J. Østergaard, A. H. Nielsen, "Wind power system of the Danish island of Bornholm: Model set-up and determination of operation regimes", *World Wind Energy Conference 2009*, Jeju, Korea, 23-26 June 2009, 10 p.