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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 DlgSILENT 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 DlgSILENT 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 DlgSILENT 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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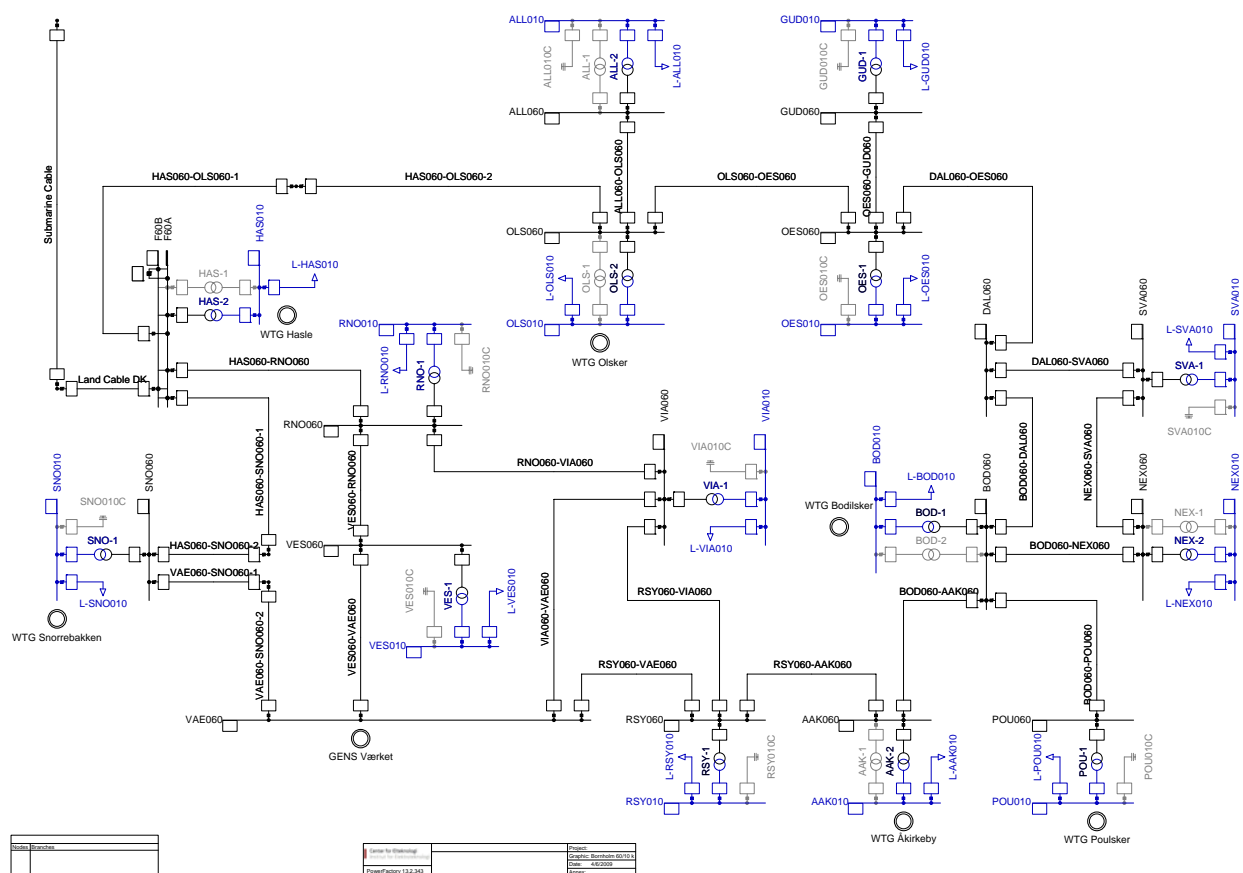


Fig. 2.1 Power System Model of Bornholm with a Cable Connection to Sweden

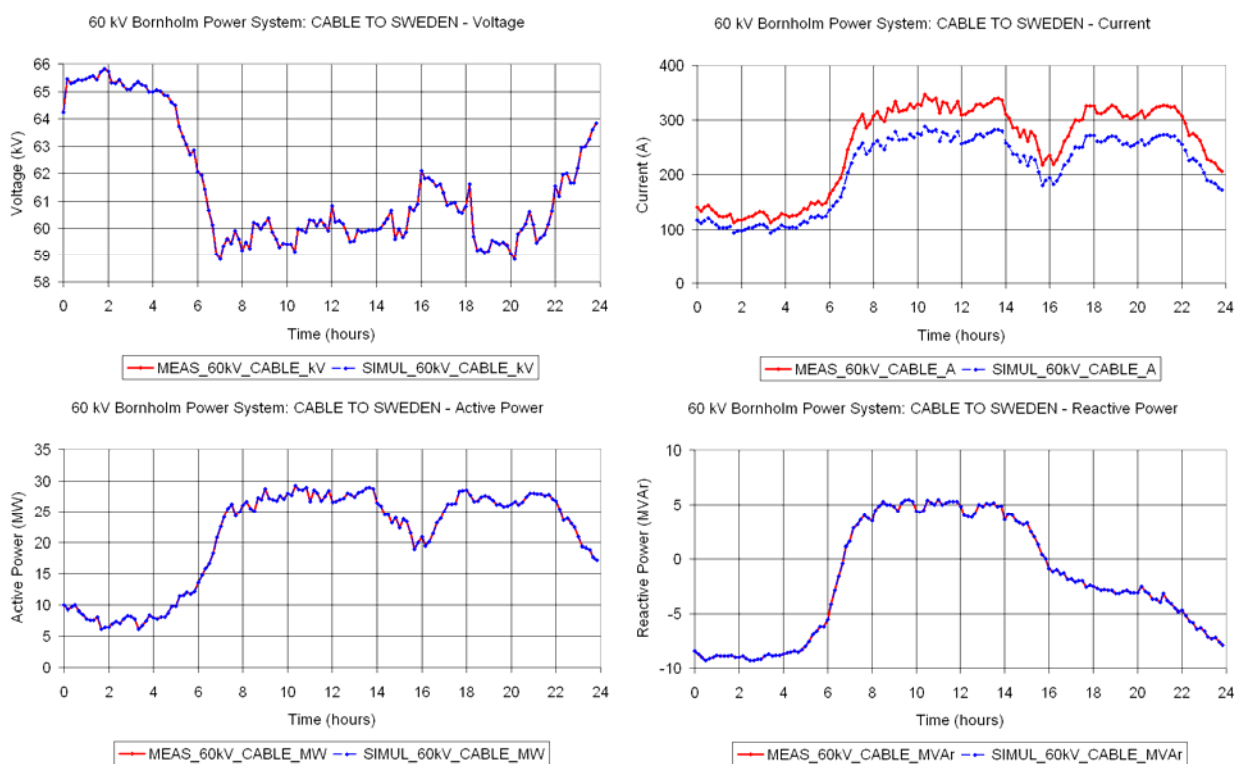


Fig. 3.1.1 Measured and Simulated Voltage, Current, Active and Reactive Power in the 60 kV Cable Connection to Sweden

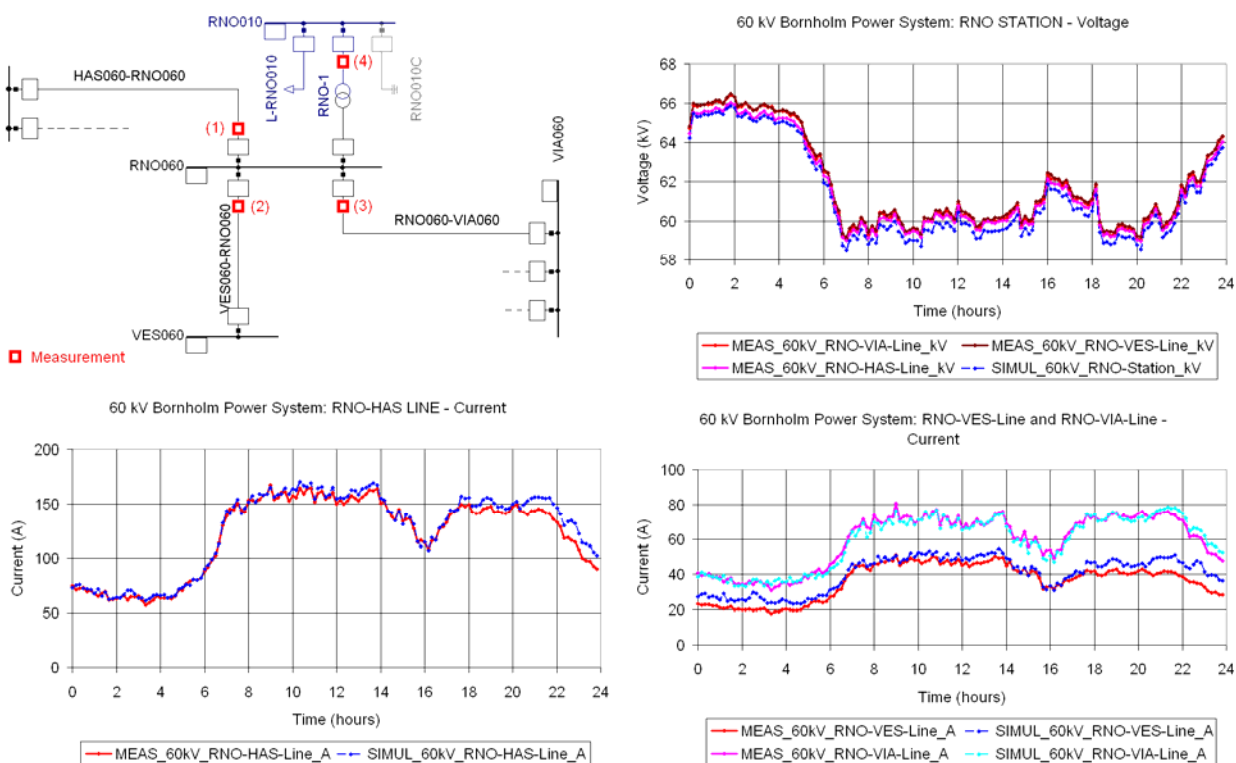


Fig. 3.2.1 Voltage and Current Measurements in the Selected 60 kV Station with

Respective Voltage and Current Measurements and Simulations

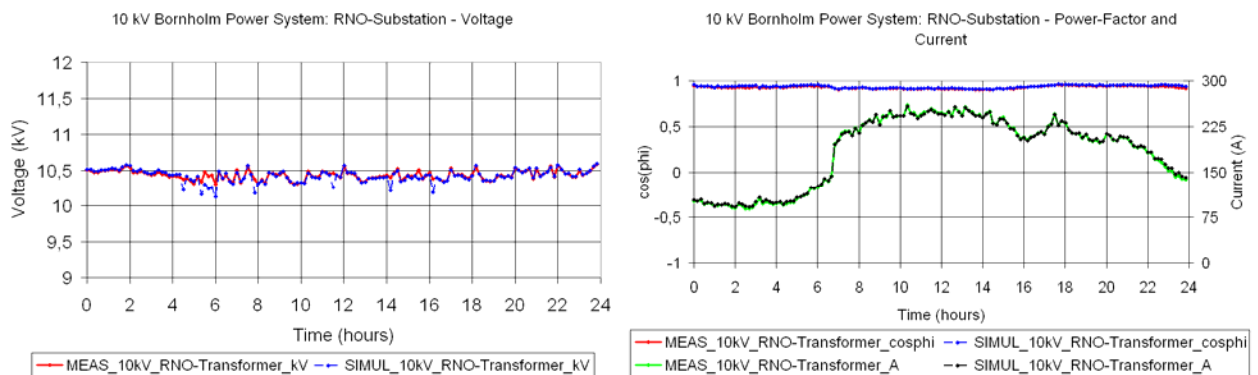


Fig. 3.3.1 Voltage, Power-Factor (Absolute Value) and Current Measurements and Simulations in the Selected 60/10 kV Substation, See Figure 3.2.1 for the Measurement Location

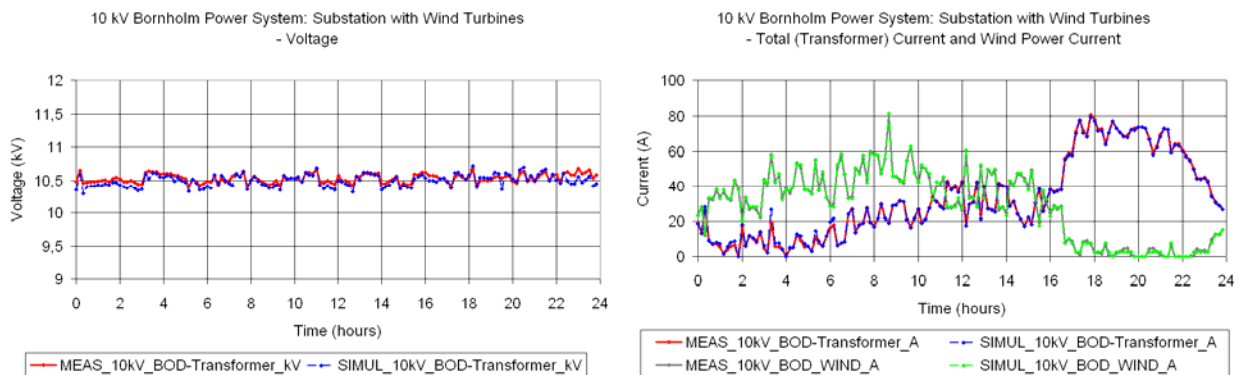


Fig. 4.1 Voltage, Total Current through the Substation Transformer and Wind Turbine Current Measurements and Simulations in a Substation with Wind Turbines

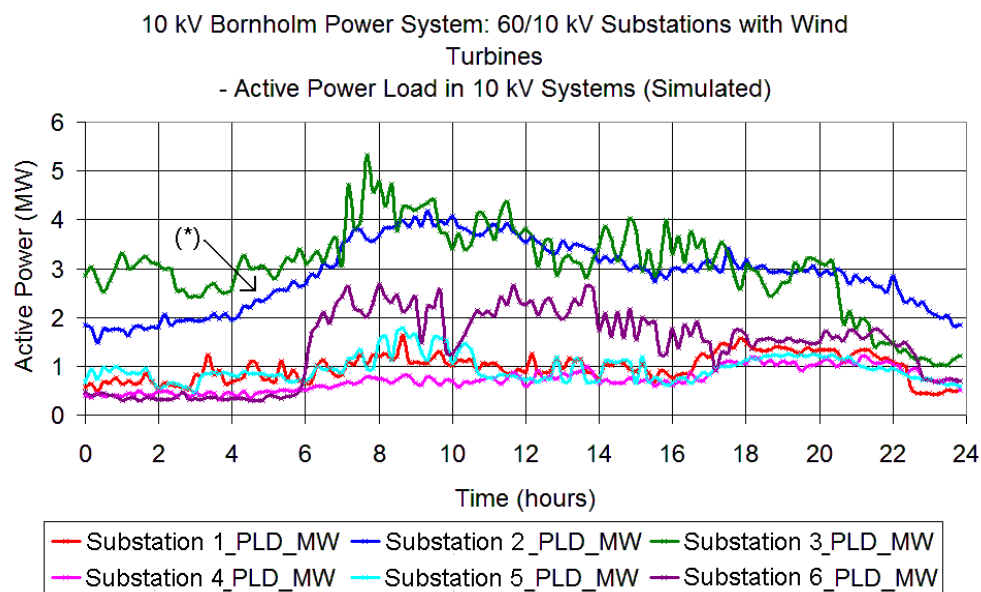


Fig. 4.2 Active Power Load (Simulation) in Substations with Wind Turbines; curve (*) is

compared to measurements in Fig. 4.4

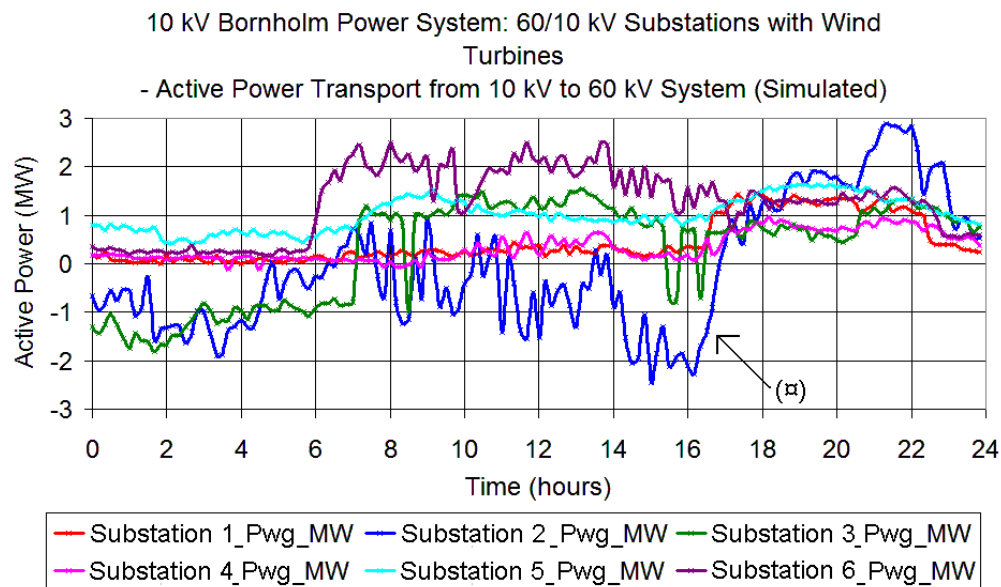


Fig. 4.3 Active Power Transport Between 60 kV and 10 kV Systems (Simulation) in Substations with Wind Turbines; Positive Means Import from and Negative Means Export to the 60 kV System; curve (α) is compared to measurements in Fig. 4.4

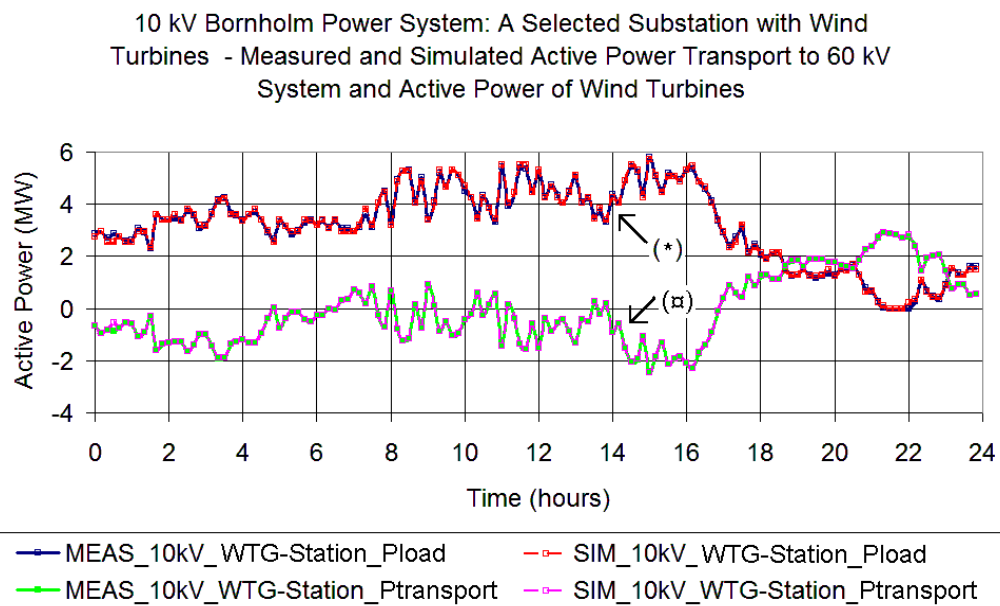


Fig. 4.4 Measured and Simulated Curves of (*) – Active Power of Wind Turbines and (α) – Active Power Transport Between 60 kV and 10 kV Systems in a Selected 60/10 kV Substation with Wind Turbines