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POWER BALANCING CONTROL WITH LARGE SCALE WIND POWER INTEGRATION IN DENMARK

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ABSTRACT
The Danish power system starts to face problems of integrating thousands megawatts of wind power, which produce in a stochastic behavior due to natural wind fluctuations. With wind power capacities increasing, the Danish Transmission System Operator (TSO) is faced with new challenges related to the uncertain nature of wind power. In this paper, the control strategies of generations and control system are presented which analyze the deviation of power exchange at the western Danish-German border, taking into account the fluctuating nature of wind power. The performance of the secondary control of the power generating units and the regulating power control from the other sources to achieve active power balance with the increased wind power penetration is presented.

KEY WORDS
Automatic Generation Control, Power Balancing, Secondary Control, and Wind Power Generation

1. Introduction

Large scale wind turbines installation represents a new challenge to the Danish power system operation. The rapid power fluctuations from the large scale wind farms introduce several challenges to reliable operation and contribute to deviations in the planned power generation which may lead to power system control and balancing problems. The rapid power fluctuations from wind farm will also contribute to the planned power exchange deviation between the western Danish system and the UCTE (Union for the Coordination of Transmission of Electricity) system. Therefore, power balancing control should be developed to manage the imbalance taking into account the uncertain nature of wind power. The contributions of the regulating power control from different power generating units should be investigated with regard to their control capabilities.

This paper focuses on solving the power imbalance caused by rapid fluctuations observed in the offshore wind farms and also to examine the ability of the secondary control of the power generating units to reduce the affect caused by wind power fluctuations in the power system. The impacts on power system operation with the increased wind power are discussed. Control strategies of an Automatic Generation Control (AGC) system which includes large scale wind farms for long term dynamic simulation are presented. Results from simulation studies illustrate the capability of the secondary control of the thermal power plants and DCHP units, the power control of wind farms and the regulating power control of HVDC connection to manage the imbalance at the system interconnections with the increased wind power.

2. Impacts on Power System Operation

2.1 Danish power system operation

The western Danish power system is based on a 400 kV and 150 kV transmission system with HVDC connections to Nordel systems, Norway and Sweden in the north and a 400 kV AC connection to the UCTE system, Germany in the south, as shown in Figure 1. A significant proportion of the generation comes from wind turbines and DCHP units. The total installed wind power is approaching 20% of the yearly power consumption. The random nature of the wind energy supply means that control and compensation of regulating power requirement, for the provision of which Transmission System Operators (TSO) are responsible, are constantly increasing. In an offshore wind farm, the power fluctuations can be much more intense than from the aggregated wind power production on land, due to the geographically distributed nature of wind production. The active power fluctuation have been measured and found to be in the time scale from tens of minutes to a few hours [2]. With the increase of large scale offshore wind farms in the future, the fluctuating nature of wind power may introduce several challenges to reliable operation of the power system and may lead to power system control and balancing problems.

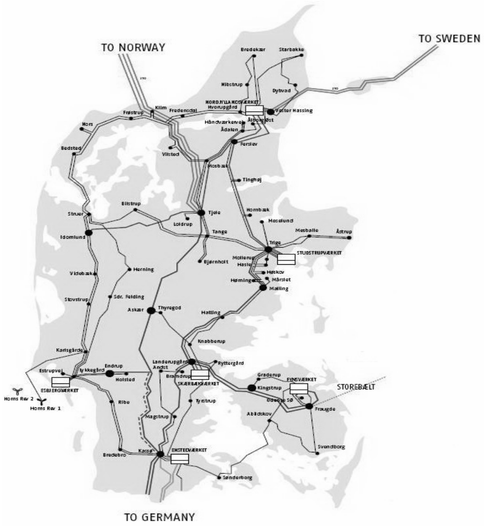

Figure 1. The Danish power system – west [1]

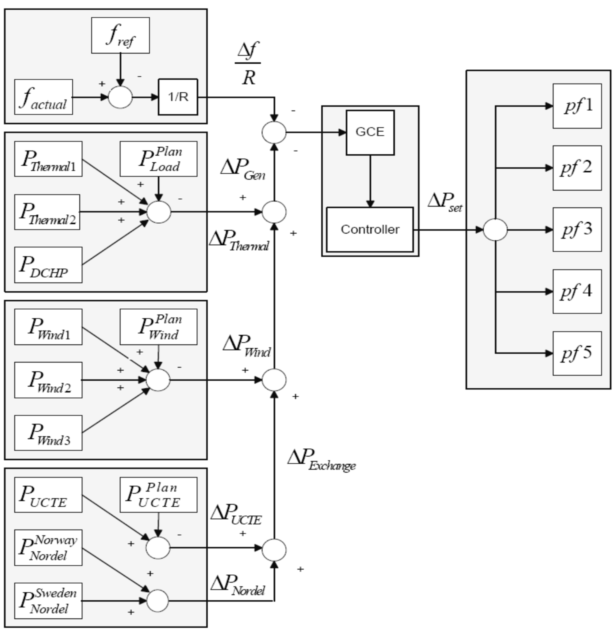

Figure 2. AGC system model

2.2 Power system control issues

System integration of large scale wind power is raising a long list of important issues that must be evaluated. This includes transmission capacity, frequency control, voltage stability, power balance control and reserves. Frequency control problems can be found in power systems, such as a stand alone system and small systems with large scale wind power penetration and has been studied earlier in [3]. On the large interconnected systems, power balancing problem is one of the main challenges. Therefore, the major issue in this paper is to comply with the fluctuating nature of wind power production. The power fluctuations generated by wind farms at different weather conditions are of interest with respect to the needed regulating power. Variability and controllability of wind power will affect the need for the secondary control.

If thermal power generation is replaced by wind power, this will have an effect on the system reliability. This effect from productions from wind farms has to be considered. Power system reliability can be affected by extreme wind conditions since they may result in loss of a large amount of wind power within minutes.

2.3 Power balancing problem

Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generating units. These include the secondary control from the thermal power plants, as well as from the DCHP units, to smooth out the fluctuating power from wind turbines and wind farms to increase the overall reliability of the power system. The main target here is to keep the power generation in balance to the power consumption and to keep the power exchange between the western Danish power system and the UCTE system at the planned power exchange. Earlier studies in [4] and [5] have shown that the power exchange through the HVDC links with the Nordel system is limited with the new settlement model. Therefore, the better and more intense use of domestic regulating power is required.

3. System Control Strategies

In Figure 2, an AGC system model which includes wind farms is presented. The Generation Control Error (GCE) is represented by the contribution from frequency deviations and the deviations from the wind power plan. The deviation in actual power generation from planned power, contributes to GCE, and the difference in power is then distributed according to participation factors (*pf*) among selected units. The implementation of an AGC system model for power and frequency control simulation can be found in [3], [6], and [7]. Based on measurement of system frequency and unit generations, the AGC sends power set-point change commands (□P_{set}) to the selected units. The selection is based on ramping capability and electricity market conditions determined by the *pf*. This is mathematically written as:

$$GCE = -\Delta P_{Gen} - \frac{\Delta f}{R} \quad (1)$$

$$\Delta P_{Gen} = \Delta P_{Thermal} + \Delta P_{Wind} \quad (2)$$

$$\Delta P_{Thermal} = \sum_{i=1}^{n} P_{Thermal} - P_{Load}^{Plan} \quad (3)$$

$$\Delta P_{Wind} = \sum_{i=1}^{n} P_{Wind} - P_{Wind}^{Plan} \quad (4)$$

$$\Delta P_{set} = K * GCE + \frac{1}{T}\int GCE \quad (5)$$

$$\Delta P_{UCTE} = P_{UCTE} - P_{UCTE}^{Plan} \quad (6)$$

$$\Delta P_{Nordel} = P_{Nordel}^{Norway} + P_{Nordel}^{Sweden} \quad (7)$$

where ΔP_{Gen}, $\Delta P_{Thermal}$, ΔP_{Wind} are the deviation of total power generation, thermal power and wind power from the planned power respectively, Δf is the frequency deviation in the system, 1/R is total frequency bias, K is the proportional factor , T is the integration time constant, ΔP_{UCTE} is the deviation from planned power exchange with UCTE, ΔP_{Nordel} is the power exchange with Nordel.

4. Power Balancing Control

A power control system monitors the power exchange activity. When deviations from the planned power exchange are observed, the AGC system will adjust the available power production in the available power plants and the power exchange via the HVDC connections. The overall model includes the power gradient limit and the necessary time constants of the processes and the response of the available power plants. With the use of the AGC system, the deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{Dev} = P_{Meas} - P_{Plan} - P_{Ctrl} \qquad (8)$$

The deviations from the planned power (P_{Dev}) between the measured power (P_{Meas}) and the planned power (P_{Plan}) with the UCTE system shall be minimized by the power balancing control (P_{Ctrl}). The power gradient and delta control of the wind farm [8] operated, as shown in Figure 3, and the fast secondary control from DCHP units is developed to maintain the power deviation within the acceptable range. Establishment of the Great Belt Link (GBL) HVDC connection with 600 MW capaciy, between the eastern and the western Danish power systems is expected for the solution to utilize the regulating power control incorporated in the eastern Denmark to work together with that established in the western Denmark.

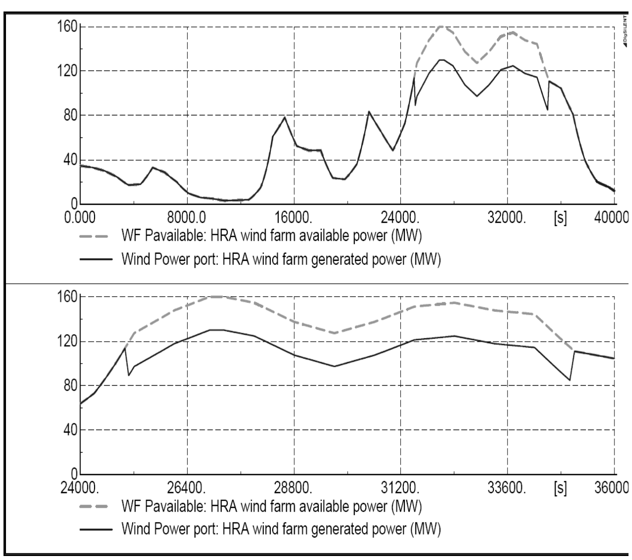

Figure 3. HRA wind farm operate with 30 MW delta control and power gradient limit with 10 MW/min.

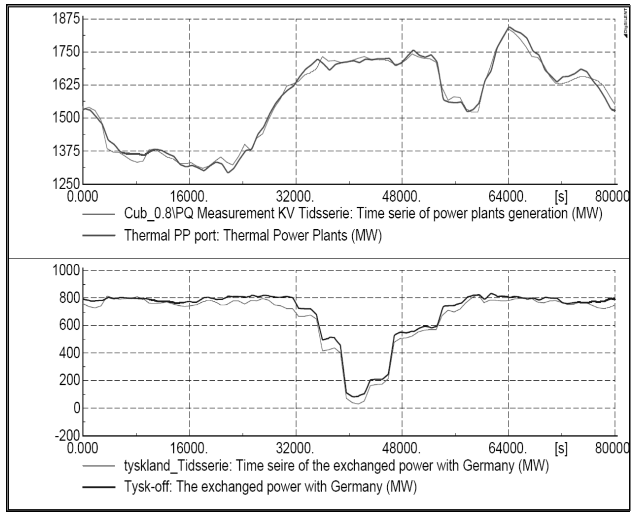

Figure 4. Comparison between the measured value and the simulation results of a) power generation from thermal power plants (above), and b) power exchange with Germany (below)

A dynamic simulation of the power balancing control system with the given time series data of wind power generations, loads, and power exchange with the Nordel system on a day in 2003 is demonstrated. The power balancing system model applied in this analysis has been implemented and developed in the earlier study in [9] and has been successfully validated against the measurement as shown in Figure 4.

5. Simulation Studies

The impacts of power fluctuations from large scale wind farms on power system with regard to power balance control have been simulated in simulation studies. One is considering the power gradient control used in wind farms, together with the secondary control from the thermal power plants in the system, and the other is considering power balance control with all the above functions, together with the secondary control of DCHP units and the delta control from the wind farm.

The worst case scenario simulation study when a new large offshore wind farm Horns Rev B (HRB) with 215 MW rated power is presented. Commissioning of the HRB wind farm in the same geographical area with HRA wind farm will increase the intensity of the wind power fluctuation and the deviation in the planned power exchange. The last simulation study is considering the regulating power control from the GBL HVDC connection. The deviation between the forecasted planned power to be supplied and the power generation from the Horns Rev wind farm A (HRA), with 160 MW rated power, is shown in Figure 5.

5.1 Secondary control of the thermal power plants

The power fluctuation generated from the offshore wind farm may give a significant contribution to the deviation from the planned power exchange between the western Denmark and Germany. The new settlement model introduces restriction on the use of the fast power control of the HVDC links with the Nordel system, it is therefore included in this study as time series data of planned power exchange (HVDC links operate according to their plans with regard to the new settlement model with the restrictions on the use of the fast control of the HVDC connections). In this simulation study, the measured power from HRA is rescaled to 160 MW as shown in Figure 5. Figure 6 shows the simulated result of the power deviation computed with the use of the power gradient limit on wind farm HRA and the use of the secondary control of the thermal power plants ($P_{Ctrl}^{Thermal}$). The deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{Dev} = P_{Meas} - P_{Plan} - P_{Ctrl}^{Thermal} \tag{9}$$

This analysis has shown the limit capability of the available power plants which nearly eliminate the power deviations with the UCTE system.

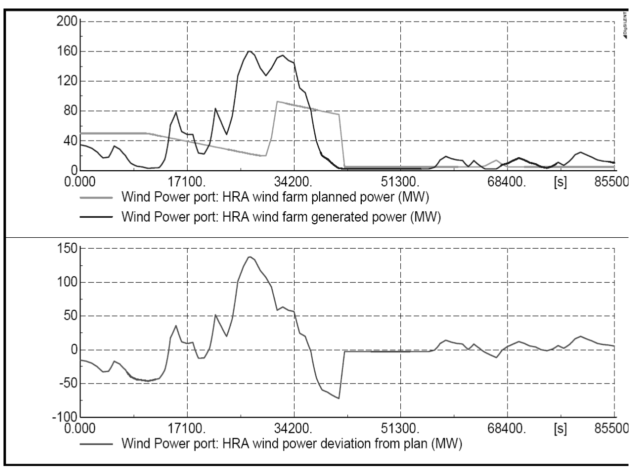

Figure 5. Forecasted and measured active power from HRA wind farm (above) and wind power deviation from plan (below)

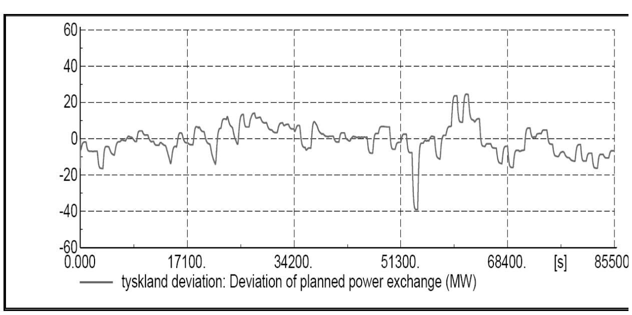

Figure 6. Deviation of planned power exchange when the secondary control of thermal power plants is applied

5.2 Regulating power control from DCHP units

Figure 7 shows the simulated result of the power deviation computed with the use of the power gradient limit on wind farm HRA, the use of the secondary control of the available power plants and the additional use of the fast secondary control (P_{Ctrl}^{DCHP}) from DCHP units. This analysis has shown the better capability of the available regulating power which decreases the power deviations with the UCTE system. The deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{Dev} = P_{Meas} - P_{Plan} - P_{Ctrl}^{Thermal} - P_{Ctrl}^{DCHP} \tag{10}$$

5.3 Regulating power control from DCHP units with Delta control from wind farms

Figure 8 presents the deviation from the planned power exchange at the western Danish-German border with the use of the secondary control of the thermal power plants and the additional use of the secondary control (P_{Ctrl}^{DCHP}) from DCHP units and the power gradient limit of ± 10 MW/min., together with the delta control of 10% *pf* on HRA wind farm (P_{Delta}^{HRA}). This analysis has shown the even better capability of the available regulating power which decreases the power deviations with the UCTE system even more. The deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{Dev} = P_{Meas} - P_{Plan} - P_{Ctrl}^{Thermal} - P_{Ctrl}^{DCHP} - P_{Delta}^{HRA} \tag{11}$$

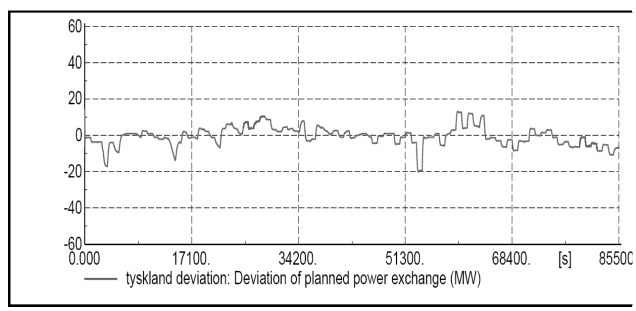

Figure 7. Deviation of planned power exchange when $P_{Ctrl}^{Thermal}$ and P_{Ctrl}^{DCHP} are applied

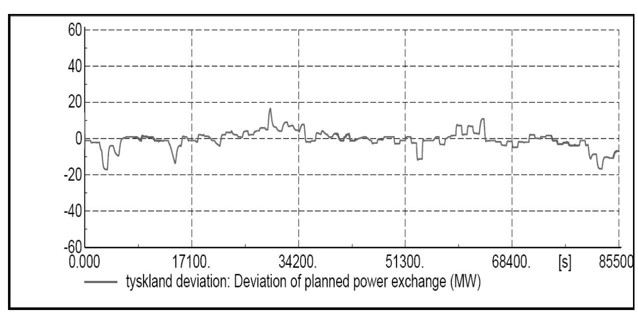

Figure 8. Deviation of planned power exchange when $P_{Ctrl}^{Thermal}$, P_{Ctrl}^{DCHP} and P_{Delta}^{HRA} are applied

Figure 9 shows the comparison of the deviation from planned power exchange between the use of the secondary control of thermal power plants and DCHP units and as previous with the delta control of HRA wind farm. The use of the delta control contributes to small reduction of the P_{Dev} due to the fast pitch control on wind turbines.

5.4 Worst case scenario with the new wind farm

Commissioning of the new offshore wind farm, Horns Rev B (HRB), with 215 MW rated power, in the same geographical area with HRA wind farm will increase the intensity of the wind power fluctuation and the deviation in the planned power exchange. Large power deviation from planned power exchange can be expected. Therefore, the regulating control and operational strategies is needed to prevent such a large power deviation in the future. Complying with the total regulating power implies that the deviations in the power exchange with the UCTE system is kept within an acceptable limit.

In this simulation study, the simulated power from the HRB is rescaled to 215 MW and the output is 100% correlated with the output from HRA as shown in Figure 10. Figure 11 presents the simulated power deviation at the western Danish-German border when the secondary control of thermal power plants is applied. Large power deviation exceeding ± 50 MW can be expected. In Figure 12, the simulated power deviation at the western Danish-German border with the use of the power gradient limit ± 10 MW/min. and the delta control of 10% *pf* value on wind farm HRA and wind farm HRB, the use of the secondary control of the available power plants and the DCHP units is presented. This analysis has shown the better capability of the available regulating power which decreases the power deviation with the UCTE system.

5.5 The regulating power control from the GBL HVDC connection

From the simulation result in Figure 12, there is a small, residual power imbalance caused by the power gradient limit of the power generating units. With the GBL HVDC connection, the utilization of the regulating power control incorporated in the eastern part of Denmark is expected to work together with that established in the western Denmark. Figure 13 presents the resulting power deviation at the western Danish-German border with the use of the regulating power control from the GBL HVDC connection. Figure 14 shows the comparison of the deviation from planned power exchange when the commissioning of the new offshore wind farm, Horns Rev B (HRB) for the cases shown in Figure 11, Figure 12 and Figure 13. The utilization of the regulating power control of GBL contributes to reduction of the P_{Dev} due to the very fast ramp rate capability on the HVDC connection.

This analysis has shown the even better capability of the available regulating power which decreases the power deviation with the UCTE system. The deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{Dev} = P_{Meas} - P_{Plan} - P_{Ctrl}^{D} - P_{GBL} \quad (12)$$

The P_{Dev} between P_{Meas} and P_{Plan} shall be minimized by the domestic power regulating control (P_{Ctrl}^{D}) which consist $P_{Ctrl}^{Thermal}$, P_{Ctrl}^{DCHP}, P_{Delta}^{HRA}, P_{Delta}^{HRB} and the regulating power control via GBL connection (P_{GBL}).

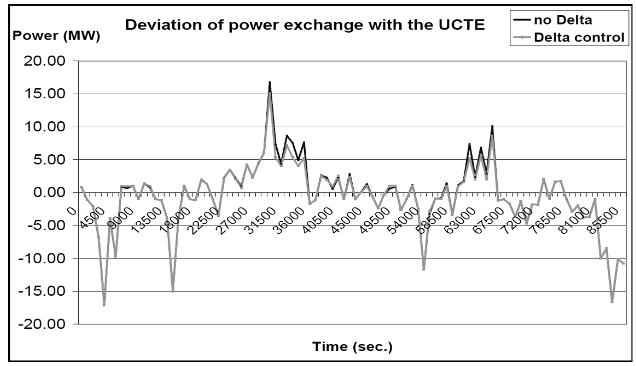

Figure 9. Comparison of the deviation in Figure 7 and Figure 8

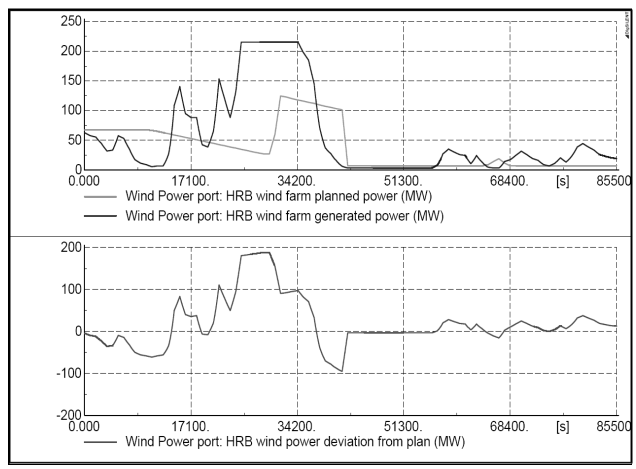

Figure 10. Forecasted and measured power from HRA wind farm (above) and wind power deviation from plan (below)

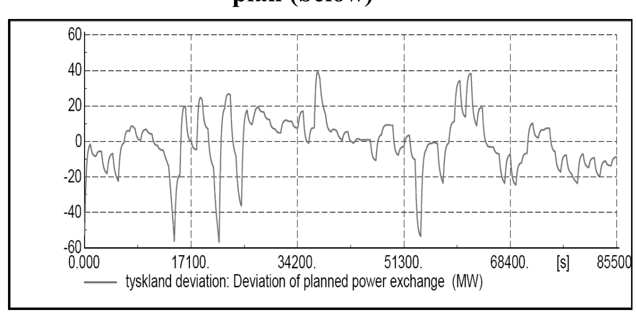

Figure 11. Deviation from plan when $P_{Ctrl}^{Thermal}$ is applied with the commissioning of HRB wind farm

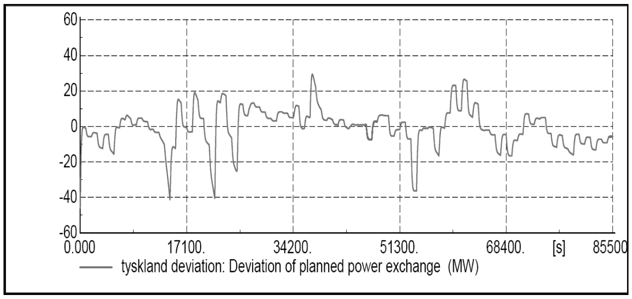

Figure 12. Deviation of planned power exchange when $P_{Ctrl}^{Thermal}$, P_{Ctrl}^{DCHP}, P_{Delta}^{HRA} and P_{Delta}^{HRB} are applied

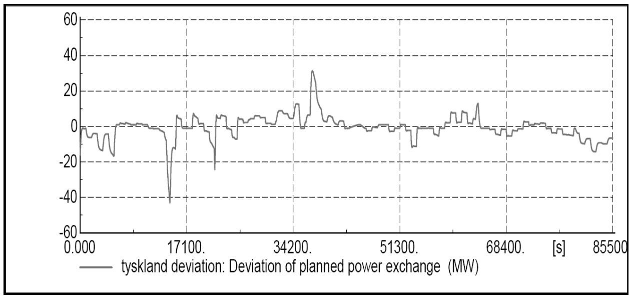

Figure 13. Deviation of planned power exchange when the regulating control of the GBL is applied

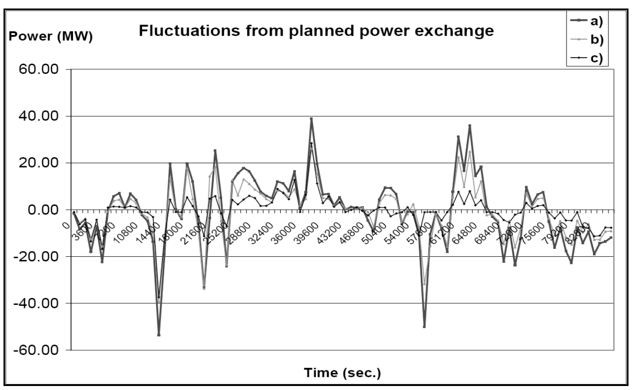

Figure 14. Comparison of the deviation in Figure 11, Figure 12 and Fi ure 13

6. Conclusion

This paper addresses problems encountered in planning and operation of power system with the large scale wind power penetration. Commissioning of the new offshore wind farm HRB in the same geographical area with the HRA wind farm, in energinet.dk-west system, will increase the intensity of the wind power fluctuation and the deviation in the planned power exchange with the UCTE system within the period minutes to one hour. Therefore, the regulating control and control strategies are required to minimise power fluctuations and their impact on the power system.

The developed control strategies are used for the calculation of the imbalance exchanged power with the interconnected UCTE system. These system control strategies can also be used to investigate the system reliability and power system security with regard to the exchanged power deviation with the interconnected systems at different loads and generations. The limit of wind power penetration can also be analyzed with regard to the specified control strategies and the regulating power capability of generation units together with the reserve availability from the interconnected systems. It can be concluded that the wind power characteristics and power system operation strategies, which allows for active power balance might set up a limit for the wind power penetration.

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