WIND ENERGY
Wind Energ. 2007; **10**:31–49
Published online 4 September 2006 in Wiley Interscience
(www.interscience.wiley.com) DOI: 10.1002/we.206

Research Article

Technical Aspects of Status and Expected Future Trends for Wind Power in Denmark

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Key words:
electricity-producing wind turbines;
offshore wind farms;
wind forecast;
power system;
active power balance;
grid area controller;
HVDC;
reactive power;
voltage stability;
ride-through capability;
models

The power system of Denmark is characterized by significant incorporation of wind power. Presently, more than 20% of the annual electricity consumption is covered by electricity-producing wind turbines. The largest increase in grid-incorporated wind power is expected to come from large (offshore) wind farms operating as large wind power plants with ride-through solutions, connected to the high-voltage transmission system and providing ancillary services to the system. In Denmark there are presently two offshore wind farms connected to the transmission system: Horns Rev A (160 MW rated power in the western part of the country) and Nysted (165 MW rated power at Rødsand in Eastern Denmark). The construction of two more offshore wind farms, totalling 400 MW by the years 2008–2010, has been announced. This article presents the status, perspectives and technical challenges for wind power in the power system from the point of view of Energinet.dk, Transmission System Operator of Denmark. Copyright © 2006 John Wiley & Sons, Ltd.

Received 2 December 2005; Revised 4 June 2006; Accepted 5 June 2006

Introduction

The total installed wind power in Denmark is approaching 3300 MW. This figure must be seen in relation to the minimum and maximum peak loads in the system, which in the year 2004 were about 2000 and 6300 MW respectively. Wind power covers more than 20% of the annual electricity consumption in the country on average. However, there are already days when wind power generation may exceed power consumption in the area. Such situations are frequent in the western part of the country, which has the largest proportion of wind power penetration.

Being the national Transmission System Operator (TSO) of Denmark, Energinet.dk is responsible for the operation and control of the Danish transmission system. Significant incorporation of wind power introduces several issues regarding stable, safe and reliable operation of the transmission system, such as:

(1) technical specifications for grid connection of electricity-producing wind turbines that are based on prior experience with wind power;
(2) constant improvement in wind power forecasts as the share of incorporated wind power continues to increase;
(3) long-term and short-term power balances for the Danish transmission system;
(4) voltage stability and quality;

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(5) ride-through capability of large offshore wind farms, existing as well as planned;
(6) wind turbine modelling as part of the Danish power system model;
(7) preparation of the transmission system for more wind power.

Energinet.dk must meet this challenge for successful incorporation of wind power into the Danish power system. This article presents the status, perspectives and technical challenges with regard to incorporation of wind power into the power system from the point of view of Energinet.dk, TSO of Denmark. The article also gives an overview of the technical specifications formulated by Energinet.dk for grid connection of wind turbines, but without an in-depth discussion of these specifications.

Transmission System of Denmark

In Denmark the high-voltage (HV) transmission system is presently separated into two synchronous areas that are not electrically connected to each other*. The HV transmission system is defined as the network with a rated voltage above 100 kV and operated by Energinet.dk. The western part of the country contains 400 and 150 kV meshed transmission systems with AC connection to the UCTE synchronous area to the south and HVDC connection to the Nordel synchronous area to the north.

The eastern part of Denmark contains 400 and 132 kV meshed transmission systems with AC connection to the Nordel synchronous area (Sweden) and an HVDC link to Germany (the UCTE synchronous area). Figure 1 presents the transmission system of Denmark.

In relation to wind power the western and eastern parts of Denmark have different degrees of incorporation and experience different problems. Therefore specific wind power issues for the western and eastern parts of Denmark will be considered in separate sections, whereas common issues are dealt with in the same sections.

Wind Power Generation in Western Denmark

Table I gives the key figures of the power system of Western Denmark. The primary power plants are thermal, coal- or gas-fired units. A significant proportion of the power generation comes from local wind turbines and combined heat and power (CHP) units. An offshore wind farm of 160 MW rated power is commissioned at Horns Rev A (HRA) and connected to the 150 kV transmission system. In the figures for the year 2004 the installed wind power corresponded to about 33% of the generation capacity of the area, whereas wind power covered about 22% of the electrical energy consumption of Western Denmark. The system is interconnected through AC lines with Northern Germany, dominated by nuclear and thermal power plants and rapidly growing wind power, and through HVDC links to Norway and Sweden, dominated by hydro power plants.

At present, most on-land sites with good wind conditions are already occupied by existing local wind turbines. A increase in the wind power incorporated in on-land sites may occur by upgrading, i.e. replacement of existing, small wind turbines with ratings well below 1 MW (up to 900 units totalling 175 MW) by newer, more efficient wind turbines with ratings of several MW (between 150 and 200 units). This upgrading may give up to 350 MW more local wind power in the whole country. However, the major upgrading is expected in Jutland, the continental part of Western Denmark.

The increase in the wind power to be commissioned in Western Denmark will therefore come from large offshore wind farms. Commissioning of the second offshore wind farm, Horns Rev B (HRB), with a rated power of 200 MW, will take place by the year 2009. The contractor is the Danish company Energy E2. Figure 2 shows the future development for wind power in Western Denmark. Future incorporation of wind power in Denmark has to be decided by market mechanisms. As expected, the largest proportion of wind power in the future will be commissioned in the western part of the country.

*Commissioning of an electrical connection between Western and Eastern Denmark, the Great Belt Link, is planned in the very near future.

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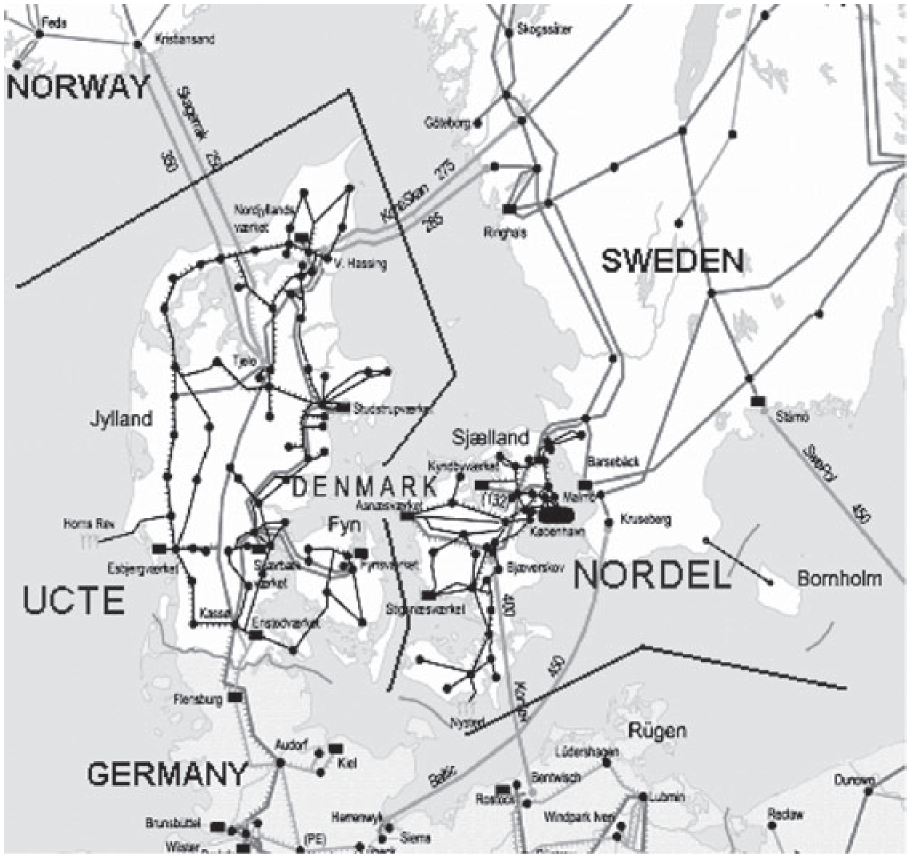

Figure 1. Transmission system of Denmark, presently divided into two synchronous areas

Table I. Key figures of the power system of Western Denmark for the year 2004[1]

	MW	GWh
Primary power plants	3516	12,951
Local CHP units	1593	6839
Local wind turbines	2379	4875
Horns Rev A offshore wind farm	160	
Consumption		21,246
Maximum load	3639	
Minimum load	1281	
Capacity export to UCTE	1200	
Capacity import from UCTE	800	
Capacity export to Nordel	1440	
Capacity import from Nordel	1460	

Wind Power Generation in Eastern Denmark

The primary power plants in Eastern Denmark are coal-fired. The system is interconnected through AC submarine cables to Sweden, dominated by nuclear and hydro power plants and lying within the Nordel synchronous area. Table II presents the key figures of the power system of Eastern Denmark.

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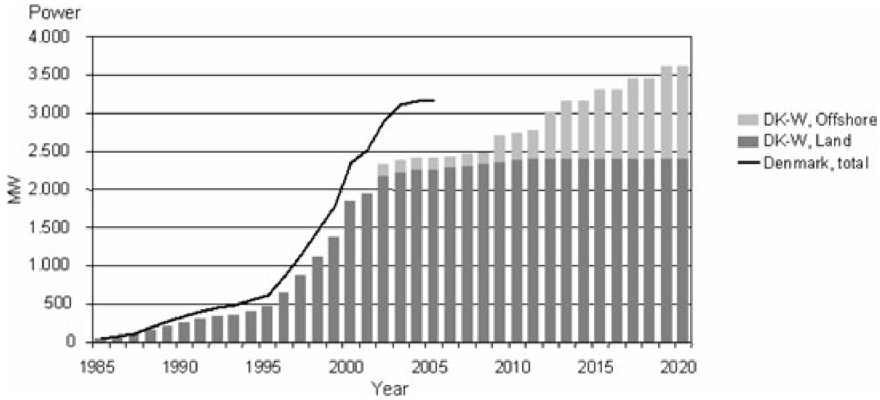

Figure 2. Present and expected wind power incorporation in Western Denmark

Table II. Key figures of the power system of Eastern Denmark for the year 2004[2]

	MW	GWh
Primary power plants	3837	9441
Local CHP units	642	2559
Local wind turbines	578	
Nysted offshore wind farm	165	1709
Consumption		14,262
Maximum load	2665	
Minimum load	~750	
Capacity export to UCTE	550	
Capacity import from UCTE	550	
Capacity export to Nordel	1700	
Capacity import from Nordel	1300	

A significant proportion of the power consumption is still covered by central power plants. The largest location of local wind turbines, about 240 MW of installed power capacity, is on the island of Lolland, just south of the main island of Zealand. An offshore wind farm of 165 MW rated power is commissioned at Nysted (NOWF) and connected to the 132 kV transmission system of Lolland. In the figures for the year 2004 the installed wind power corresponded to about 14% of the generation capacity of the area, whereas wind power covered about 12% of the electrical energy consumption of Eastern Denmark.

In Eastern Denmark, some increase in the wind power incorporated in on-land sites may come from the upgrading of existing, small wind turbines to newer, larger ones, as described in the previous section, and also from the use of new sites on the islands of Lolland and Falster characterized by good wind conditions.

The main increase in the wind power to be commissioned in Eastern Denmark will come from the construction of new, large offshore wind farms. Commissioning of the second offshore wind farm, Rødsand-2 (ROWF), with a rated power of 200 MW, has been announced by the Danish Energy Authority, with completion expected by the years 2008–2010.

Wind Technology in Denmark

There are about 5000 local wind turbines in Denmark. Most of these wind turbines are fixed speed with conventional induction generators. About 4500 wind turbines are presently rated below 0·5 MW, which is why the

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upgrading is needed. After upgrading, the proportional use of newer concepts (e.g. variable speed with doubly fed induction generators, variable speed with full converters and induction or synchronous generators) in wind power generation is expected to increase.

The large offshore wind farm HRA has 80 2 MW pitch-controlled, variable speed wind turbines with doubly fed induction generators from the Danish manufacturer Vestas Wind Systems.

The large offshore wind farm NOWF has 72 2·3 MW active stall, fixed speed wind turbines with induction generators from the manufacturer Siemens Power Generation (formerly Bonus Energy).

Overview of Danish Technical Specifications

In common, the local wind turbines commissioned before July 2004 have been operated according to technical recommendations of Danish Electricity Supply R&D (DEFU) such as KR 111.[3] According to KR 111, local wind turbines must disconnect from the grid for grid protection reasons when the grid voltage has been below 0·7 pu for longer than 0·5 s. At least 4500 local wind turbines in Denmark follow these recommendations.

The large offshore wind farms connected to the Danish transmission grid before 2004 must comply with technical specifications TP98-328b.[4] Large offshore wind farms must maintain uninterrupted operation at a short-circuit fault subject to transmission grid. This requirement is today called the ride-through capability.

In normal grid operation the large offshore wind farm must be reactive power neutral with the transmission grid at the connection point. The reactive power control of the wind farm must be available for the TSO at grid disturbances. The large offshore wind farm must also contribute to the active power balance and to the frequency control within a defined range. In the case of fixed speed wind turbines with conventional induction generators the reactive power may be controlled by thyristor-switched capacitor banks commissioned together with the offshore wind turbines. Furthermore, a dynamic reactive power control unit may additionally be incorporated at the wind farm connection point on-land. In the case of converter-controlled wind turbines, such as those with doubly fed induction generators or with full-rating power electronic converters, the reactive power control is arranged by the converters. The park controller incorporated by the wind farm's owner may co-ordinate the reactive power control between the wind turbines by, for example, sending the reference signals to the wind turbines.

In 2004 the Danish TSO formulated two new specifications for grid connection of electricity-producing wind turbines. Technical specifications TF 3.2.5[5] deal with connecting wind turbines to power grids with voltages above 100 kV (the HV transmission grid), whereas technical specifications TF 3.2.6[6] are written for wind turbines in power networks with voltages below 100 kV (local distribution networks). Obviously, the specifications TF 3.2.5 are made for the large offshore wind farms that will be commissioned in the years to come. The specifications TF 3.2.6 are made for the local wind turbines coming from upgrading of the existing, smaller wind turbines to larger and more powerful units and from commissioning on new sites.

Despite some differences in these two specifications, both require ride-through capability of electricity-producing wind turbines. Technical specifications TF 3.2.5 upgrade and clarify the terms and requirements of the former specifications TP98-328b based on the practical experience of the Danish TSO from operation of the offshore wind farms HRA and NOWF. The new technical specifications are also made to simplify some acceptance procedures for wind turbines to be connected in Denmark.

Wind and Power Forecasts (Western Denmark)

Accuracy of wind and active power forecasts is essential for improving the power balance in Western Denmark.[7] The installed amount of wind power is so large that an error in the wind forecast of 1 m s^{-1} results in an error in the active power prediction of up to 320 MW, which is significant compared with the size of the system. Figure 3 gives examples of an accurate and a less accurate wind power forecast for the western Danish power system. The existing wind forecast models have to be improved in several ways.

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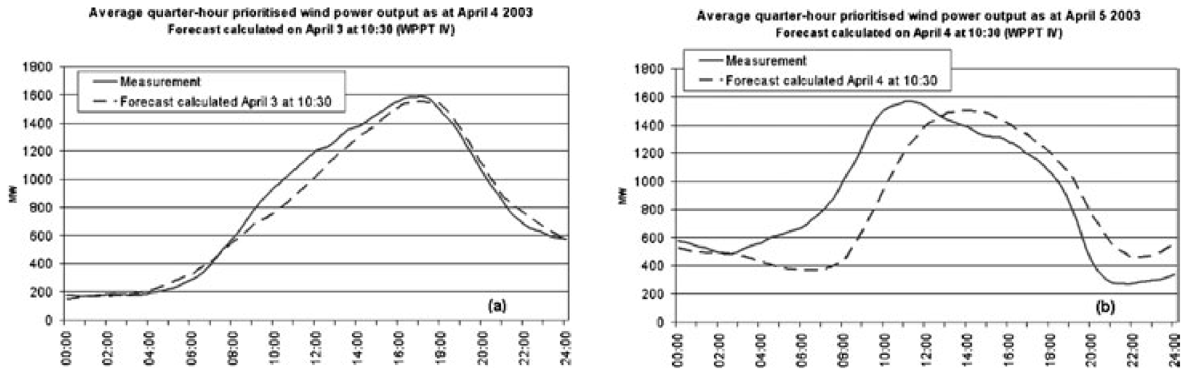

*Figure 3. Active power forecast from wind power in Western Denmark: **(a)** a good forecast; **(b)** a less good forecast*

1. Day-to-day forecasts must be improved, as the amount of grid-incorporated wind power is significant and still increasing (work in progress).
2. Hour-by-hour forecasts are required to comply with the power balances and planned operation of the central power plants, planned power transits via Western Denmark and consumption (work in progress).

A real-time prediction system for wind power has been running in Energinet.dk since 1997. This system uses the wind power prediction tool (WPPT) from the Institute of Mathematical Modelling (IMM), Technical University of Denmark, together with meteorological forecasts from the Danish Meteorological Institute (DMI). As an alternative to WPPT, a forecasting tool developed in-house has been used.

The need for accuracy improvement of the real-time prediction tools was especially demonstrated by the storm affecting Denmark on 7–9 January 2005. Figure 4 illustrates the wind and active power generation (predicted and actual) during the storm. The prediction was that the maximum active power would be generated by the wind turbines. However, the local wind turbines started to trip when the wind speed exceeded $20\,m\,s^{-1}$. The Horns Rev offshore wind farm also tripped when the wind speed exceeded $25\,m\,s^{-1}$. Prediction inaccuracy resulted in the difference between the expected and the actual power production reaching about 1800 MW when the wind speed reached its maximum (about $30\,m\,s^{-1}$). Activation of power reserves was immediately required.

Energinet.dk also undertook to look into an area of meteorology that deals scientifically with the day-to-day variations in the predictability of the atmosphere: ensemble forecasting. In 2002, Energinet.dk funded a research project on ensemble forecasting at University College Cork (UCC), Ireland.

The real-time version of the MSEPS (multi-scheme ensemble prediction system) application is named MELTRA and has been elaborated in close co-operation between Energinet.dk and the meteorological research company WEPROG (www.weprog.com).

In MELTRA the outcome of 75 ensemble members, e.g. the forecasts, can be evaluated by a graphic package for visualization of the forecasts. The system generates 3 day forecasts every hour and consists of around 6000 forecasts per day. Half of the forecasts are carried out as nested forecasts in higher resolution. The forecasts are converted into probabilities, which, in combination with observations, provide the best possible forecasts of wind power. The MELTRA ensemble system is run on a 92-processor Linux cluster, which is believed to be a very cost-effective hardware solution. The resolution in the meteorological model is 45 km, with a finer 5 km nested grid covering Denmark. Figure 5 shows an example of forecasted wind power production (in % of installed capacity) from the MELTRA prediction system calculated at 12:00 on 19 March 2004.

The major benefits of the real-time experience with the MELTRA system have been as follows.

1. Averaged over 1 year, the implemented ensemble technique has a potential of at least 20% better forecasts of wind power compared with a single forecast.

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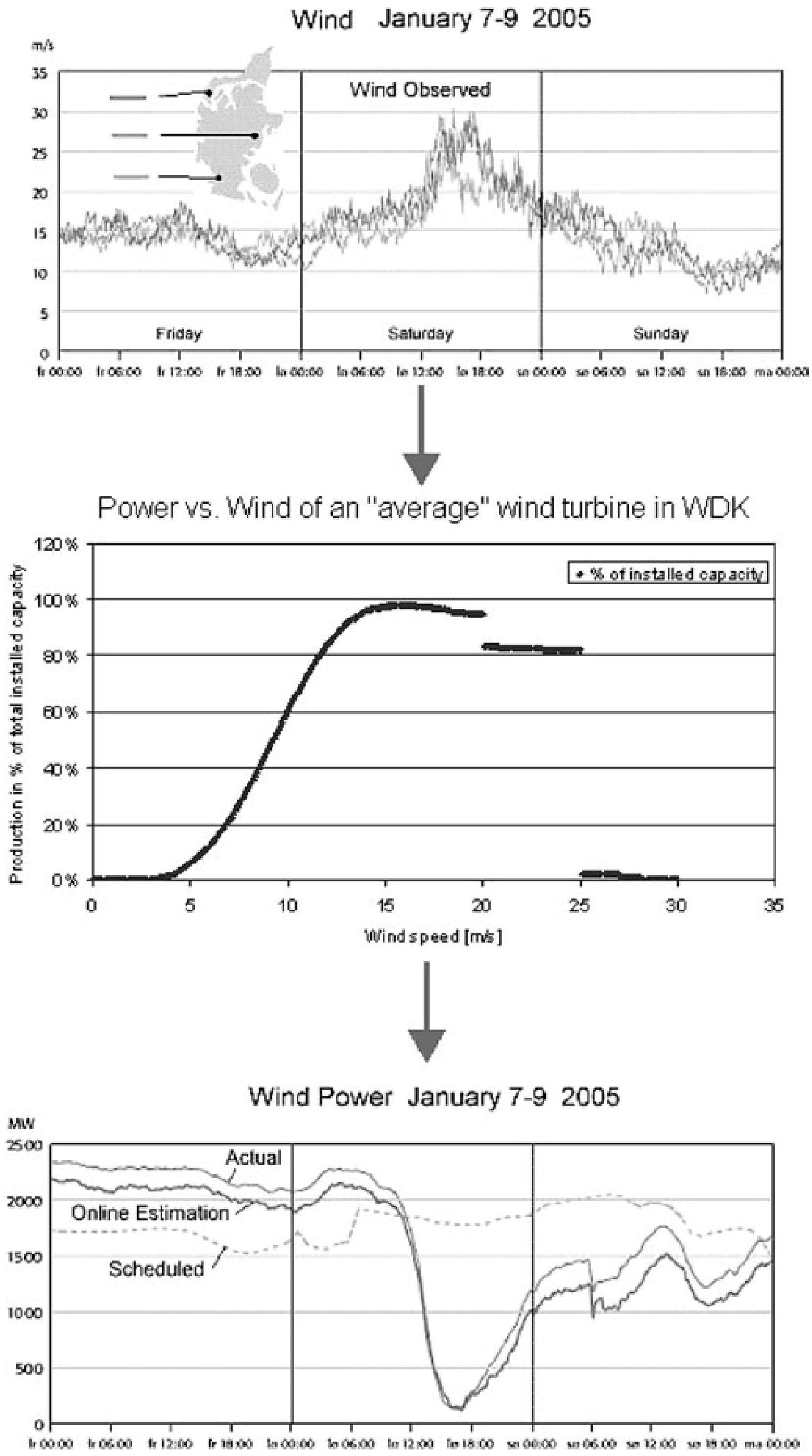

Figure 4. Wind and power generation from wind turbines in Western Denmark during the storm in January 2005

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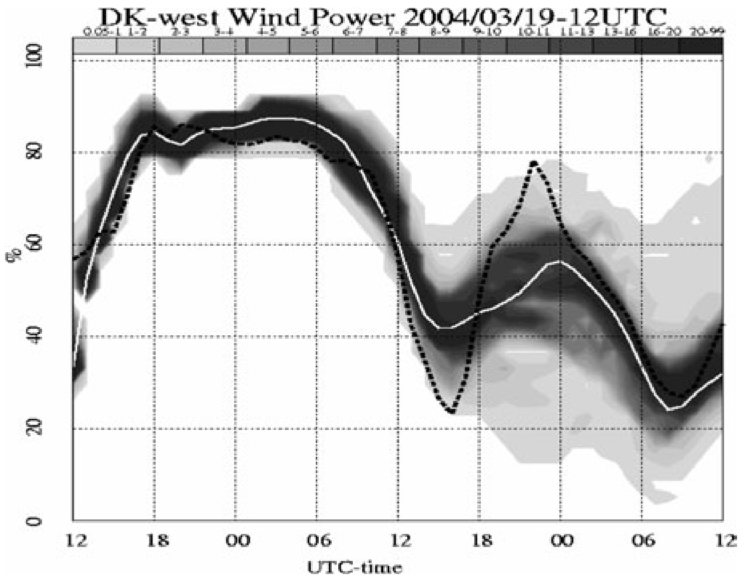

Figure 5. Forty-eight hour load factor prediction for wind power for Western Denmark calculated at 12:00 on 19 March 2004. Probability distribution is indicated by grey colours. Dark grey indicates high density of ensembles, narrow bandwidth of results and small uncertainty of wind power production; light grey indicates low density of ensembles, large bandwidth of results and large uncertainty of production. The white curve represents the average prediction and the black dotted curve the measured production

2. Most periods with high wind power output (>70%) and low uncertainty are predicted accurately up to 2 days ahead.
3. Periods with low wind power and low uncertainty are also predicted accurately.
4. Uncertain periods are only rarely predicted with too much or too low uncertainty.

The ensemble technique is running in a final test version together with the above-mentioned traditional forecast concepts. The improvements due to the ensemble technique are needed for a quantitative estimation of wind power prediction uncertainty and for improved power balance achievement.

Issue of Short-term Power Balance (Western Denmark)

Wind power is characterized by fluctuations of the produced active power due to the fluctuating nature of the wind and wind fronts passing areas with incorporated wind turbines. At the offshore wind farm HRA in Western Denmark the active power fluctuations can be much more intense than ever seen in the aggregated wind power production on land.[8] Figure 6 shows an example of the intense power fluctuations observed at the connection point of HRA, the 150 kV substation Karlsgaarde. For the given summer day in 2003 the maximum (measured) power reaches 120 MW at Horns Rev. The measurements at the connection point of HRA have shown that the active power of the offshore wind farm HRA can change by up to 100 MW in 15–20 min. In part, this can be explained by the large amount of wind power concentrated within a relatively small area (about 25 km^2), resulting in a stronger correlation of the power outputs from the turbines in the farm. However, the complete explanation of such intense power fluctuations may also be related to the specific wind behaviour at Horns Rev.

Similar power fluctuations to those of the Horns Rev offshore wind farm have been observed on dispersed wind turbine sites on land[8] and also at the large offshore wind farm NOWF in Eastern Denmark.[9] However, the total active power of the dispersed wind turbines is smoother, because these wind turbines are scattered

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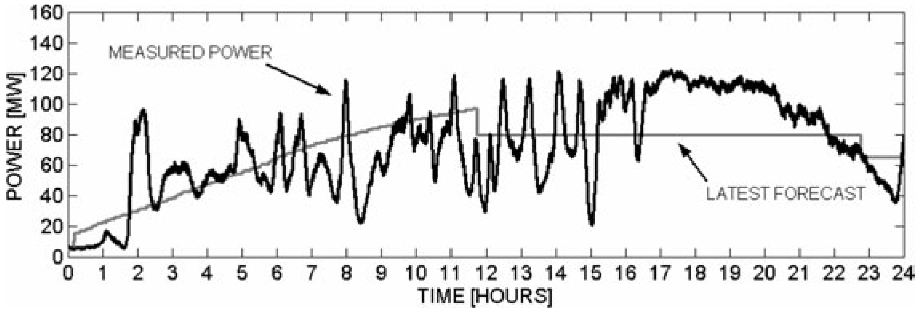

Figure 6. Measured power and forecast for the Horns Rev A offshore wind farm on a summer day in 2003

throughout the country. This gives a small correlation between the total power outputs of the different local wind turbines, which may eliminate the fluctuations that last from tens of minutes to 1 h. The active power fluctuations at Rødsand are not as intense as those at Horns Rev either.

The planned active power supply from the offshore wind farm HRA is based on wind forecasts transformed to active power forecasts. The first active power forecast is made a day ahead but can be updated during the day. The active power supplied from the offshore wind farm HRA forms part of the power supplied from a group of power plants available to the Power Balance Responsible Player (PBRP). The PBRP controls the active power from this group of power plants according to the latest power forecast in such a way as to comply with the planned total power production. For the given summer day in 2003 the latest power forecast is shown in Figure 6. The deviations between the power forecast, i.e. the planned active power to be supplied, and the total active power from HRA are injected into the transmission system of Western Denmark. In the case of HRA, such power deviations form power fluctuations with a period ranging from 15 min to 1 h. These power fluctuations can even be distributed to neighbouring transmission systems, e.g. the UCTE synchronous area. As defined, positive power imbalance means that the actual power production from HRA is less than planned.

Commissioning of the second offshore wind farm, Horns Rev B (HRB), just 5 km from the existing offshore wind farm HRA will presumably increase the intensity of active power fluctuations and deviations with a period of up to 1 h. Such close location will introduce a strong correlation between the power fluctuations at the two wind farms.

Besides the power fluctuations and deviations introduced by the Horns Rev wind farm, deviations from the planned power generation, demand and exchange to Scandinavia contribute to the total deviations in the power exchange between Western Denmark and the UCTE synchronous area.

Furthermore, the power flow of Western Denmark is superimposed by a large power transport due to the geographical location between two large, but different, AC power systems.[7] To the north the active power exchange has a 15 min resolution, and the settlement of the power exchanged between Western Denmark and the Nordel synchronous area is arranged as the net power exchanged hour by hour. At the border with Germany to the south the active power exchange follows a schedule with a 5 min resolution.

The issue is to keep the power generation, including the power import, in balance with the power consumption, including the power export, in Western Denmark and to keep the power exchange between Western Denmark and the UCTE synchronous area at the planned power exchange. Only small deviations in the range of approximately ±50 MW from the planned power exchange may be acceptable.[7,8] Compliance with the planned power exchange between Western Denmark and the UCTE synchronous area makes it necessary that the Danish wind power and the other sources of power imbalance be brought into balance with the same or a better resolution. The challenge is to operate the system with large internal power deviations and different resolution of the exchange schedules on the interconnections to achieve the common goal of active power balance and reliable power transport between the Nordel and UCTE synchronous areas.

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Area Grid Controller

The studies performed by Energinet.dk have shown that the target of ±50 MW can be reached by applying the western Danish Area Grid Controller (AGC) accessing the secondary control at the central power plants of Western Denmark and the HVDC connections with the Nordel synchronous area.[8] In the studies the second offshore wind farm at Horns Rev was obliged to comply with a power gradient limit of 5 MW min^{-1}. Figure 7 presents the resulting active power deviations at the Danish–German border without any control *versus* those with the use of the western Danish AGC. Here the central power plants were separated into two groups performing slow and relatively fast secondary control respectively. The HVDC connections were able to provide almost instantaneous power control on demand, but within a limited range. It has been found that the use of the fast power control of the HVDC connections will be essential for keeping the power deviations within the desired range.

Hour-by-hour Settlement Model

The incompatibility of the power systems has resulted in an agreement between Energinet.dk and the other transmission system operators of Nordel. The power exchange through the HVDC connections between

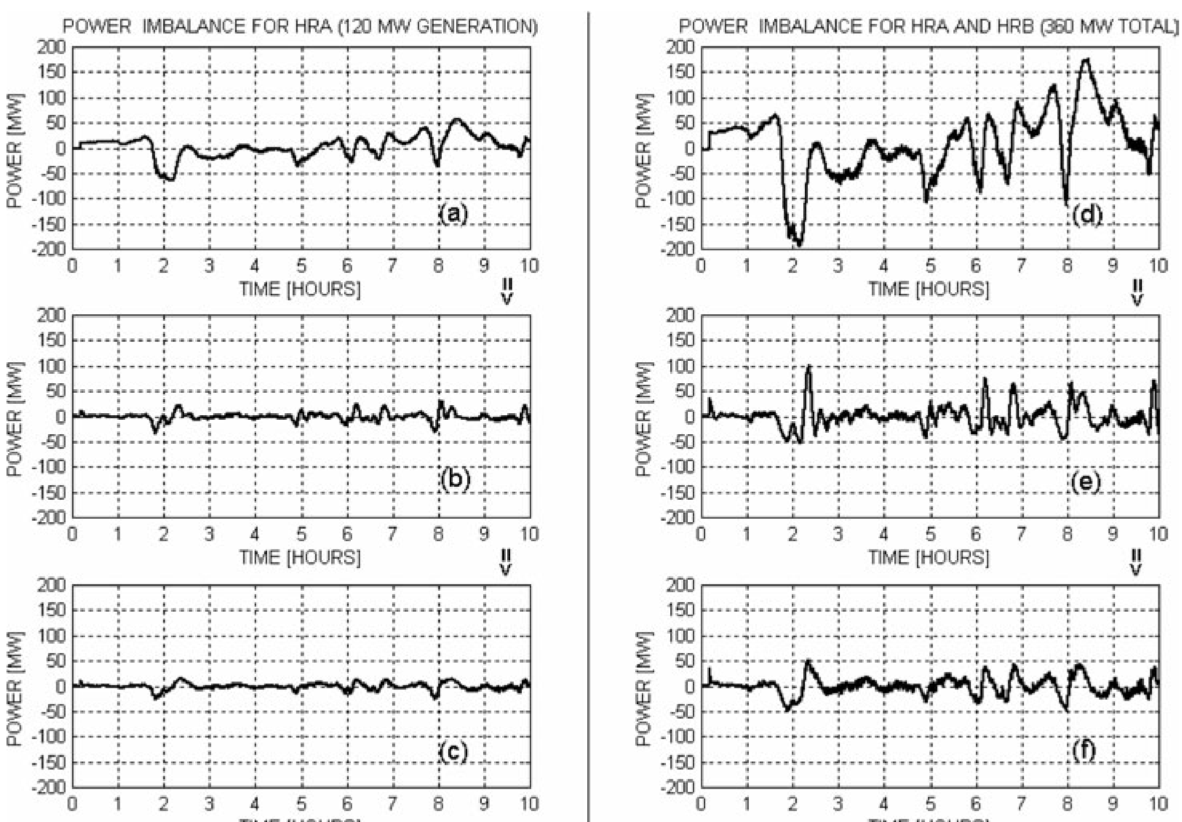

Figure 7. Computed power deviations caused by the Horns Rev A wind farm on a summer day in 2003: (a) no control is applied to minimize such deviations; (b) secondary control of primary power plants is applied; (c) as previous and also with access to the fast power control of HVDC links. Computed power deviations after commissioning of the Horns Rev B offshore wind farm; (d) no control is applied; (e) HRB is subject to a power gradient limit of 5 MW min^{-1}, together with use of secondary control of primary power plants; (f) as previous plus access to the fast power control of HVDC connections

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Western Denmark and the Nordel synchronous area must follow the present settlement model. According to this settlement model, the power transactions are based on the bids given to the Nordic real-time balancing market NOIS. A transaction may start at the beginning of each hour or, when preferred, at the beginning of at least each quarter within the given hour. The transaction ends at the end of each hour and then the new transaction may begin. A transaction must start with the largest required power exchange and may be reduced each quarter of an hour within the given hour (a new bid). A transaction must not have any change in the direction of power flow. The characteristic time of the power ramp between different power levels of two different transactions may be 10 or 15 min. The power ramp between different power levels of two bids may be 15 min.

Figure 8 presents the present settlement model by the power transactions. The sum of the transactions gives the plan for the power exchange through the HVDC connections with the Nordel synchronous system. Obviously, application of the present settlement model introduces restrictions on the use of the fast control of the HVDC connections to balance the Danish wind power.

Present Arrangements for Power Balance

The present settlement model may imply that the ability of the HVDC connections to keep the power balance in Western Denmark is reduced. Figure 9(a) compares the total demand for regulating power in Western Denmark with a 5 min resolution and the contribution from the HVDC connections operated according to the present settlement model. The case shown is for an autumn day in 2004. The difference between the

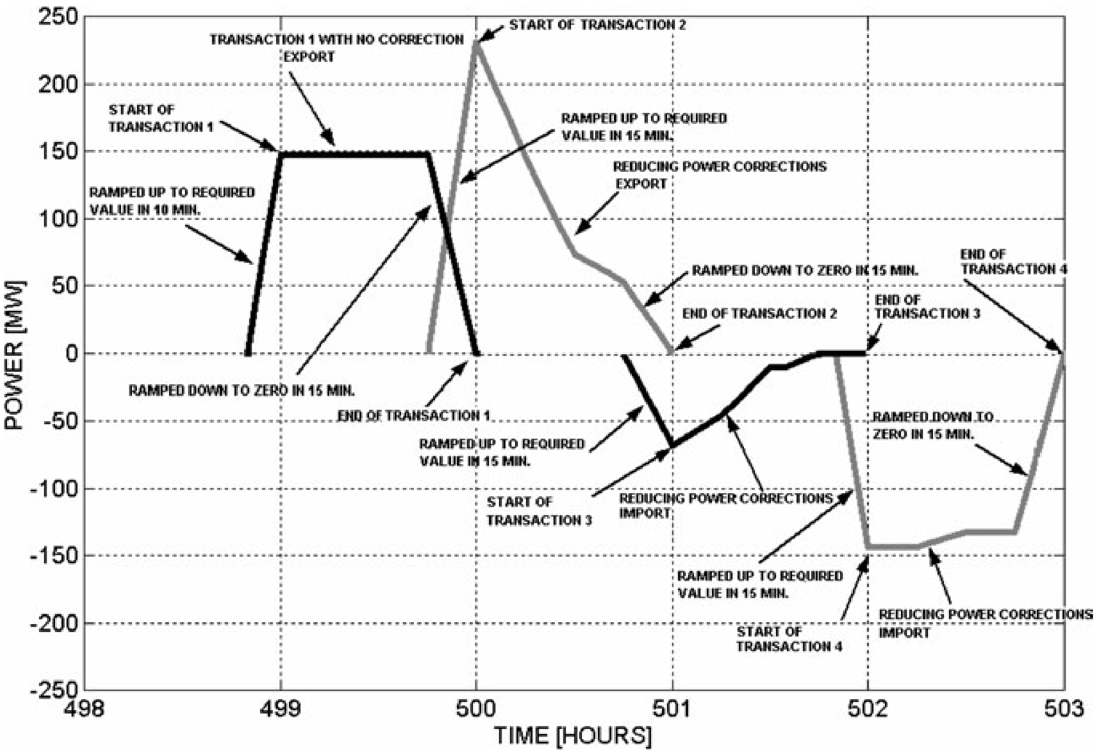

Figure 8. Present settlement model by power transactions each hour: the first two transactions represent export and the last two transactions import of power through HVDC connections. A quarter of an hour before the next transaction starts, power is ramped up to the required value. Then the power may be adjusted during this hour with the restriction that the power transaction may only be ramped down. The power transaction may decay to zero but not cross zero. In the last quarter of the hour the power is ramped to zero, where the power transaction must end. The transaction may be started at any time during an hour, except during the last quarter

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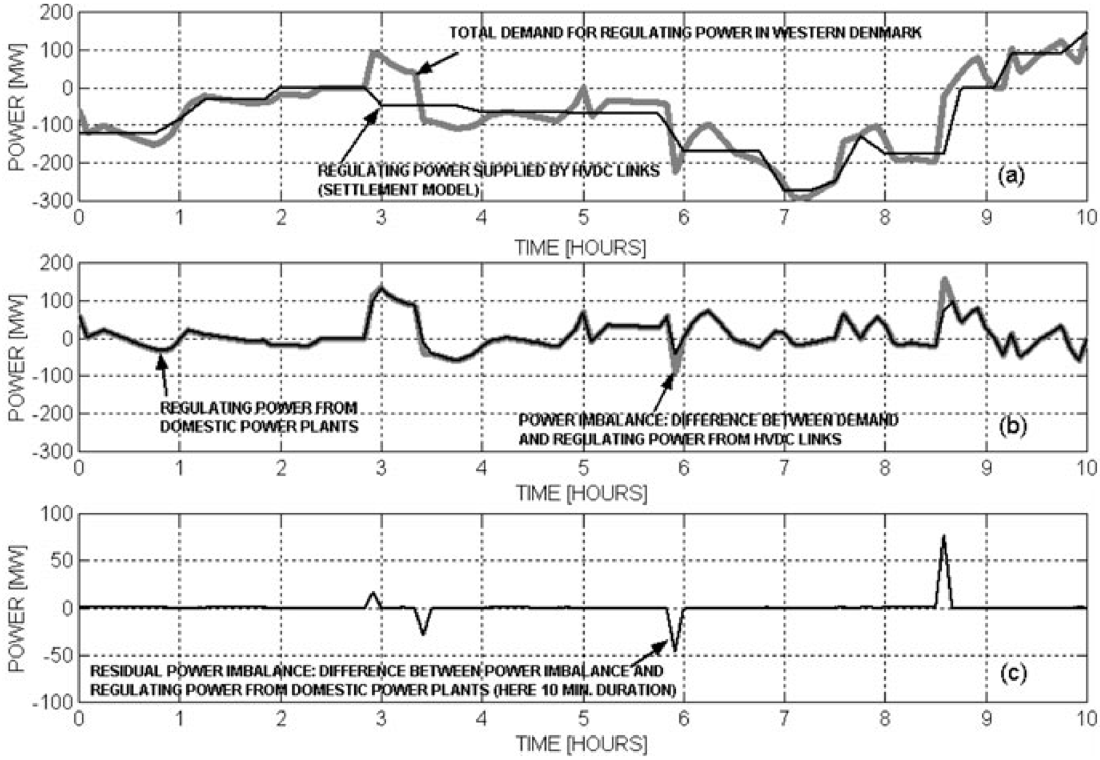

Figure 9. Application of the present settlement model for power exchange through HVDC connections between Western Denmark and Nordel: (a) comparison between total demand for regulating power in Western Denmark and regulating power supplied from HVDC links subject to the present settlement model; (b) comparison between residual power imbalance from (a) and regulating power that can be supplied from domestic thermal power plants in Western Denmark; (c) resulting residual power imbalance from (b) that requires use of other power control. The example is for an autumn day in 2004; Horns Rev B is not commissioned

regulating power demand and the regulating power supplied by the HVDC connections gives the power imbalance and is shown in Figure 9(b). So long as the other sources of regulating power are not activated, this power imbalance will be present in the western Danish power system and through the AC lines be transported to the UCTE synchronous area.

There are several ways to minimize such a power imbalance. The regulating power required can be ordered from the domestic power plants. Still, there may be a small, residual power imbalance caused by the power gradient limits of the thermal power plants. This small, residual power imbalance is shown in Figure 9(c) and will be transferred to the neighbouring areas or treated with the use of other control when available.

The regulating abilities of the Danish power system operated as presently are close to being exhausted. Notice that the total demand for regulating power as shown in Figure 9(a) is for a given day in the year 2004. It therefore does not include a contribution from the second offshore wind farm, Horns Rev B. Such regulating power demand will indeed increase when the second offshore wind farm is commissioned at Horns Rev B by the year 2008. This problem still requires a complete solution.

Revision of the present settlement agreement and access to the fast power control of the hydro power plants in the Nordel synchronous area may be an additional option for maintaining active power balance in Western Denmark. Regulating power required can be ordered from the hydro power plants located in the Nordel synchronous area. For example, the Danish TSO may agree with the Norwegian TSO that a few selected hydro power plants in Norway are available for the regulating power in Western Denmark or accessed by the western

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Danish AGC. This will of course require a separate agreement with the Nordel system and with the selected hydro power plants and, furthermore, allocation of the transmission capacity at the HVDC connections for this regulating power exchange in both directions.

Activation of Local CHP Control

Most of the large thermal units in Denmark are coal-fired CHP units that can extract steam for heat production and have an operating domain between 20% and full power load without heat production. However, the operating range for the power depends on the heat production: with higher heat production the minimum power load increases and the maximum power load decreases. This is illustrated in Figure 10(a). According to the Danish power plant specifications, these thermal units have a regulating capability of 4% of full load per minute in the operating range from 50% to 90% and of 2% of full load per minute below 50% and above 90% load.[7] Besides the normal regulating capabilities, these units can disconnect the heat production and, for a short period, utilize the extracted steam for power generation, which is marked as ΔP in Figure 10(b).

The local CHP units range in size from a few kW up to 100 MW. Most of these units are gas turbines or gas engines. To eliminate the coupling between heat and power production, these units are equipped with heat storage tanks so that they can operate more independently from the heat demand.

In the beginning the distributed CHP units were not subject to the same kinds of specifications as the large thermal units. Furthermore, the local CHP units do not have the same operating range with coupling between generation of heat and power. The smaller distributed CHP units below 10 MW operate mostly as on–off depending on the tariffs: they produce full power when the tariffs are favourable or they are disconnected from the grid when the tariffs are low. From 1 January 2005 the CHP units above 10 MW have been operating according to market signals.[7]

Although these local units are small, their total power capacity is significant compared with the peak load in the Danish power system. Therefore the target is to allow the largest of such CHP units to participate in the regulating power market and contribute to the power balance in the Danish power system. Application of heat storage facilities calls for new techniques with regard to regulating power.[7] From a regulating point of view it is possible to start or shut down these CHP units by using the heat storage for decoupling heat and power production. Figure 11 shows the expected contribution from the distributed CHP units to the regulating power demands for the year 2005.

Other Domestic Arrangements

Better utilization of the domestic regulating power resources is among the vital arrangements for better power balancing. This includes, as explained above, better utilization of local CHP units, activation of load control according to the agreements with selected customers, activation of the power control of the large offshore wind farms, avoiding making 'clusters' of large offshore wind farms, etc. Establishment of the Great Belt Link will

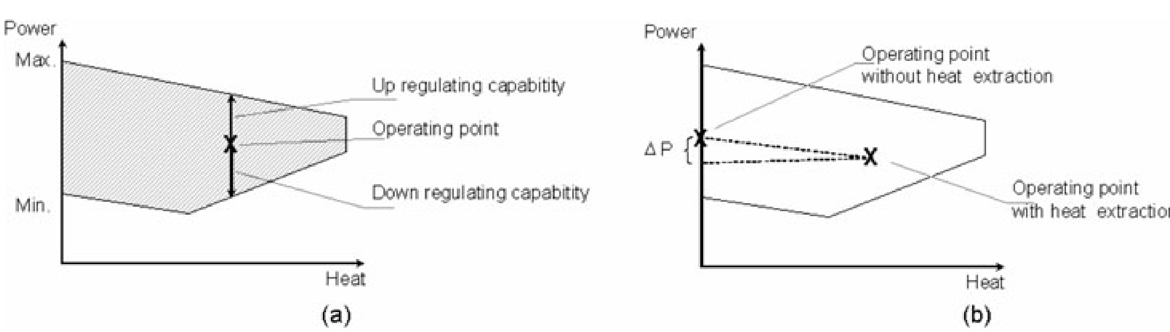

Figure 10. Operating range for the large thermal power plants as heat versus power diagram

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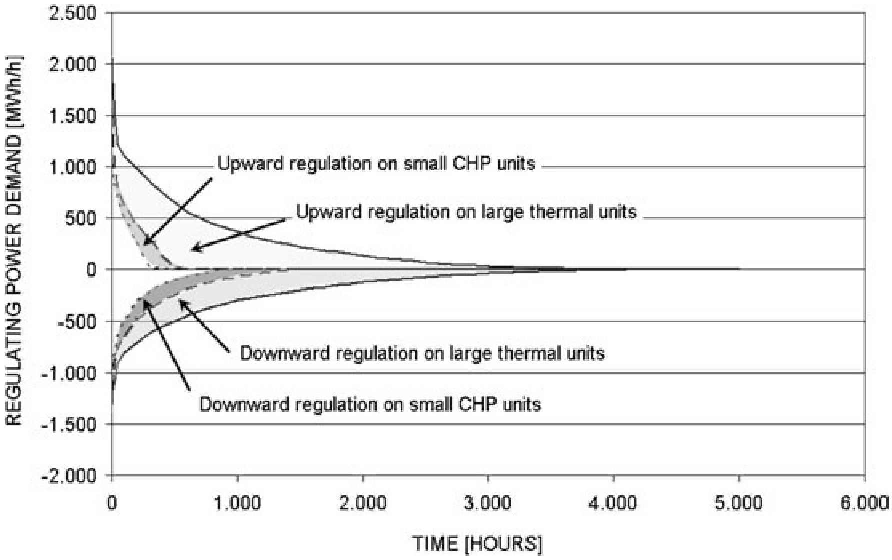

Figure 11. Needs for regulating power: duration curves for regulating power demand. Regulation by utilizing large thermal units (primary power plants) followed by utilization of small CHP units

make it possible to utilize the regulating power control incorporated in the eastern part of Denmark to work together with that established in Western Denmark.

Issue of Voltage Quality (Eastern Denmark)

The Horns Rev offshore wind farm has variable speed wind turbines equipped with doubly fed induction generators and partial load frequency converters. In such generators the active and the reactive power are controlled independently. Therefore significant active power fluctuations at Horns Rev do not lead to fluctuations of the reactive power or the grid voltage at the connection point of the wind farm.

The offshore wind farm NOWF has fixed speed wind turbines equipped with conventional induction generators.[9] In such electromechanical generators the active power supply and the reactive power absorption are strongly coupled. Then the active power fluctuations result in similar fluctuations of the reactive power absorption of this large offshore wind farm, and an insufficient dynamic reactive compensation may affect the grid voltage in the transmission grid of Eastern Denmark.

NOWF is connected to the 132 kV substation Radsted in the transmission grid of the Danish island of Lolland. This is the periphery of the eastern Danish transmission network, whereas the central power plants and the main consumption are located on the main island of Zealand with a strong transmission system. Prior to the commissioning of NOWF in the year 2003, the submarine cables between Zealand and Lolland were reinforced.[9] This was done in order to increase the thermal ratings in the grid and enable the grid to handle full production at the wind turbines also during outages in the grid. However, the reinforcements only increased the short-circuit level marginally, which is why the voltage in this area is still sensitive to reactive power fluctuations.

Figure 12 shows the active power fluctuations at NOWF resulting in grid voltage fluctuations at the 132 kV substation Radsted in a summer week in 2004. Usually the active power production is below 100 MW and so the voltage variations are relatively small. However, in periods with a high active power generation, there are voltage drops—such a drop occurs on day 4 of the week shown in Figure 12.

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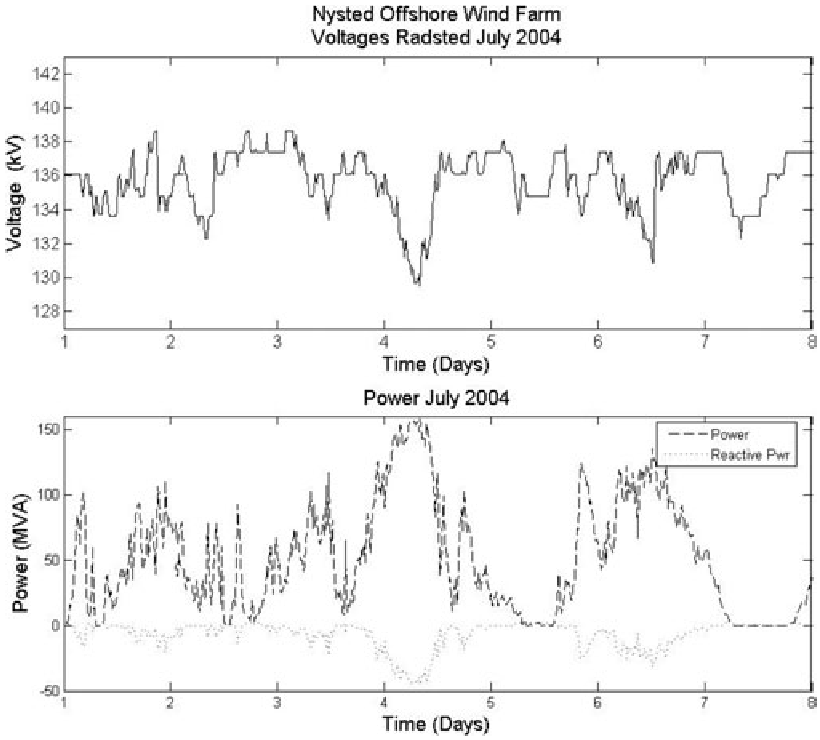

Figure 12. First week of July 2004: voltage in Radsted (top) and active/reactive power exchange between the offshore wind farm NOWF and the transmission system at Radsted (bottom)

Such voltage fluctuations can be distributed to other parts of the transmission system.[9] Figure 13 shows the voltages at two substations during a winter week in 2005. The first substation is Radsted, which is the 132 kV connection point of NOWF and distant from the 400 kV grid. The second substation is Spanager, which is close to the strong 400 kV backbone grid. Notice that the voltage fluctuations at Radsted are considerably larger than those at Spanager.

It has been decided to incorporate a static VAR compensator (SVC) unit at the 132 kV substation Radsted to reduce such undesired voltage fluctuations.[9] The SVC unit is the first of its kind in the Danish power system and is financed by the Danish Public Service Obligation (PSO) fund as part of a research programme to demonstrate the operation of dynamic reactive compensation together with a large offshore wind farm. The contractor is the power distribution company SEAS-NVE. The SVC unit will be delivered from the manufacturer Siemens TDP and have a rating of 85 MVAr.

Modelling and Ride-through Capability

Modelling of the electricity-producing wind turbines and evaluation of the ride-through capability of the large offshore wind farms are very relevant issues for short-term voltage stability. In common, the wind turbine models consist of the models of the generator applied in the wind turbine, the frequency converter, if any, the shaft system, the wind turbine rotor, the blade angle control, if any, and the protective system.[10] Energinet.dk has developed, implemented and validated the simulation models of different wind turbine concepts that are relevant for investigations of short-term voltage stability of the Danish transmission system. Usually the validation is made in co-operation with the wind turbine manufacturer.

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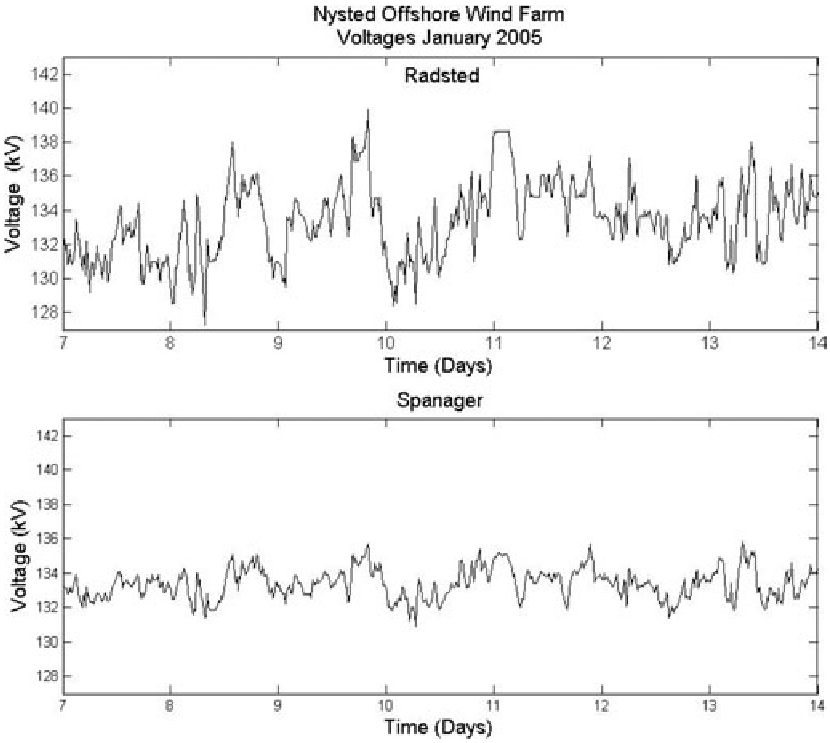

Figure 13. A winter week in 2005: voltage in Radsted (top) and in Spanager (bottom)

The *local wind turbines* are represented as fixed speed, equipped with induction generators. The local wind turbines may disconnect from the grid when the monitored parameter exceeds the relay setting.

The *Horns Rev A offshore wind farm* has pitch-controlled, variable speed wind turbines equipped with doubly fed induction generators and partial load frequency converters. Energinet.dk implemented the dynamic model of the wind farm and its controller in co-operation with the manufacturer Vestas Wind Systems and the consulting company Elsam Engineering on behalf of the power company Elsam. The wind farm model is validated from the measurements of Vestas Wind Systems from full-scale validation cases performed on simple test grids.

Recently, Energinet.dk had an opportunity to evaluate the interaction of the large wind farm model with the transmission system model from a short-circuit fault registered in the transmission system. The wind farm produced 89 MW when a single-phase, short-circuit fault occurred at a given 150 kV transmission line. Energinet.dk monitored the voltage and current in three phases at the substation Karlsgaarde, which are plotted in Figure 14(a). Then Energinet.dk performed computations with the use of the complete transmission net model, including the central power plants, consumption, the local wind turbines, the local CHP units and the dynamic model of HRA. The simulation results are plotted in Figure 14(b). The measured and simulation figures are in good agreement.

The *Nysted offshore wind farm* has active stall-controlled, fixed speed wind turbines equipped with asynchronous generators. The dynamic model was previously validated by measurements in co-operation with the wind turbine manufacturer Siemens Power Generation (formerly Bonus Energy).[11]

Owing to the significant amount of induction generator-based wind power on Lolland, this power grid may show a tendency to voltage collapse when subject to a three-phase, short-circuit fault.[12] To improve the short-term voltage stability, the power ramp control is applied to the Nysted offshore wind farm.[10,13] The power ramp control implies that the large wind farm is ordered to reduce the mechanical power of the wind turbine rotor

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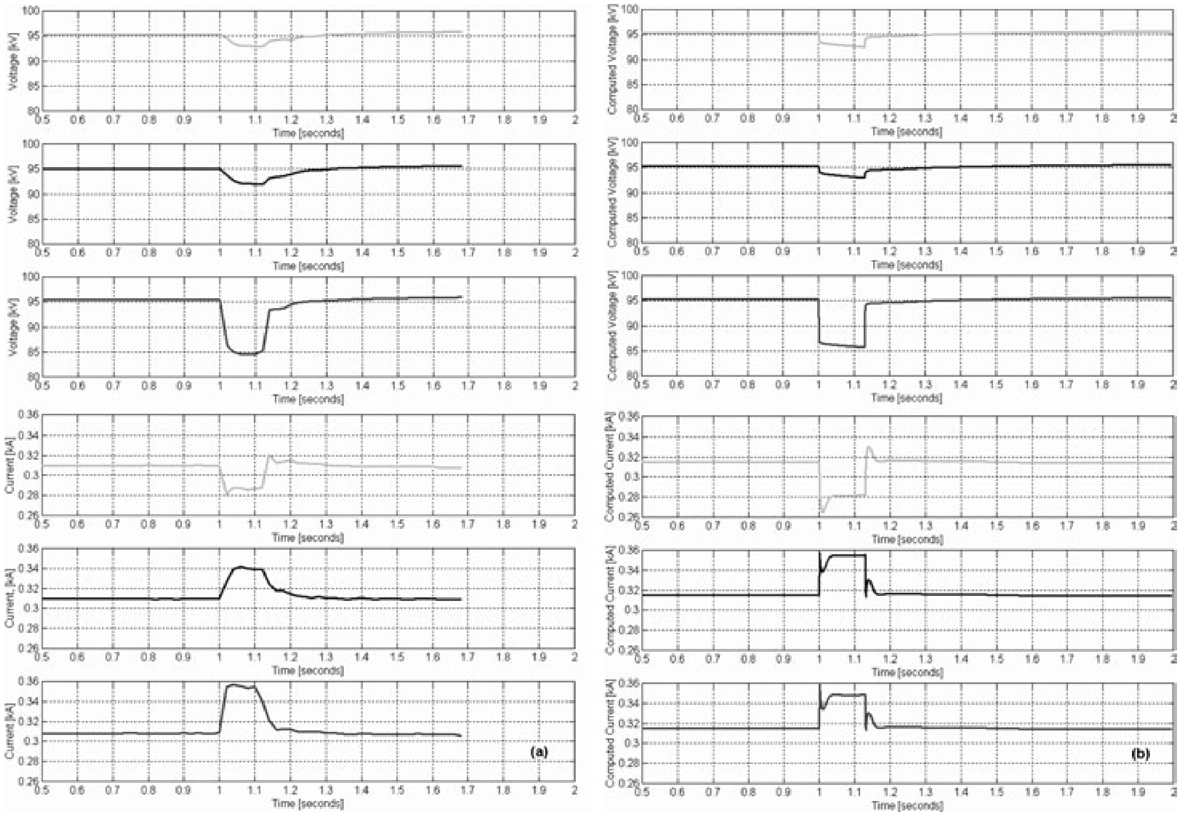

Figure 14. Voltage and current in three phases at the 150 kV substation Karlsgaarde: (a) measured with 20 ms sampling; (b) simulated

from an arbitrary level down to 20% of the rated power in less than 2 s.[4] The power ramp control stabilizes the operation of the large offshore wind farm, leading to voltage restoration. Figure 15 illustrates the operation of the large offshore wind farm with application of the power ramp at a severe short-circuit fault. The power ramp is realized with the use of active stall control of the wind turbines.

The modelling work is essential for collecting the Danish experience on interaction between the large offshore wind farms and the transmission system. Involving the wind turbine manufacturers in the modelling work is valuable for the Danish TSO, because it provides unique information about the newest ride-through solutions that is not accessible from other sources. Co-operation with the Danish TSO has also been useful for the wind turbine manufacturers, because it helps the manufacturers with understanding how the large power systems operate and what challenges the large offshore wind farms may introduce to the power systems. From the point of view of the Danish TSO, this may be interpreted as a win–win situation for both sides.

Summary

Presently, about 20% of the annual electric energy consumption in Denmark is covered by wind power. The proportion of wind power in the Danish electric power supply continues to increase. The largest proportion of grid-connected wind power is in the local wind turbines on land in the western part of Denmark. However, the largest increase in wind power in Denmark will come from the commissioning of large offshore wind farms, with the main projects in the North Sea/Western Denmark. Energinet.dk, the national TSO of Denmark, must

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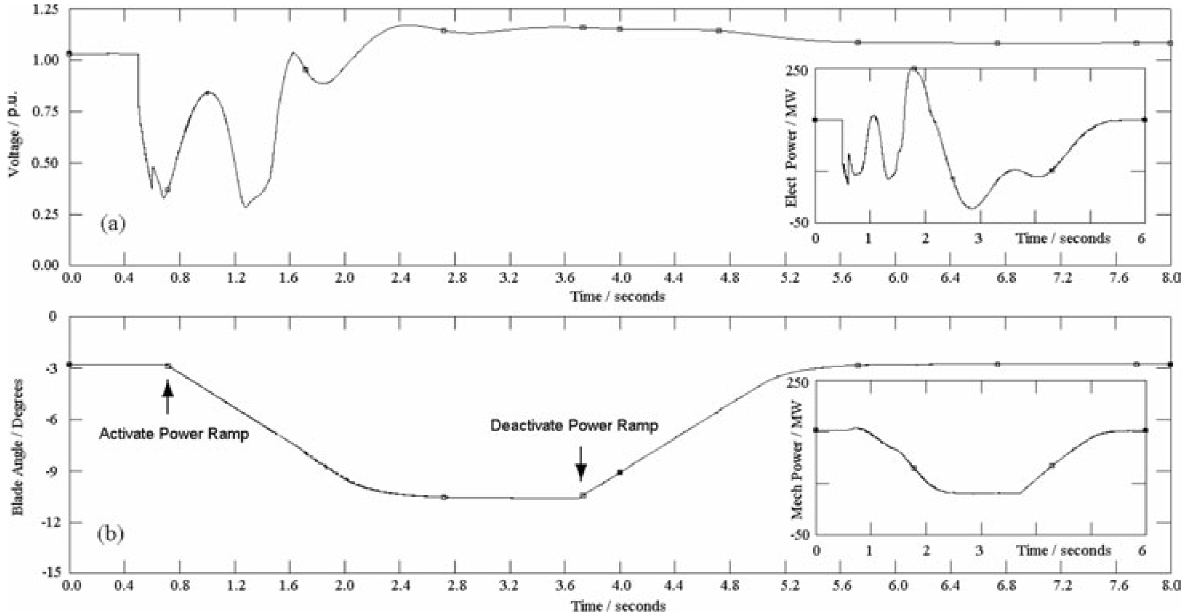

Figure 15. Ride-through operation using the power ramp control: (a) voltage and active power as insertion; (b) blade angle control and mechanical power as insertion

ensure stable, reliable and economic operation of the Danish transmission system despite the massive incorporation of wind power.

Energinet.dk has formulated the technical specifications for connection of the electricity-producing wind turbines (the large offshore wind farms to the high-voltage transmission networks as well as the local wind turbines to the distribution networks). Among the main requirements of the technical specifications are maintainance of the grid voltage stability, the ride-through capability, the active power control and adjustment to the desired level or by the desired gradient limit.

The western and eastern parts of Denmark have experienced different kinds of problems with regard to wind power. In Eastern Denmark, intense commissioning of wind power has taken place in the weak transmission system of the islands of Lolland and Falster. In combination with the fixed speed wind technology and the wind fluctuations at the Nysted offshore wind farm, this has resulted in grid voltage fluctuations. Such voltage fluctuations are distributed to other parts of the transmission system of Eastern Denmark. The voltage fluctuations occur owing to insufficient dynamic reactive power control. Incorporation of an SVC unit at the wind farm connection point showed minimize such undesired voltage fluctuations.

Keeping the power balance is the main issue for the western part of Denmark. Therefore it focuses on constant improvement of the wind and power forecast methods. Such wind and power forecasts can be made for a day ahead or a few hours ahead.

Experience from operation of the offshore wind farm Horns Rev A in Western Denmark shows the frequent occurrence of intense active power fluctuations within periods of tens of minutes. The power gradients may reach values of 15 MW min^{-1} for the 160 MW wind farm, resulting in the generated power changing between zero and rated power in 10–15 min. Such power fluctuations are introduced into the transmission system in an uncontrolled manner and may be distributed to neighbouring transmission systems. As the applied wind turbines have doubly fed generators with independent active and reactive power control, the active power fluctuations do not start similar intense voltage fluctuations.

The Danish power system has a sufficient amount of regulating power to compensate for such intense power fluctuations from Horns Rev A. However, introduction of the new settlement model for power exchange

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through the HVDC links with the Nordel synchronous area will require better and more intense use of domestic regulating power (thermal). Commissioning of the second offshore wind farm Horns Rev B just 5–10 km from the existing wind farm Horns Rev A may introduce problems with regard to compensation of the power fluctuations from these two wind farms using the domestic regulating power only. In part, such power fluctuations can be reduced by the control applied to the large offshore wind farms themselves. For example, application of the power gradient limit will reduce the up-going power gradients. Already at this stage, use of the HVDC connections will be necessary to keep the power balance in the western Danish power system. Revision of the present settlement agreement and access to the fast power control of the hydro power plants in the Nordel synchronous area may be an additional option to be investigated.

Incorporation of more wind power in the North Sea and maintenance of the power balance in Western Denmark require focus on the necessary regulating power. Better utilization of the domestic regulating power resources is vital. This includes better utilization of local CHP units, activation of load control according to the agreements with selected customers, activation of the power control of the large offshore wind farms, avoiding making 'clusters' of large offshore wind farms, etc. Establishment of the Great Belt Link will make it possible to utilize the regulating power control incorporated in the eastern part of Denmark to work together with that established in Western Denmark.

Incorporation of more wind power in the North Sea requires international co-operation and global thinking. Access to the fast power control of the hydro power of the Nordel synchronous area will improve the power balance in Western Denmark. Further, establishment of an offshore transmission system connecting future large offshore wind farms of different nationalities with the grids of Norway, Denmark, Germany and The Netherlands may be a future viable strategy for complying with large-scale wind power in international co-operation.

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