Technical University of Denmark

DTU

Report with data for system behaviour at storm passage with original (uncoordinated) and coordinated control
Deliverable no: 12.2

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Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Detlefsen, N., Litong-Palima, M., Cutululis, N. A., Farahmand, H., Huertas-Hernando, D., & Sørensen, P. E. (2013). *Report with data for system behaviour at storm passage with original (uncoordinated) and coordinated control: Deliverable no: 12.2.*

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"Report with data for system behaviour at storm passage with original (uncoordinated) and coordinated control"
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Assessment of storm forecast

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Document info sheet

Document Name:	D12.2
Responsible Partner:	DTU
WP:	12
Task:	12.3
Deliverable nº	12.2
Revision:	01
Revision Date:	27.04.2013

Diffusion list

All Partners

Approvals

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Assessment of storm forecast

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1   EXECUTIVE SUMMARY

In this report the focus has been on explaining the operational procedures that are important in order to maintain balance in the electricity system to understand how unexpected events are handled. The unexpected events discussed in this demo are sudden unexpected loss of wind power production due to stormy weather conditions. When handling the system it is important both to have good forecasts of wind power production so that the wind power production can be anticipated as precise as possible as early as possible so that regulating power can be activated to restore the anticipated balance. In addition it is important to have access to enough automatic restoration reserves to restore balance when unanticipated deviations from schedules occur. What the trade-off between these two types of reserves should be is an on-going discussion.

During the duration of the project, several high wind speed events were recorded at Horns Rev 2, with both the High Wind Shut Down (HWSD) controller and the High Wind Ride Through™ (HWRT) controller which was developed in this project. The analysis presented in this report has shown that when the wind turbines are equipped with HWRT, the maximal wind power forecast error decreases with more than 50%. Similarly, the energy production during the high wind events increased with the HWRT controller compared to the HWSD controller, although the amounts are negligible compared to the yearly production.

The storm front event on February 7th -8th, 2011, which was followed by the unexpected failure on HVDC line between Western Denmark and Sweden, illustrates the consequences and challenges the power system faced/will face in the future when these events (will) occur. The measured values indicate that the large part of the imbalances caused by storm is compensated by exchanged balancing power, activated from the NOIS list, across Konti-Skan link. This shows the pivotal role of hydro power in the Nordic system to balance large wind power variations in Western Denmark especially during the storm events. However, the frequency in the Nordic system experienced large deviations due to large deviation on exchange across Konti-Skan link.

2   Introduction

From a system perspective the effect of losing power due to a storm is no different from other events causing loss of power in the system as ex. failures of interconnectors or power plants. The challenge for the system is a sudden unexpected change in production and/or consumption. Therefore, from a systems viewpoint, it is important to quantify the magnitude of sudden change of power due to storms. The quality of the forecasts is important for the system in order to anticipate a change in production and therefore take action accordingly by for example activating regulating power or even start up production if necessary. In addition, to avoid really fast changes in production it is important if the amount increases radically compared to today. For the time being the amount that Western Denmark is in danger of losing in a very short time due to stormy conditions is much less than the size of the largest unit. Since the system is prepared to lose the largest unit there are

reserves enough in the system to maintain balance during storms. Therefore storms are presently not considered to cause severe problems in the Western Danish system.

This report is on implications for the transmission system of events where uncontrolled variable production changes fast as can be the case in storm situations for large offshore wind power plants. In the future the nature of the production mix is expected to change since most countries have plans to integrate large amounts of wind power in addition to large amount of photovoltaic production. Understanding the important operational processes of today's system is necessary in order to develop the future transmission system in an optimal way. In this report data for the system is reported for 6 storms events at Horns Rev 2 (also referred to as HR2). Horns Rev 2 is located off the west cost of West Denmark, see Figure 1.
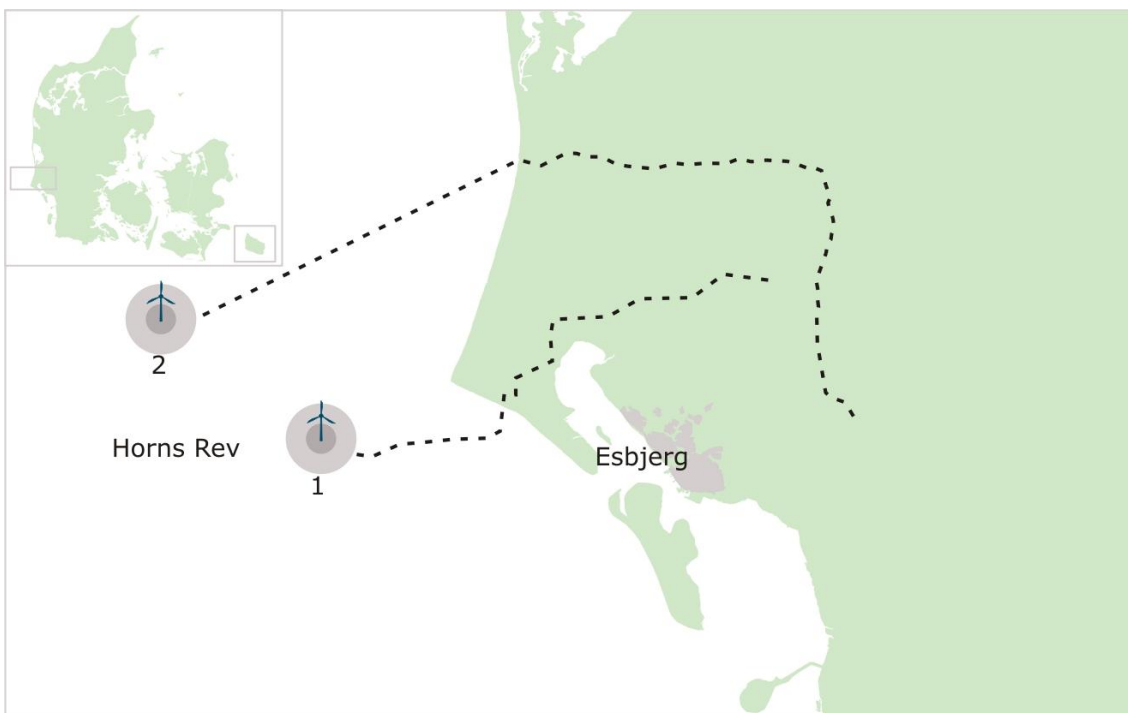

Figure 1: Horns Rev 2 wind farm

The wind farm is owned by DONG Energy and the turbines are supplied by Siemens and are of the type SWP 2.3-93. Each wind turbine has a capacity of 2.3MW. With a total of 91 wind turbines the wind farm has an overall capacity of 209MW. The wind farm became fully operational in September 2009.

The observed storm events will be discussed and relevant details are reported.

In order to understand the system implications related to storm events it is important to have some understanding of the Nordic electricity system and the electricity markets involved. Therefore an introduction

to the Nordic and Danish power system is given first. Then a description is given of the markets in which the power is traded. Then the report focuses on 6 storm events where detailed data for the system is collected. Especially one of these storms is discussed in detail since there was a failure of the HVDC connection to Norway following the storm.

3   Danish/Nordic power system

The interconnected Nordic system is made up of four national control areas: Norway, Sweden, Denmark, and Finland, where a different TSO is responsible for the security of supply and balancing between production and consumption in each of the countries. These TSOs are: Statnett SF in Norway, Svenska Kraftnät in Sweden, Energinet.dk in Denmark, and Fingrid in Finland. Table 1 gives an overview on the state of power generation and consumption in the Nordic countries (Source: NordPool Spot market data).

Table 1. Overview on power generation and consumption in the Nordic countries in 2012

	Nordic	Denmark	Finland	Norway	Sweden
Population (mill.)	**25.5**	5.6	5.4	5.0	9.5
Total consumption (TWh)	**396.1**	33.8	82.9	128.2	141.7
Maximum load in 2012 (GW)	**68.8**	6.1	14.3	23.4	26.5
Electricity generation (TWh)	**402.3**	28.7	65.7	146.3	161.6

The Nordic power supply is dominated by hydro, but also conventional fossil fuel and nuclear generation plays an important role. Norway covers most of the consumption with hydro power generation. Sweden and Finland have a mixture of hydro power, nuclear power and conventional thermal power generation. In both countries, hydro power stations are mainly located in the northern areas. The southern areas are, however, dominated by thermal power stations. Also, consumption is concentrated in the southern areas in the Nordic countries. In Denmark, conventional thermal power plants and Combined Heat and Power (CHP) plants provide much of the need for energy, along with a considerable contribution from wind power production. In 2012 the total wind power production in Denmark summed to 30% of the total consumption (source Energinet.dk webpage).

Detailed system data for 2011 is shown in Table 2 (Source: ENTSO-E SAR data 2011).

Table 2. Generation portfolio in the Nordic countries in 2011

	Nordic	Denmark	Finland	Norway	Sweden
Installed capacity (MW)	96824	11644	17110	31639	36431
Hydro power (MW)	49448	9	3160	30079	16200
Fossil fuels (MW)	22270	7156	8970	1026	5118

Nuclear power (MW)	12043	-	2680	-	9363
Wind power (MW)	7379	3745	200	534	2900
Bio fuel (MW)	5624	734	2040	-	2850

As hydropower dominates the system and the annual hydro generation capability may vary significantly from year to year, cross-border transmission capacity for electricity import and export is a key element for reliable and efficient operation of power system. The main cross-border transmission capacities are shown in Figure 2. The interconnections are divided into overhead AC transmission lines and HVDC submarine cables. The capacities as of October 1st, 2012 are indicated on the map (Source: NordPool Spot market data).

Figure 2. Main cross-border transmission capacities given as aggregated values, Source: NordPool Spot market data

Western Denmark is synchronised with the central European power system, and is interconnected to the Nordic system through HVDC links. Therefore, the frequency in Western Denmark is not affected by the rest of the Nordic system's imbalances. However, Western Denmark takes part pro-actively in the Nordic frequency control by delivering and using the balancing services through HVDC links.

4 Nordic Electricity Market

The Danish electricity market is an integrated part of the common Nordic Electricity Market. The power exchange, Nord Pool Spot [6], facilitates both the common day-ahead and the common intraday market for the Nordic countries where the different Market Players can trade. Beside these two markets, the Nordic countries have a common regulating power market, organised by the Nordic Transmission System Operators (TSOs). On the regulating power market the Nordic TSOs trade tertiary regulating power. The different markets are illustrated on a time horizon in Figure 3. First the day-ahead market opens, after its gate closure the intraday market opens and finally the regulating power market can be used by the TSOs to manage the real-time balancing.
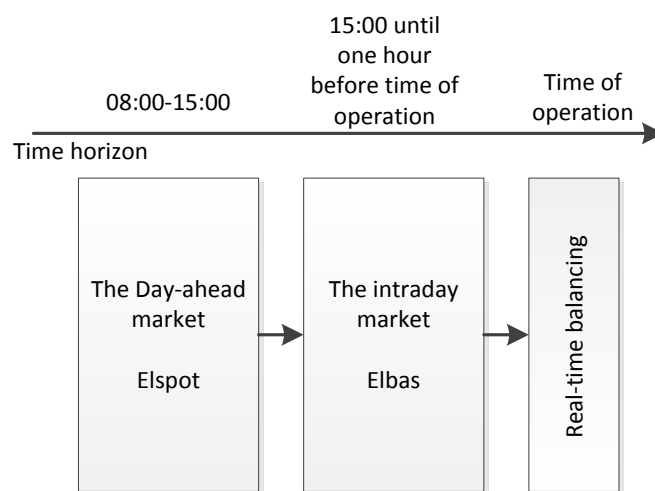
Figure 3. Markets.

4.1 The day-ahead market - Elspot

The day-ahead market, Elspot, within the Nordic Countries is a market where contracts for delivery of energy for the following day are made. The gate closure for submitting orders to Elspot is 12:00 p.m. the day before *the day of operation.* There is a high liquidity or volume in the market since it is where the larger part of the electricity is traded within the Nordic countries. Figure 4 is an overview of the operational settings surrounding the day-ahead market.
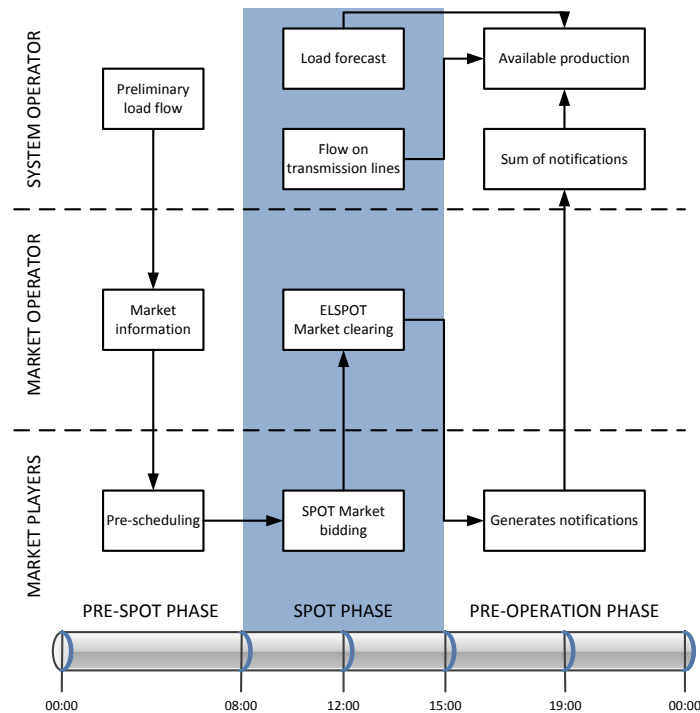

Figure 4. The operational settings of the day-ahead market.

The figure shows three phases; pre-spot, spot and pre-operation. *Pre-spot* is where information is shared between TSOs, Market Operators and Market Players. An example of shared information is transfer capacity between markets nodes. The *spot* phase is where the contracts between sellers and buyers are agreed upon. All Market Players submit bids to the market with an amount of energy and a corresponding price for each hour in the day of operation. The market is cleared by equilibrium between production and consumption for each hour. Subsequently the equilibrium price in an hour is determined by the highest price for activated production. All the energy is then traded to this price in the corresponding hour (marginal pricing). The *pre-operation* phase is where the Market Players are informed on which of their bids that are activated. When notified, the producers and consumers have to submit a schedule for the energy production/consumption for each of their units for the entire day of operation to the local TSO.

4.2 The intraday market – Elbas

Since Elspot closes between 12 and 36 hours before the time of operation it is not certain that the contracts made on Elspot are still optimal or even feasible for the Market Players closer to *the hour of operation*. Take for example a wind producer, he is not able to predict precisely which amount of energy he is going to produce the following day, in fact, the forecast error is smaller the closer you get to the time of operation. Therefore, it could be beneficial for the wind producer to trade in the intraday market such that he has a smaller risk of not fulfilling his contracts and therefore has to pay fewer penalties for not fulfilling contracts. Outages on interconnection lines or production units can likewise give incentives for Market Players to trade in the intraday market. Thus, the purpose of Elbas is to make it possible for Market Players to buy and sell energy closer to the hour of operation in order for them to be able to minimize deviations from contracts.
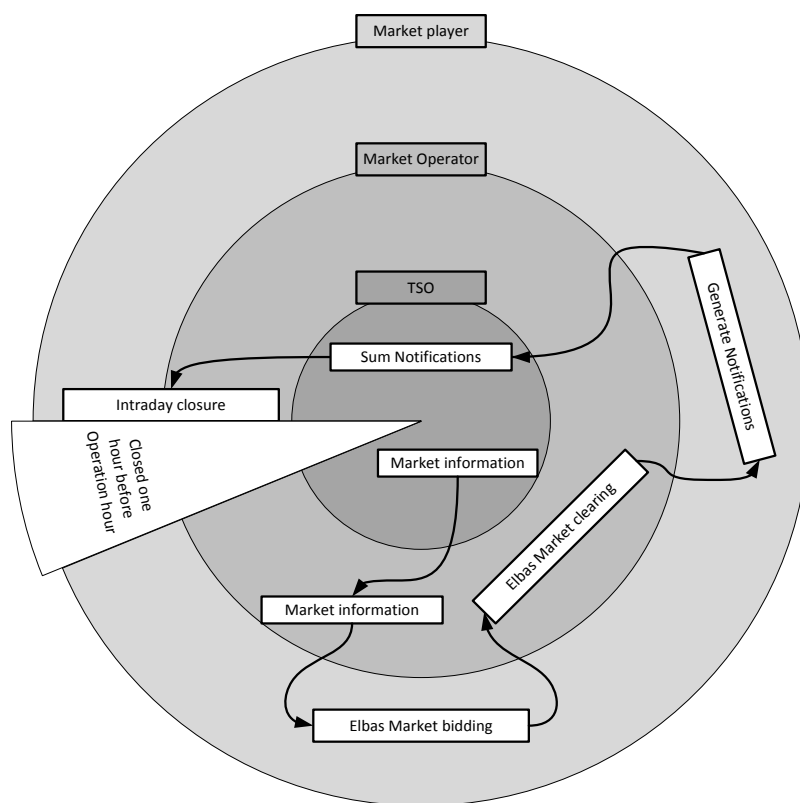
Figure 5. The aspects of the intraday market

Figure 5 gives an overview of the flow of information in the intraday market. The market opens at 15:00 and it closes one hour before the hour of operation. Before opening, the Market Operator (in this case Nord Pool Spot) gathers information relevant for Market Players to give bids to the market fx. free capacity on transmission lines. Then the Market Players can submit bids and contracts are made based on the pay-as-bid

principle. When a contract is made, new production schedules for the involved units have to be submitted to the TSO.

4.3 The regulating market - NOIS

After gate closure of the intraday market, Elbas, Market Players do not have the opportunity to trade electricity anymore and thereby change their position. If a Market Player is not able to fulfil his contract at this point, we say he is in imbalance. When we reach the hour of operation the balance of the system is calculated by summing up the imbalances of all the participants. Contracts made in the day-ahead and intraday market are based on hourly amounts. The conversion of these hourly amounts down to real time production can also cause imbalances in the electricity system. This is due to ramping restrictions on both production units and transmission lines in addition to fluctuating wind power and consumption during the hour. So even in the case where no Market Player is in imbalance there might be short periods during the hour where the system experiences an imbalance.

However, it is important that production and consumption is balanced constantly. Therefore, after gate closure of Elbas it is the task of the local TSO to ensure balance in the electricity system. They can keep the balance by activating additional production or reduce consumption (upward regulation) or they can reduce the production or increase consumption (downward regulation). However, a TSO does not own any production units and therefore they have to buy the upward or downward regulation from producers or consumers. This upward or downward regulation is bought by the TSO in the regulating power market, NOIS (Nordic Operational Information System).

NOIS is common for the Nordic countries and a TSO can activate bids outside its local area as long as there is available capacity on the transmission lines connecting the local area with the area holding the bid. If a bid is activated by a TSO the producer has 15 minutes before the bid has to be fully activated and transported to the area. This way Western Denmark can activate regulating power from a Hydro Power Plant in Norway.

The price settlement is marginal pricing, which means that all the activated bids for upward regulation in one hour get the price of the marginal bid that is activated. The same principle holds for downward regulation; here all the activated bids pay the smallest price of all the activated bids. First the TSO pay for upward regulation, and receives money for downward regulation but in the end the participants that cause the imbalance end paying the balancing costs. In reality the producers earn money on downward regulation, since they have sold the energy in the day-ahead market at the day-ahead price, then the producer "buys" the energy back from the TSO to a smaller price than the day-ahead price and therefore the producers earns the difference between the day-ahead and regulating price by doing nothing.

In a perfect market, where all bids are based on marginal cost and gaming is non-existent, the regulating power market is just as cheap as the intraday market. In this case, the incentive for a Market Player to trade imbalance in the intraday market instead of letting the TSO take care of the imbalance in the balancing market is much less. The risk for the Market Player is to trade their own imbalance in a situation it would not have been necessary because other Players had opposite imbalances. The pricing in the regulating power market where there is much more competition is most probably lower than in the intraday market.

5 Balance management in the Danish power system

In this section the principles of balance management in Denmark is described. In general the TSO's should balance the power in the areas they are responsible for. Optimally power should only be balanced in the areas where, if not balanced, it will create congestions in the underlying network. In Denmark we balance the area of Western Denmark and Eastern Denmark separately. In Eastern Denmark agreement has been made that balance is not maintained for Eastern Denmark only but the whole Nordic area is balanced as one area – as long as there are no congestions in the area. If there are congestions in ex. the Swedish network they can ask Eastern Denmark to maintain the balance on the interconnector in order to not increase congestions. In Western Denmark balance has to be maintained towards the border of Germany. Negotiations have been initiated in order to optimize the combined system as long as there are no congestions. No agreements have been committed on this yet.

The following will concentrate on the processes involved in balance management in Western Denmark. Many of the principles works for Eastern Denmark, but with slightly different time resolutions and only if Energinet.dk is asked to do so.

In Western Denmark detailed schedules for production, consumption and flows on interconnectors are available at all times. Market participants are obliged to send their most updated schedule for a given day to Energinet.dk at all times starting after they get a notification from Elspot. If trades are made in the Elbas market the participants just change their schedules and send in new ones. These notifications have a 5-min resolution; they are power-schedules and can be considered as snapshots of the power system every 5 minutes. This means that thermal production will send in 5-min schedules for planned production. Offshore wind parks are considered large units and the power producer is obliged to send in detailed schedules. The producer will base these schedules on forecasts. For the interconnectors Energinet.dk will generate detailed schedules respecting the ramping rules. Towards Nordic countries and between the Danish areas ramping happens at hour shift +/- 15 minutes at present. Towards Germany ramping happens at hour shift +/- 5 minutes. This means that if there is big change in transit from Nordic countries to Germany this can cause temporarily (~ 5-10 minutes) large imbalances in the Western Danish system. For onshore wind power the

market participants can chose to let Energinet.dk generate detailed schedules based on forecasts. The same applies for consumption where Energinet.dk also generates detailed schedules based on forecasts.

All the schedules are added and the result is an expected (im-) balance. Based on this expectation, actions can be taken, ex. activation of regulating power via the NOIS list.

Energinet.dk uses the detailed schedules to anticipate large problems in the system. By continuously monitoring the expectations for imbalances in the system in the next hour large imbalances is reduced by activating manual regulating power in due time. This way the imbalances are reduced already before they happen and will never be seen in the system. Traditionally reserves are used such that when an imbalance is seen, primary reserves are activated to restore frequency, then automatic (slow) reserves are activated to free the primary reserves and finally manual (slow) reserves are activated to free the secondary reserves so that the system is prepared for the next event. In addition to this way of using the reserves, Energinet.dk also minimizes the realized imbalances by continuously updating schedules and anticipating the imbalances in the system. This way of activating regulating power when imbalances are foreseen in the near future, is also used in Eastern Denmark when the area needs to reduce imbalances towards Sweden.

As already noted, when activating manual regulating power the bids shall be fully activated within 15 minutes. This means that all imbalances could be balanced by manual regulating power if:
- wind power, solar power and consumption could be forecasted perfectly 15 minutes before the operational minute
- there are no restrictions to activation of bids (size and time)
- all producers followed their schedules perfectly.

However, this is not the case today and probably will never be.

The Elbas market for a given operational hour closes one hour prior to the operational hour. About an hour before the hour of operation participants in the regulating power market are allowed to change their bids (price and volume). The operational procedures for the time being is that half an hour prior to the hour of operation the system balance is calculated and 15 minutes before the operational hour regulating power is activated. Within the operational hour forecasts and schedules are updated continuously and adjustments are made if needed. If for instance there is an outage causing a sudden deviation one will act upon this. This is in line with the traditional use of reserves. However, the operator also monitor the system continuously and if he experiences that the balance is not maintained within a band due to unexplainable factors he will activate regulating power within the operational hour.

For the case of storm management from a system perspective the important issue is how much actual production can deviate from a schedule for an off shore wind power plant. Two time frames are important.

First the main balancing routine is based on the forecast available 30 minutes before the operational hour, secondly the continuous evaluation of the need for adjustment is based on the available forecasts. However, the activation of regulating power has a lead time of 15 minutes. If we can forecast the production 15 minutes or more in advance then the anticipated reduction off shore wind can be neutralized by activating regulating power. Due to other restrictions and manual interference it is not possible to activate small amounts of regulating power continuously.

Within Demo 4 a new controller has been developed where the turbines keep producing at higher wind speeds and when the power is reduced due to high wind speeds this happens more gradually. This new controller from Siemens is referred to as High Wind Ride Through (HWRT), se Deliverable 12.1 for a detailed description. The HWRT controller will have an impact on the anticipated balance in the system and this will be described in the sections to follow.

6   Case studies/Recorded events

Several events with very high wind speed occurred during the project period - both before installing the High Wind Ride Through™ (HWRT) controller and after. In total, six events were recorded and will be presented in this section. Dates for the recorded events are presented in Table 3, where it is also indicated which storm controller was installed at Horns Rev 2 wind farm at that time of the event.

Table 3 Recorded high wind events

Event nr	Date	Controller
1	11-Nov-10	HWSD
2	12-Nov-10	HWSD
3	07-Feb-11	HWSD
4	24-Sep-12	HWRT
5	14-Dec-12	HWRT
6	30-Jan-13	HWRT

Legend:
HWSD - High Wind Shut Down;
HWRT - High Wind Ride Through

The HRWT controller was developed, implemented and tested by Siemens Wind Power [9]. The dynamic controller consists of two systems working in parallel: the first one curtails the rotor speed based on the rotor acceleration, while the second curtails the power based on the pitch angle. For the work presented here, the High Wind Ride Through™ controller was parameterized in the form of power curve, in a manner similar to the HWSD control. The wind turbine power curves corresponding to the two control strategies are presented in Figure 6 and Figure 7. The wind speed value is defining the behavior of the wind turbine. The wind speed

thresholds for which the wind turbine will shut down, indicated with dotted lines and down pointing arrows in the figures, are based on the instantaneous wind speed (32 and 39 m/s, respectively), the 30 sec. mean value (28 and 34 m/s) and the 10 min mean value (25 and 30 m/s).
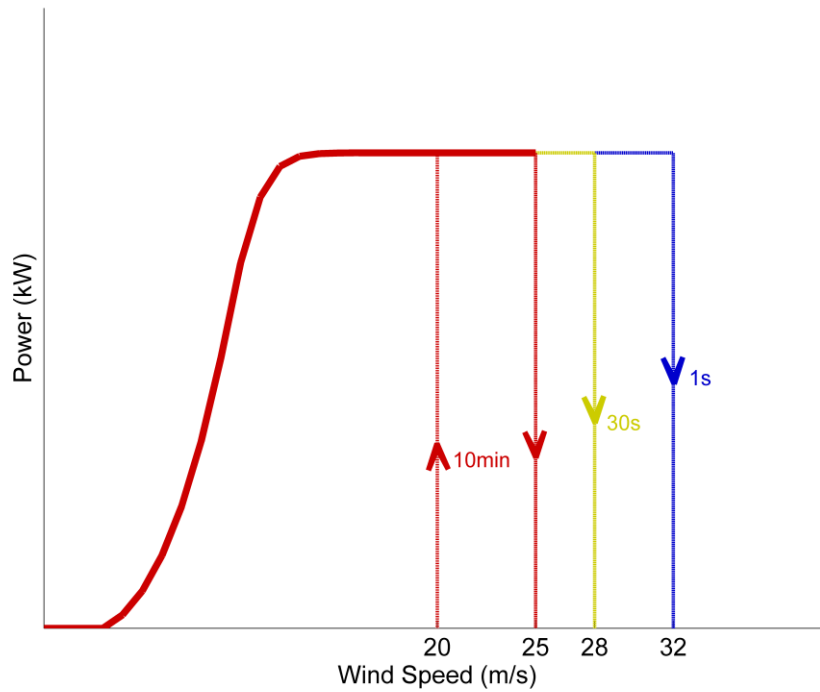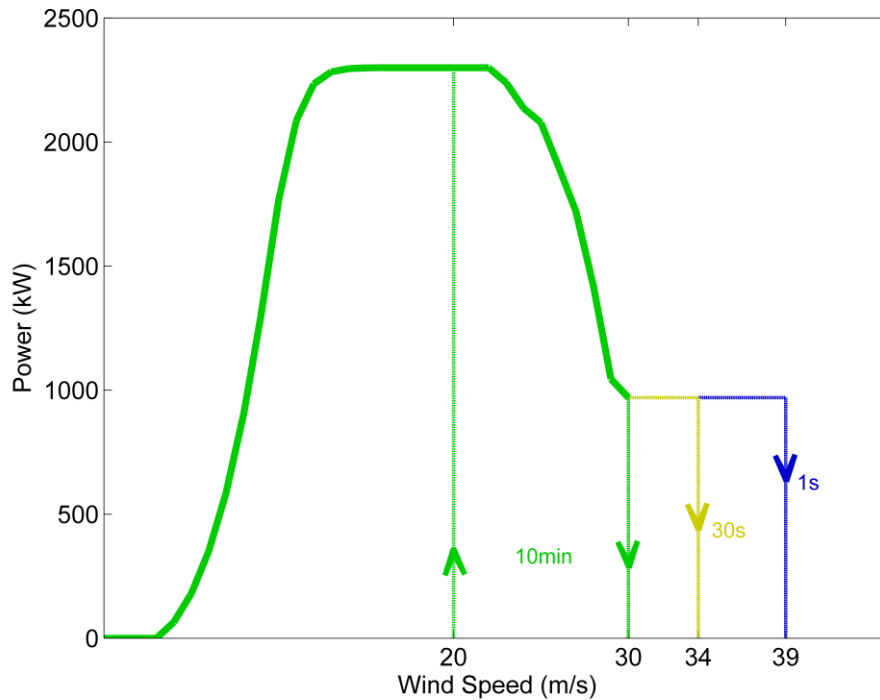

Figure 6. HWSD power curve

Figure 7. HWRT power curve

In both controllers, after a shut-down, the wind turbine will start again when the 10 min mean wind speed will go down to 20 m/s (dotted line with an up arrow in both figures).

Based on both power curves and wind speed measurements from the individual turbines it is possible to simulate output from the wind park. The simulations can then be evaluated for the controller in operation during specific storms.

6.1.1 Event 1 – 11 November 2010

The event happened in the afternoon of 11th of November 2010.

In Figure 8 the average wind speed of all 91 turbines is indicated by the black line. It is worth to note that the average farm wind speed did not exceed the 25 m/s threshold. Nevertheless, the wind speeds at the individual wind turbines reached the thresholds, resulting in their shut down and consequently, the total wind farm output dropped down to zero (blue line in Figure 8). Using the HWRT based power curve (Figure 7) and the wind speeds measured at the wind turbines, the wind farm output with the HWRT controller was simulated. The result is the green curve in Figure 8, indicating that the wind farm output would have been very close to maximum during the whole period of high wind speed.
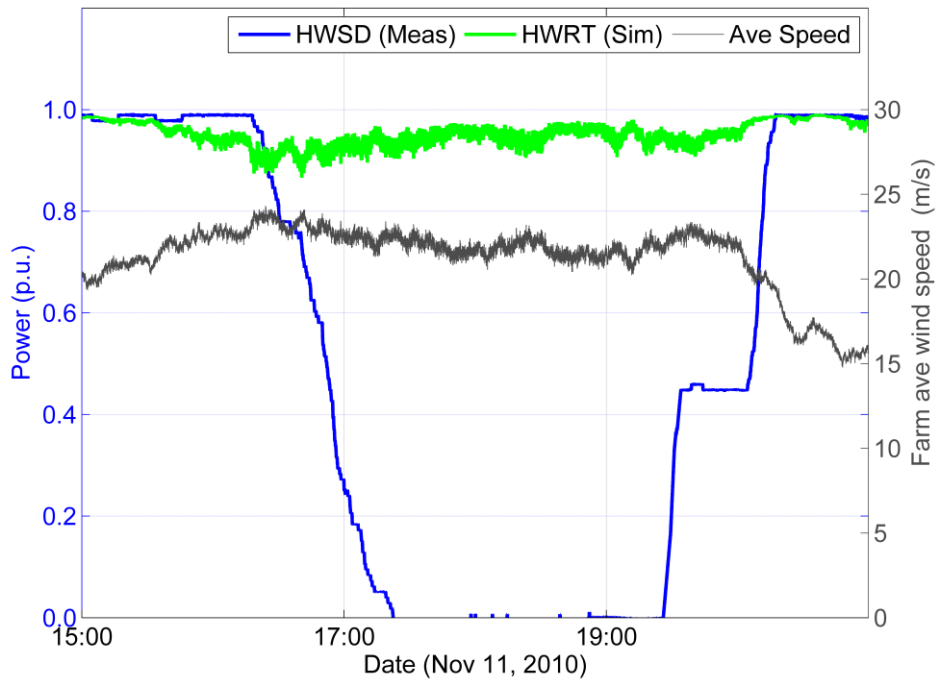
Figure 8. High wind speed event on November 11, 2010

6.1.2   Event 2 – 12 November 2010

The second event recorded during the project followed shortly after the first one, in the morning of November 12th, 2010. The wind speed level is similar to the one the evening before. Also in this case did output from the wind farm power with HWSD controller drop to zero (blue curve), while the simulation with the HWRT controller show that the wind farm output would have been practically insensitive to the high wind speed, producing very close to maximum for the whole period (green curve).
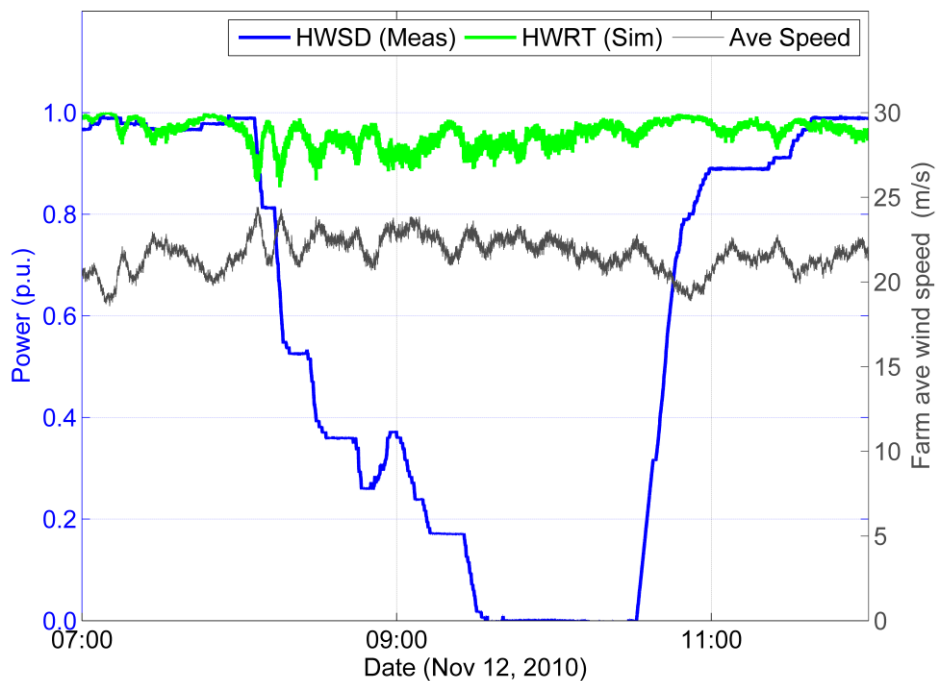
Figure 9. High wind speed event, November 12, 2010

6.1.3   Event 3 – 7-8 February 2011

The third event recorded during the project period happened during the night between 7th and 8th of February 2011. This event was significantly more intense than the previous two, with the wind farm average wind speed getting close to 28 m/s (black line in Figure 11). In Figure 10 the wind speeds from the individual turbines is plotted, the blue line is the average of all turbines and the red lines indicates the minimum and maximum. Minute-values are plotted. In can be seen that at wind turbine level, there were moments in which the value of the instantaneous wind speed went close to 40 m/s in one or a few turbines. The wind farm power output dropped down to zero with a significant slope, as the blue curve in Figure 11 shows. Even with the HWRT controller, some of the wind turbines would have stopped, resulting in a wind farm power output drop in the range of 40% (green curve).

This high wind speed event was so intense, that it affected the wind power production over whole Denmark. The overall wind power production in Denmark, during that period, is shown in Figure 12. It can be seen that the high wind speed front moved over Denmark, stopping a significant part of the wind turbines, offshore and onshore, causing a 50 % drop in the power production.
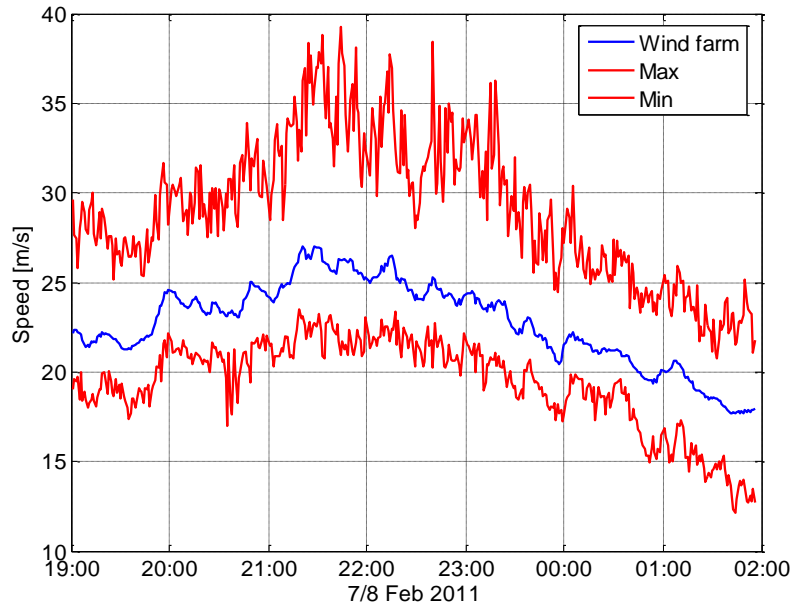
Figure 10. Measured wind speeds, February 7-8, 2011
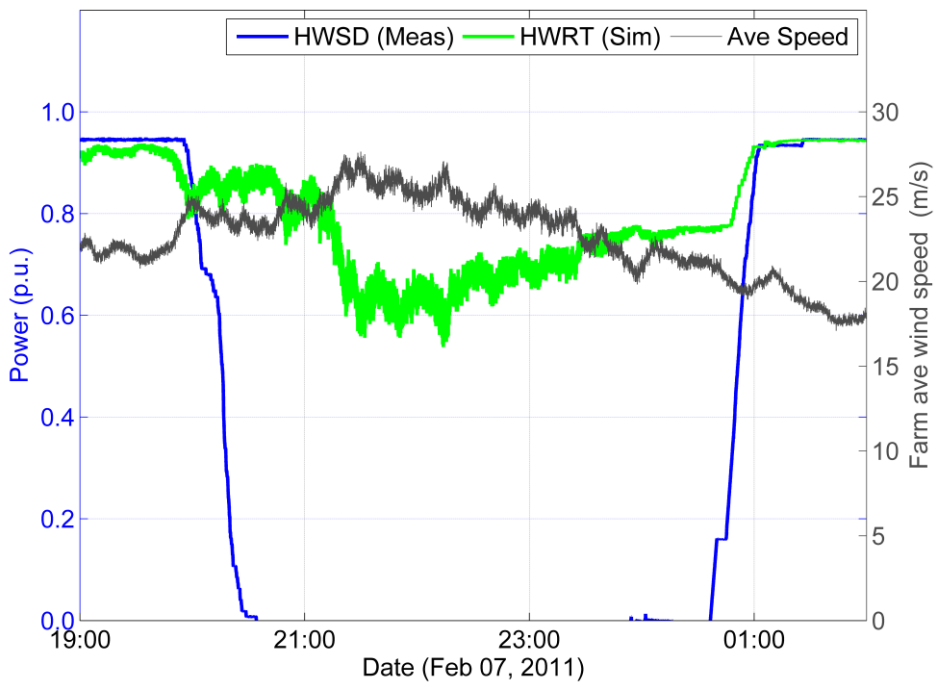
Figure 11. High wind speed event, February 7-8, 2011
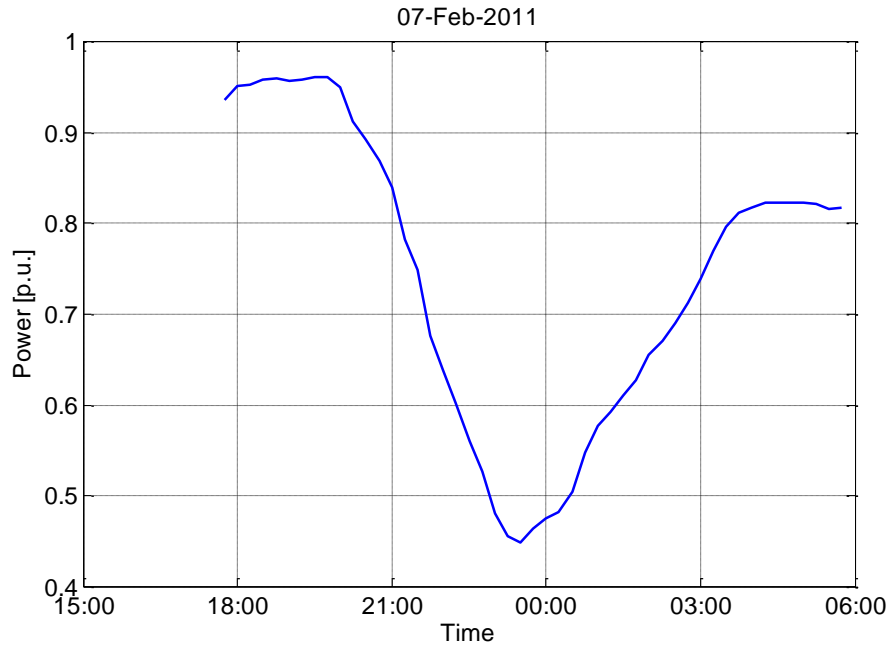
Figure 12. Wind power production in Denmark during high wind speed event

6.1.4 Event 4 – 24 September 2012

The fourth even recorded during the project period is the first one after the HWRT controller has been installed in Horns Rev 2 wind farm. The average farm wind speed exceeded 25 m/s, causing some of the wind turbines to shut down, even with the new controller, but the overall wind farm production showed only a slight decrease of maximum 20% of rated (blue line in Figure 13). In this case, the measured wind speeds were used to simulate the individual wind turbine power output with the HWSD controller, showing a wind farm production that exhibits double dip behavior (red curve).
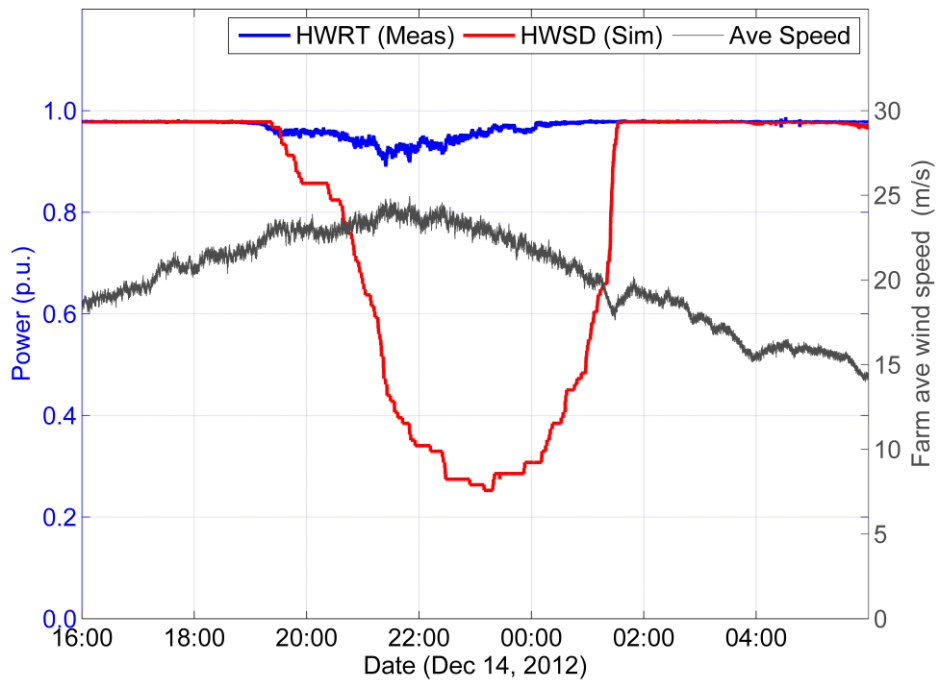
Figure 13. High wind speed event, September 24, 2012

6.1.5 Event 5 – 14 December 2012

The fifth event occurred in the evening of 14th of December 2012. In this case, the wind farm average wind speed increased steadily to a little over 25 m/s, decreasing with almost the same pace afterwards. The wind farm output was rather insensitive to this, remaining at almost rated power for the whole period (blue curve in Figure 14). If HWSD controller would have been still in place, the wind farm power output would have decreased to almost 20% of the rated power (red curve).
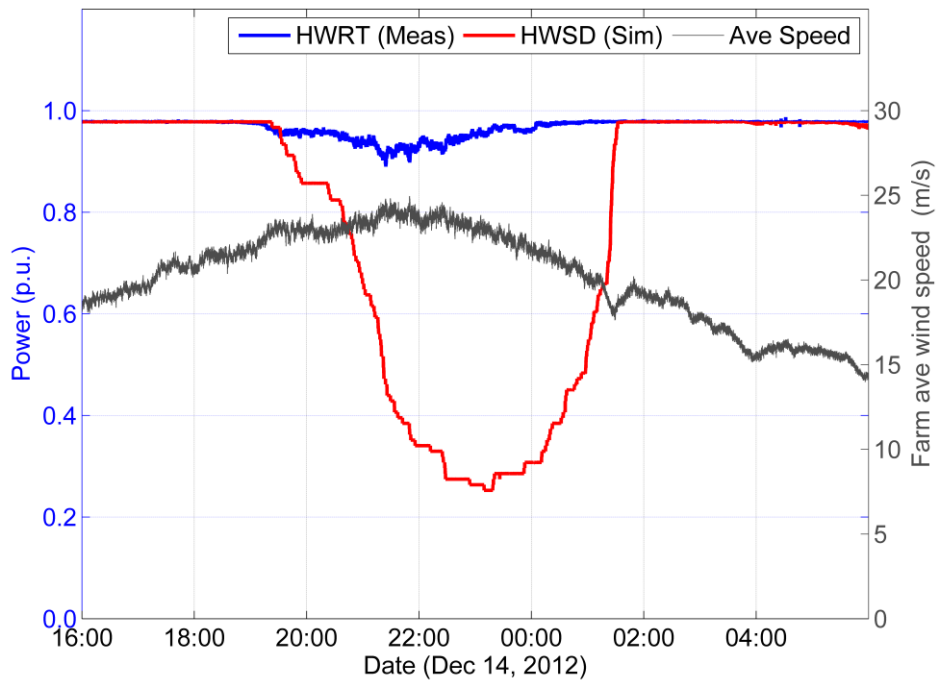
Figure 14. High wind speed event, December 14, 2012

6.1.6   Event 6 – 30 January 2013

The last event recorded occurred recently, at the end of January, 2013. This was a case of very high wind speed, with the average wind farm values close to 30 m/s. As a consequence, a rather large number of wind turbines shut-down, despite being equipped with HWRT. The total wind farm output dropped to app. 50% of the rated (blue curve in Figure 15). If the wind farm was still equipped with HWSD controller, then all wind turbines would have shut-down quite fast (red curve).
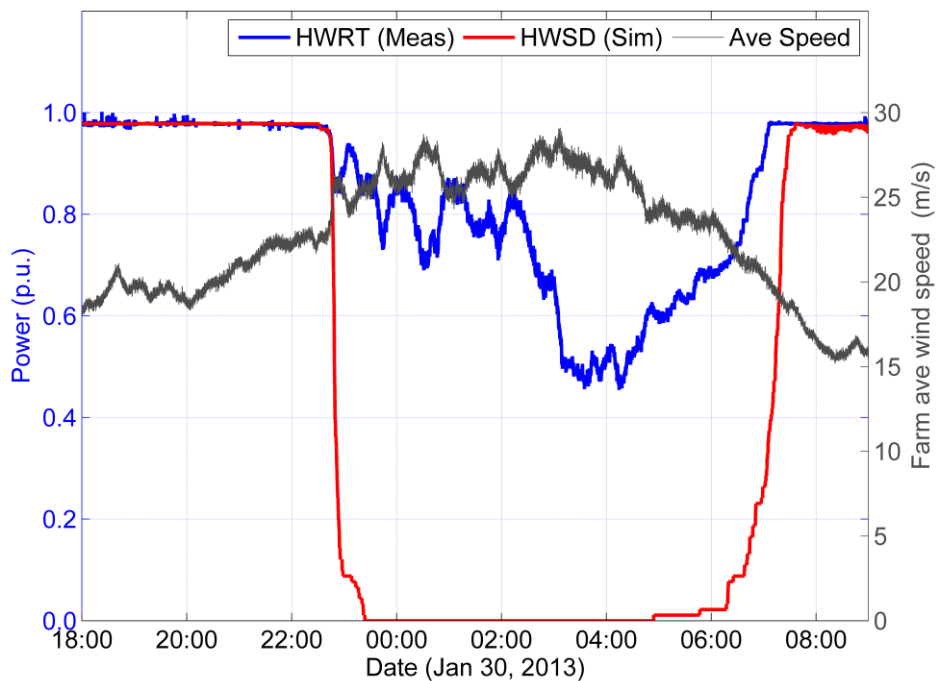
Figure 15. High wind speed event, January 30, 2013

As can be seen from the events the ramp with which power is reduced during storms is reduced considerably. This is also what was expected. This is important for the system because sudden unexpected change in production is the expensive ones to balance and the ones that are a threat to the system. Next we will focus on the ability to forecast output from HR2 during storms.

6.2   Forecast errors

High wind speed events have a significant impact on the power system operation not only due to the sudden drop of power (which in the future might become a problem), but also because they are hard to predict. The present ability of forecasting the high speed events recorded at Horns Rev 2 wind farm is presented in the following. The forecasts are the important parameters for generating production schedules which is input to the balance management at Energinet.dk.

For this study, the intra-day power forecast from Energinet.dk is used which forecast power up to 12 hours ahead. Energinet.dk has two meteorological forecasts available and calculates its own wind power forecasts optimized to minimize the aggregated wind power imbalances and not the few extreme events. This one is called the combined forecast as it combines two meteorological forecasts. The short term forecast is updated when new information becomes available. Since online measurements is updated every 5 minutes this means

that the short term forecasts is updated equally often. The meteorological forecasts are updated every 6 hours. The forecasts presented in the following are optimized based on the HWSD controller. Also, the following is focused on the forecasts available hour-ahead for the main balancing operation described in section 5. Research is going on to improve forecasts for extreme events (in ex. the SAFEWIND project funded by EU). These results are not yet implemented in the operational forecasting setup at Energinet.dk and we have chosen to focus on the forecast quality operationally at hand.

6.2.1 Event 1 – 11 November 2010

The measured versus the forecasted wind farm power output is presented in Figure 16. The wind power forecasts are given at each hour. In order to estimate the forecast error, the so-called "combined forecast error" curve was created. This curve is created for the whole period using for each hour the latest forecast available ½ an hour before the operating hour, i.e. for hour [t+1, t+2], the curve is corresponding to the latest forecast available at time t+½. The reason that the red curve has jumps is that it is put together of a many forecast, one hour from each forecast.
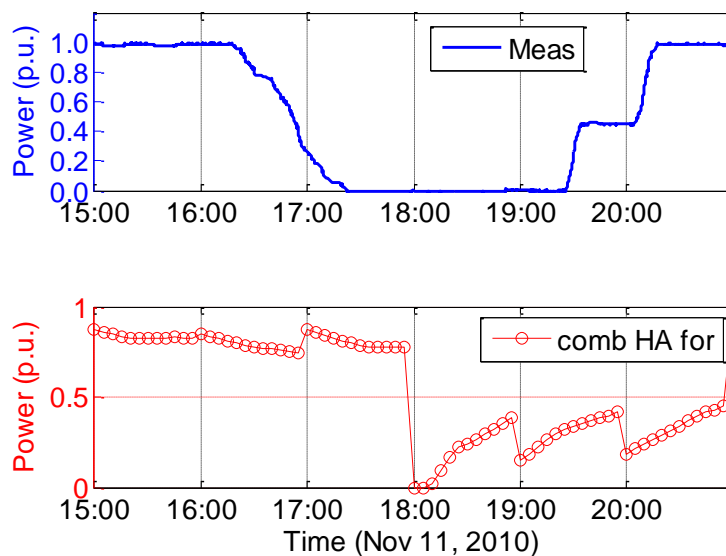
Figure 16. Measured vs intra-day forecasted power, November 11, 2010

The forecast error, calculated as the difference between the forecasted and the actual measurement, is given in Figure 17. Here we see that the forecast error for the November 11, 2010 event is close to 1 p.u. during the first hour of the storm. As the forecasts get updated the error is reduced.
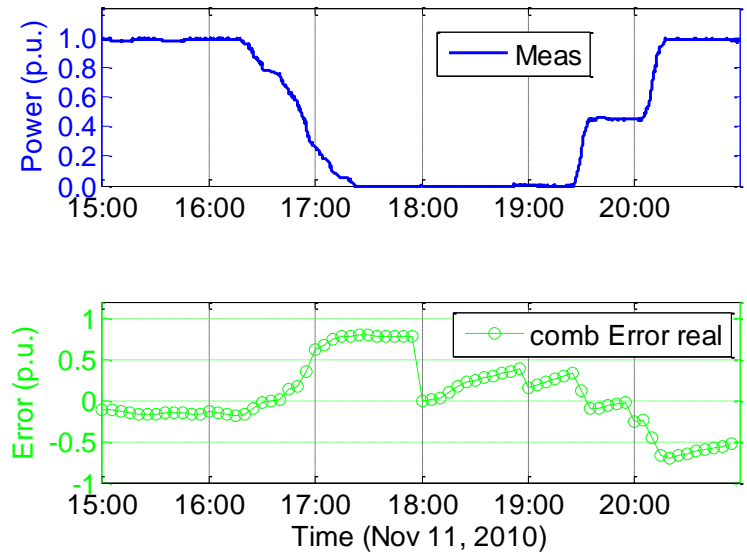
Figure 17. Measured power and forecast error, November 11, 2010

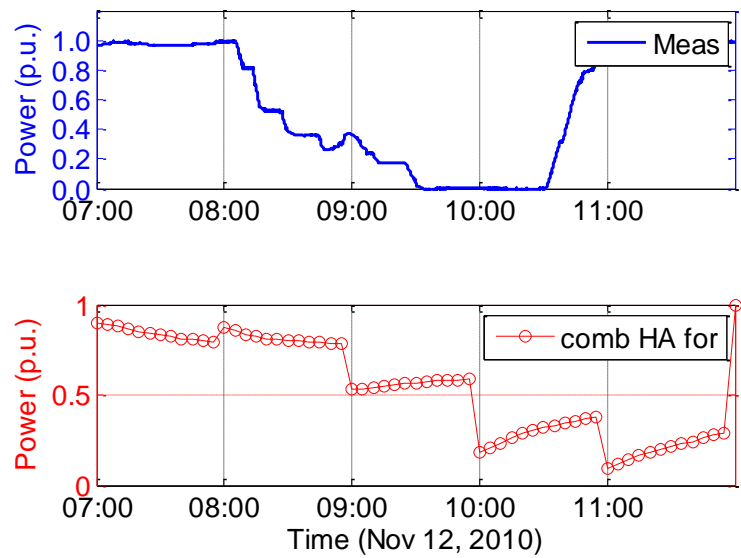For the rest of the events, the corresponding plots are shown.

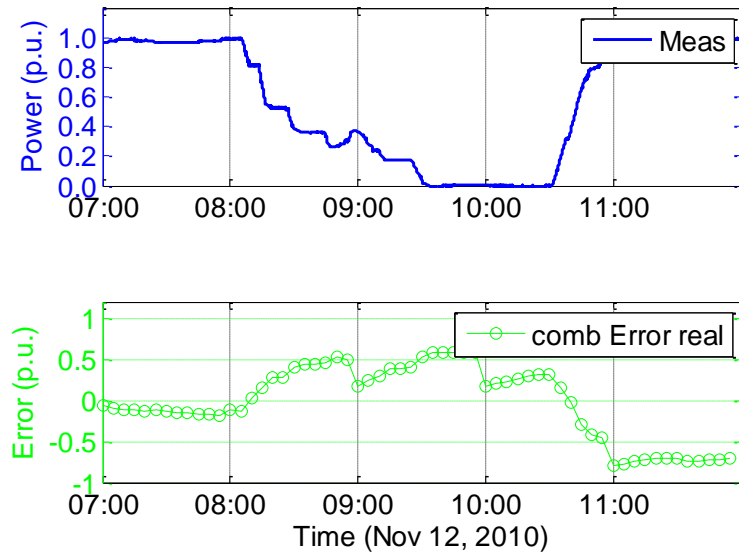**Figure 18. Measured vs intra-day forecasted power, November 12, 2010**

Figure 19. Measured power and forecast error, November 12, 2010

The error shown in Figure 19 is much smaller than the forecast error the day before. The reason for this is that the storm is much slower which leaves time for the forecast to be adjusted.
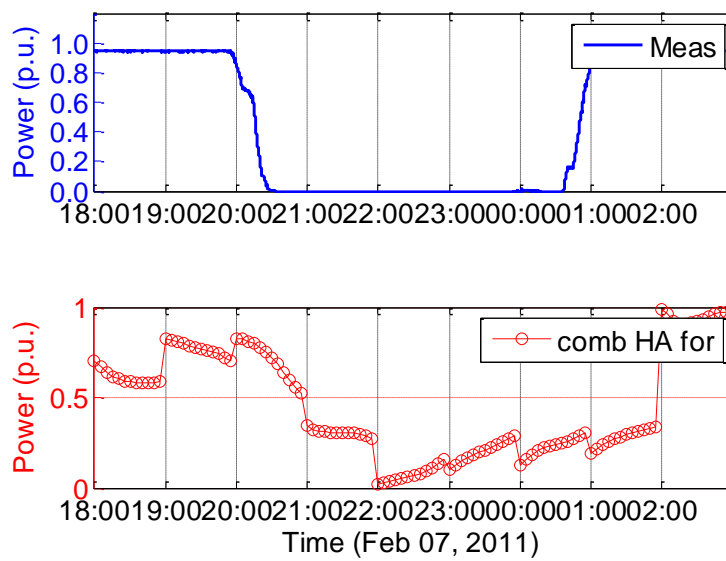

Figure 20. Measured vs intra-day forecasted power, February 7-8, 2011
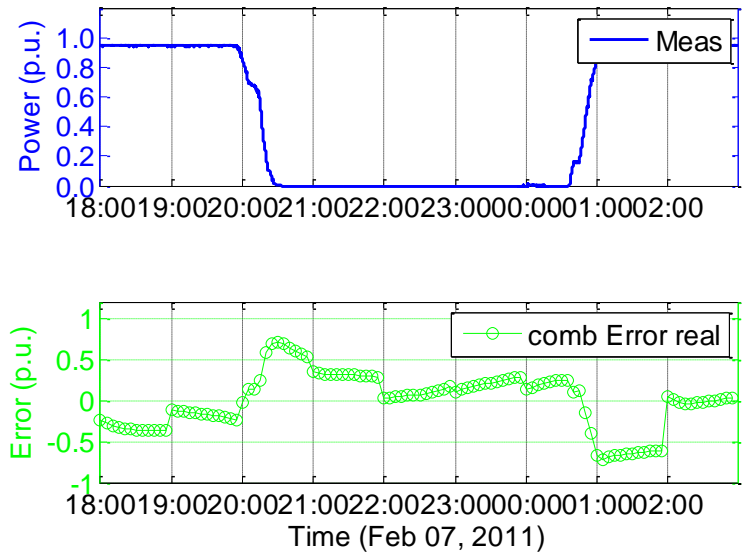
Figure 21. Measured power and forecast error, February 7-8, 2011
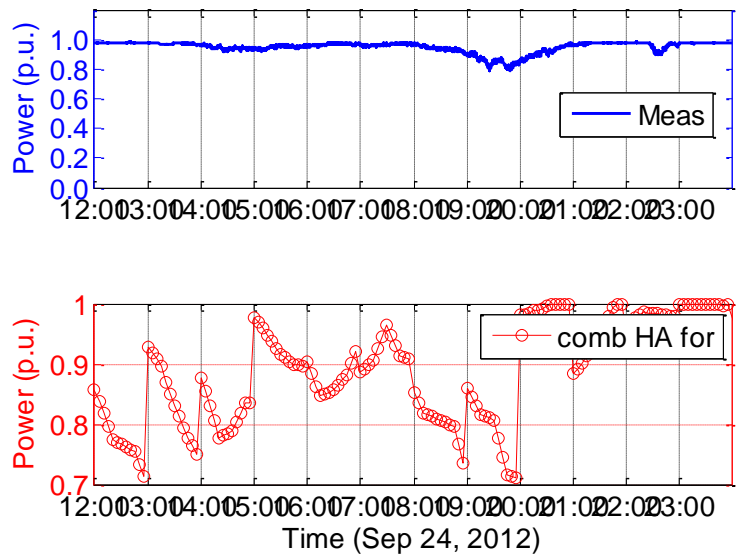
Figure 22. Measured vs intra-day forecasted power, September 24, 2012

This is the first storm where the HWRT controller was installed. The forecasts where optimized towards the old control algorithm. The forecasts keep reducing power indicating that it is expected that the wind park will reduce output. However due to the HWRT controller this is not the case. This means that if the forecasts are optimized towards HWRT they will improve.
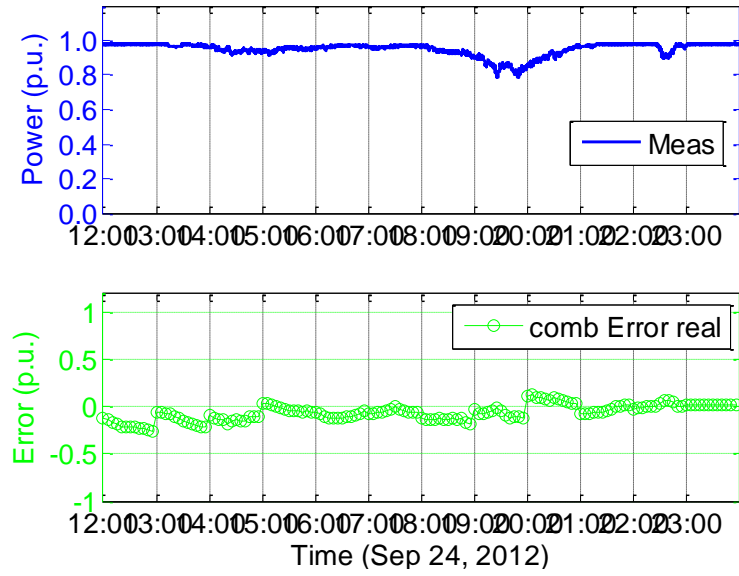
Figure 23. Measured power and forecast error, September 24, 2012
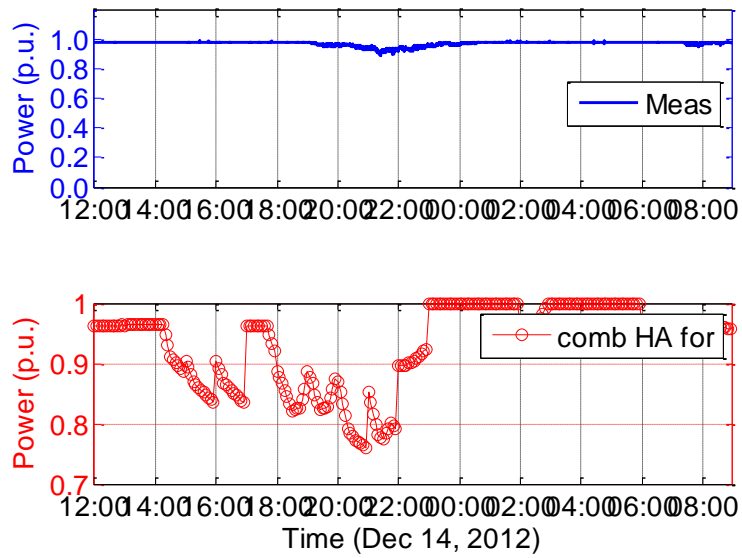
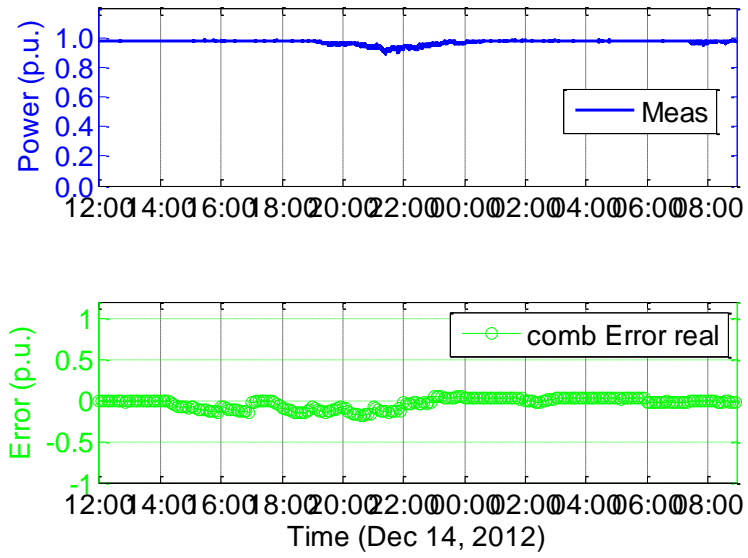**Figure 24. Measured vs intra-day forecasted power, December 14, 2012**

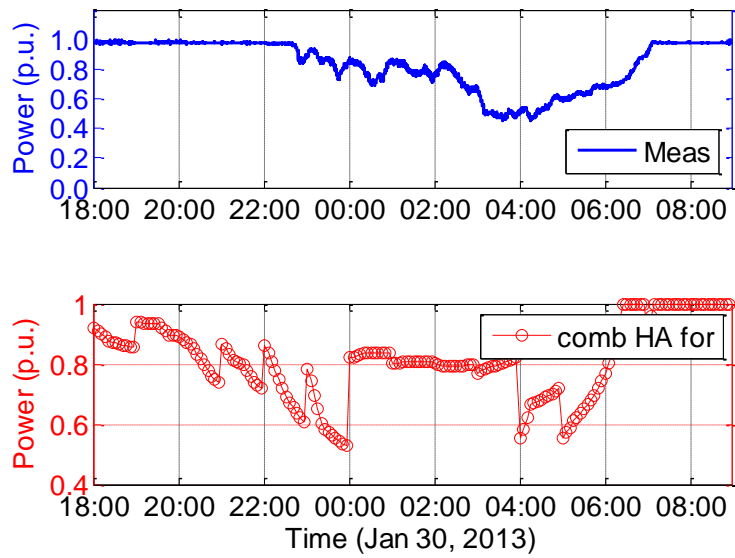**Figure 25. Measured power and forecast error, December 14, 2012**

Figure 26. Measured vs intra-day forecasted power, January 30, 2013
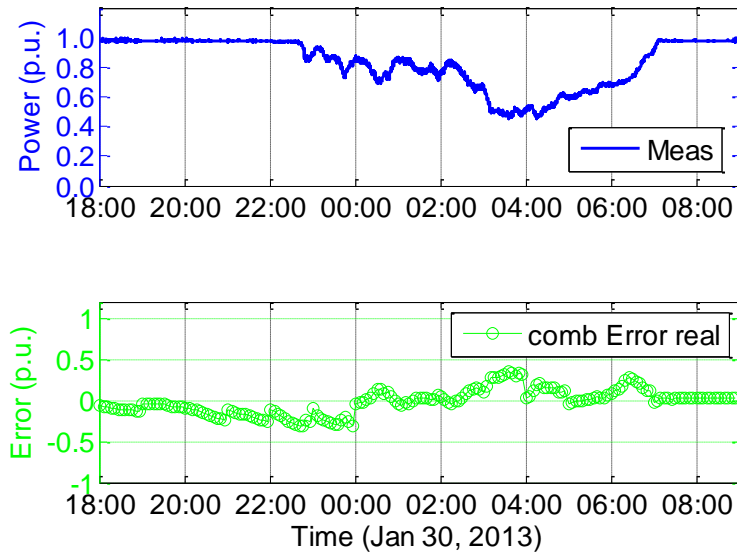
Figure 27. Measured power and forecast error, January 30, 2013

The statistics of the forecast errors, for all events, are given in Table 3. A high wind event starts when the wind speed reaches 18m/s (for detailed discussion, see D6.1). The first column gives the maximum forecast error per recorded event, while in the second column the average forecast error is calculated as the average of the maximum error for the events with the same controller – HWSD the first three and HWRT the last three. The final column shows the difference between the average maximum forecast errors, or in other words, the impact of the HWRT controller on the forecast error. The improvement is massive, with the maximum forecast error being lowered with more than 50% - expressed as fraction of installed capacity. One should take into account that the improvement is due to the improved control, since the forecast system in use at Energinet.dk has not been adapted to the new controller, i.e. equivalent HWRT power curve. When this happens, the improvement is likely to increase further.

Table 3 Forecast error statistics

Event	Max forecast error [p.u.]	Average forecast error [p.u.]	Difference [p.u.]
11-Nov-10	0.80		
12-Nov-10	0.80	0.77	
07-Feb-11	0.72		0.51
24-Sep-12	0.26		
14-Dec-12	0.18	0.26	
30-Jan-13	0.35		

In order to assess the difference in the energy produced during the events, the energy production with both controllers was calculated. It can be seen that between 400 and 1120 MWh is gained by installing the HWRT controller compared to the old HWSD controller. During a year we only expect a few (less than 10) number of storms. At the location where the turbines are located it is expected that 1MW of installed capacity will produce about 4300MWh during one year. This means that the HR2 wind farm will produce about 0.9TWh during a year. The result of introducing the HWRT controller is an increase of production during storm events although the increase in the total yearly production is insignificant.

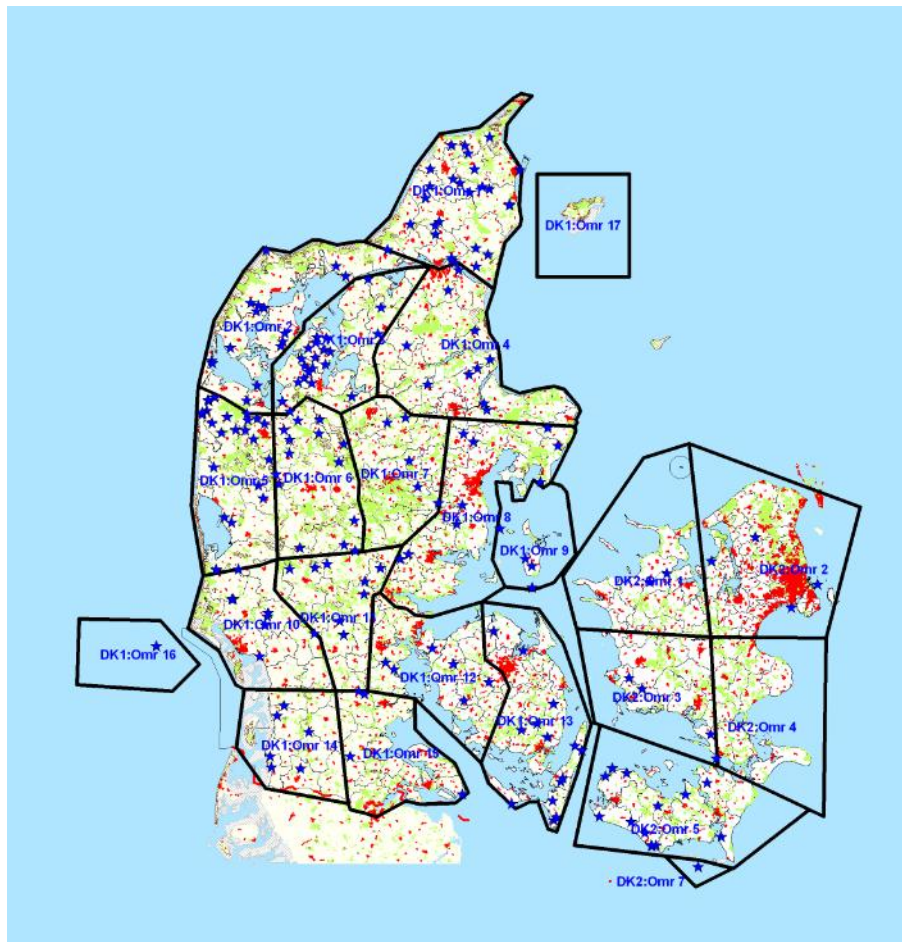**Table 4 Energy production during the recorded events**

Event	Energy [MWh]		Difference [MWh]
	HWSD	HWRT	
11-11-2010	656	1194	537
12-11-2010	600	1003	403
07-02-2011	886	1556	671
24-09-2012	1391	2296	905
14-12-2012	3680	4186	506
30-01-2013	1390	2510	1120

6.3   System Impacts of Storm, 7th – 8th February 2011

The Storm of 7th -8th February is chosen to investigate the effect of a Storm passage in the Nordic power system. The reason is that the observed storm was strong enough to affect the wind power production, not only in HR2, but generally in the total wind power production of the power system in West Denmark. We present a detailed analysis of the recorded data for the system during this period. The analysed data shows how the energy deficit caused by the shutdown of wind farms due to high wind condition was handled with regulating power as part of the system balance and illustrates the consequences and challenges the power system faced/will face in the future when these events (will) occur. Furthermore, the storm was followed by the unexpected failure in HVDC between Demark and Sweden. The data analysed considers both the 'Storm passage' and 'Failure' events in detail.

Average hourly data shown in this chapter is gathered from Nord Pool Spot website [1]as well as provided by Energinet.dk[2]. More detailed figures, on minute resolution, for scheduled trade, recorded exchanges and frequency, are provided based on data supplied by Energinet.dk.
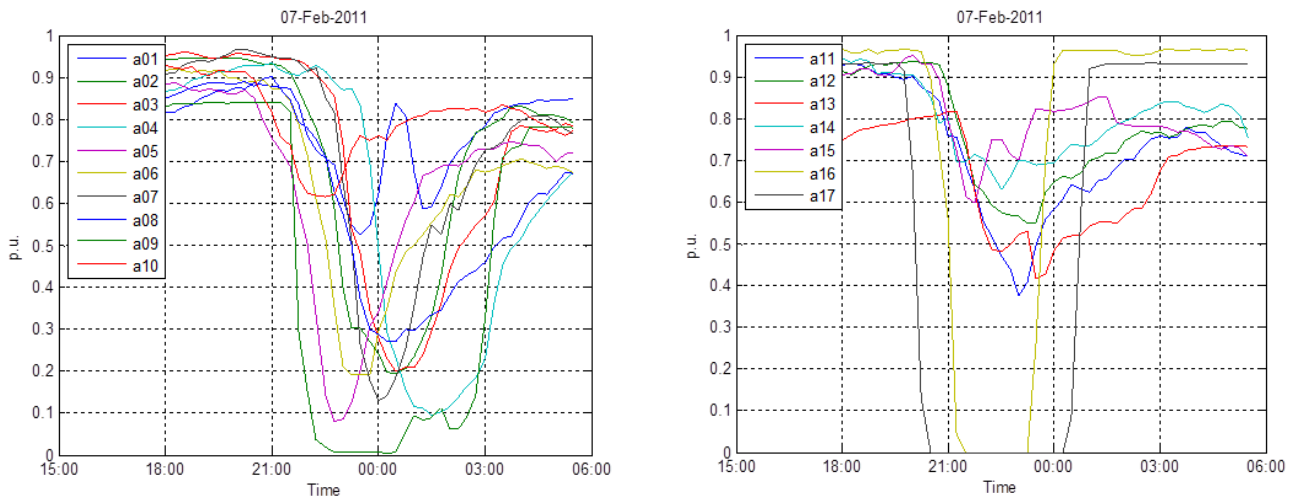
Figure 28 illustrates how the high wind event hit Western Denmark. Denmark is partitioned into areas for which the wind power production is registered. The normalized wind power productions are shown for the corresponding areas. We can see that the wind power in several regions reduces to almost 0 but slightly shifted in time. Data is online measurements for the areas having a 5-minute resolution.

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[1] http://www.nordpoolspot.com

[2] http://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

07-Feb-2011

b) Normalised measured wind power production

Figure 28. The storm propagation over Western Denmark

In Figure 29 wind power production and the forecast is shown. Data is from Nord Pool Spot and has hourly resolution. The storm passage over Denmark initially caused high wind power production in Western Danish system. Around hours 19 - 21 in Figure 29 below, wind production starts to cut-out due to excessive wind speeds. Wind power production is substantially reduced by 1057 MW (from 2121 MW to 1064 MW) over 4hour time span. The storm front affected the wind power in Western Denmark substantially and the loss of wind power production amounted to almost 25% of the load in the Danish power system. This was all due to stormy conditions. The wind production reached the minimum production value at 23h00 and started to recover from the storm event until 4h00.
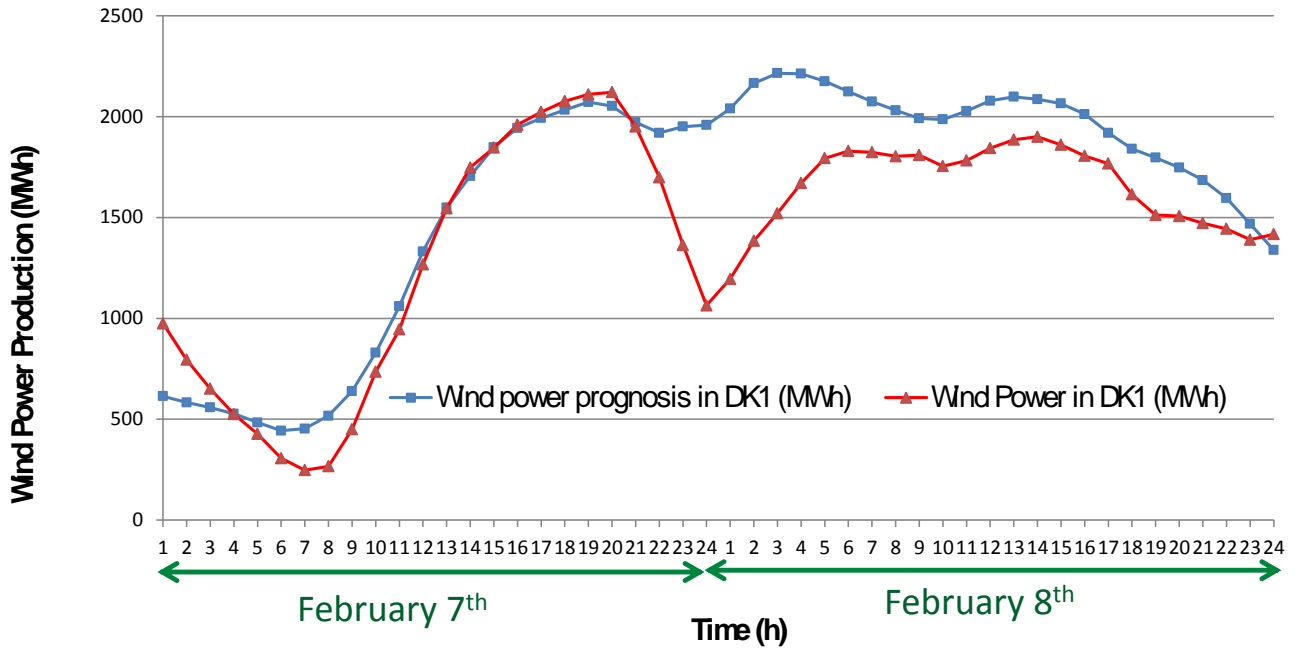
Figure 29. Storm in Western Denmark in 7th – 8th February 2011

Directly after the storm passage on February 8th, the next incident happened. Figure 30 presents the urgent market message from Nord Pool Spot concerning the outage on the HVDC cable between Western Denmark (DK1) and Sweden (SE), Konti-Skan. As shown, all the interconnected HVDC links were out of service (installed outage capacity is equal to the total transmission capacity on this link). The failure incident happened between 7h00 and 8h00 February 8th, 2011 right after the Danish wind power facilities had restored power after the storm.

Overview production/consumption: 8 day 6 week 12 month 3 year   **Overview transmission:** 8 day 6 week 12 month 3 year   **Utilities:** Search Advanced search Enable Alerts

Failure on grid affecting capacities

Message Time:	08.02.11 hour 08:04
Failure Time:	08.02.11 hour 07:15
Published:	08.02.11 hour 08:14
Company:	Svenska Kraftnät
Affected area(s):	DK1, SE
Line:	**Konti-Skan**

	DK1 to SE	SE to DK1
Installed outgoing capacity (MW):	740	680
Outgoing capacity during event (MW):	0	0
Event start:	08.02.11 hour 07:15	
Event stop:		
Duration uncertainty:	Not applicable	
Event status:	Open	
Remarks/Additional information:		

Until further notice.

Related Messages:

2011-02-08 10:41:22
2011-02-08 08:54:46
➤ 2011-02-08 08:04:22

Figure 30. Nord Pool Spot - UMM (Urgent market message)

Figure 31 provides an overview of the production and consumption within these two incidents. The figure is based on hourly data from Nord Pool Spot. As indicated above, the storm caused the production to decrease from 19h00 to 23h00. At the same time there is also a decrease in load, because of the time of day (late evening). Luckily this helped to compensate for the reduction of wind energy production during the storm. The HVDC failure lasted for four hours from 6h00 until 10h00.
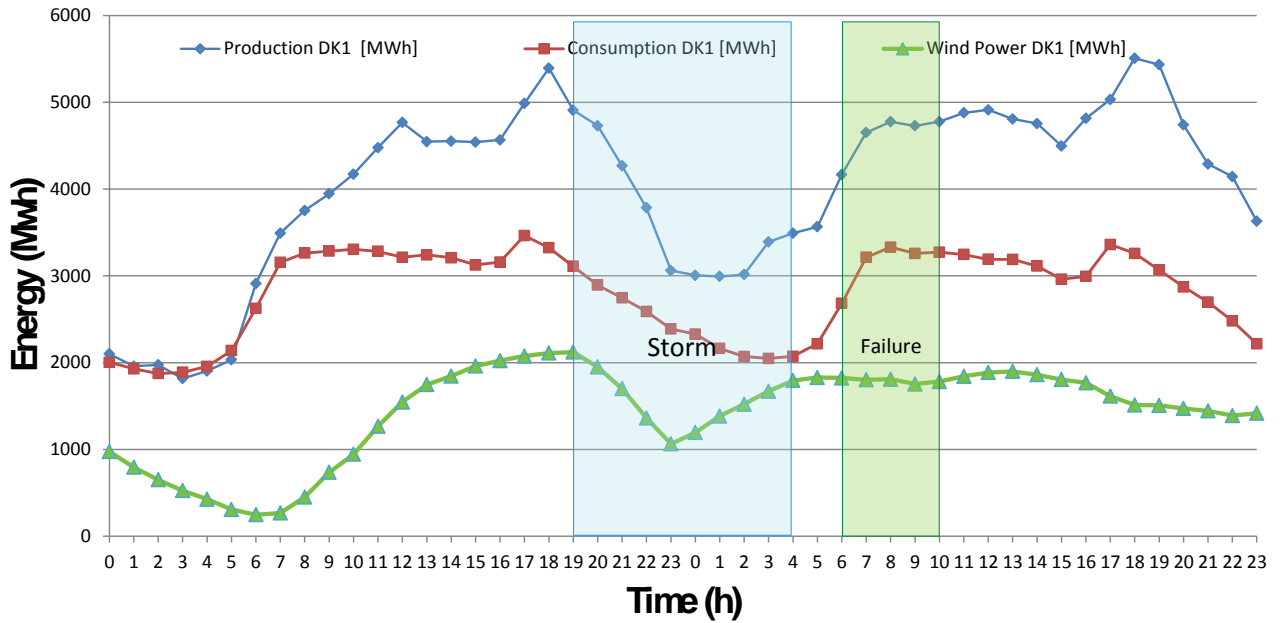
Figure 31. Production and Consumption in DK1

Figure 32 shows the scheduled trade (hourly resolution) retrieved from Energinet.dk. As shown during the storm, the scheduled trade was to export energy from Denmark to the neighbouring countries. During the failure incident, the scheduled trade was also to export energy from Denmark to Sweden.
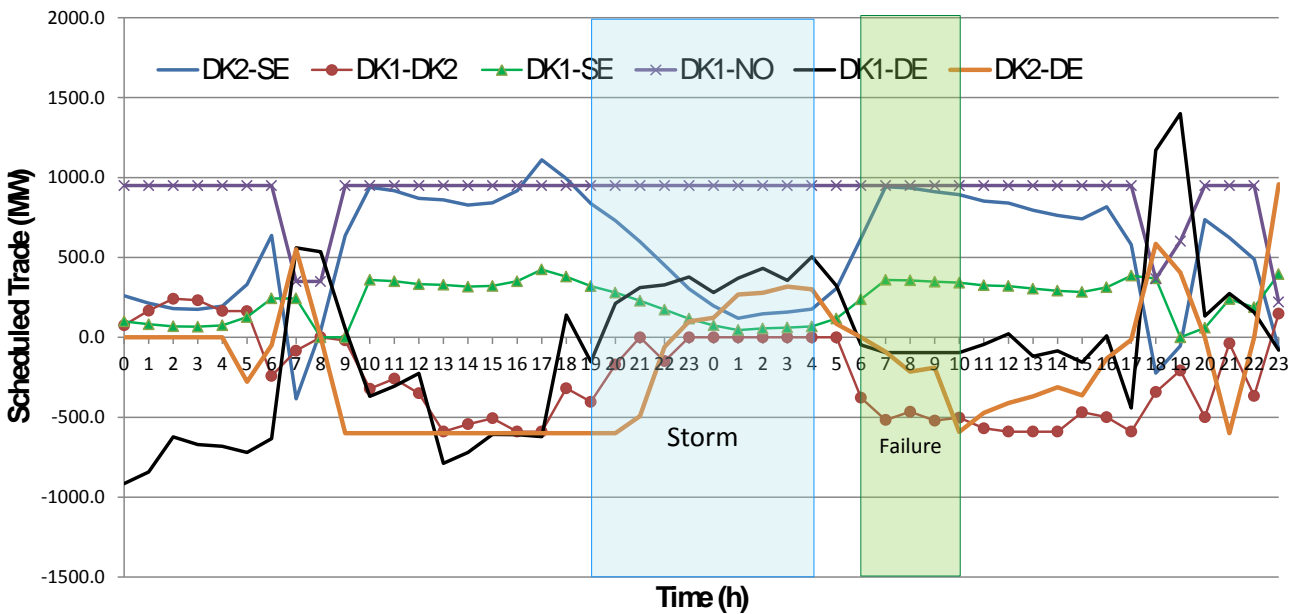

Figure 32. Scheduled Trade

Figure 33 is also based upon the data with hourly resolution retrieved from Energinet.dk and shows the actual exchange on the interconnectors. Comparing this figure with Figure 32 reveals that the exchange between DK1 and SE has changed from export scheduled trade to import leading to the fact that DK1 has imported power from SE during storm to restore power balance. During the failure incident, the export to the German system is fulfilled and the exchange across HVAC corridor connecting DK2 to SE has slightly increased. In parallel, the exchanged between DK1 and DK2 has been changed from import to export in order to transfer excessive power from DK1 to DK2.
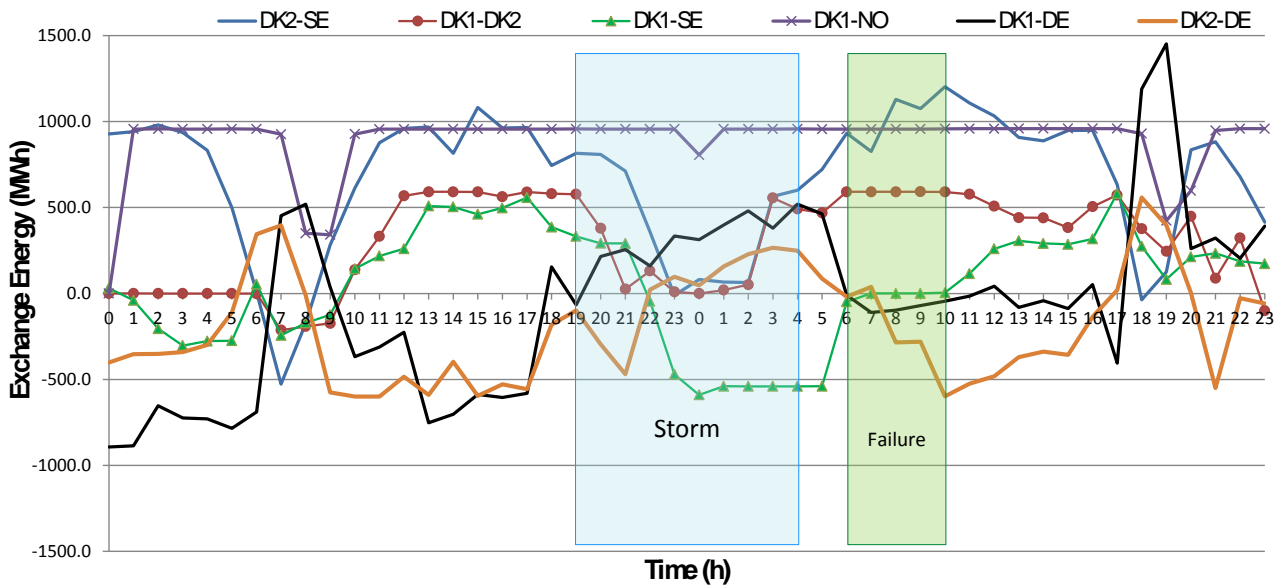

Figure 33. Exchange between Denmark and Neighbouring Countries

The deviation from scheduled trade is illustrated in Figure 34. The recorded flow between DK1 and SE changed from export to import in order to restore balance in the Danish power system. On the other hand during the transition between two incidents, the flow on DK2-SE increased to restore the deviation from the schedule exchange to Sweden. Also, the flow on DK1-DK2 changed significantly during the failure incident.
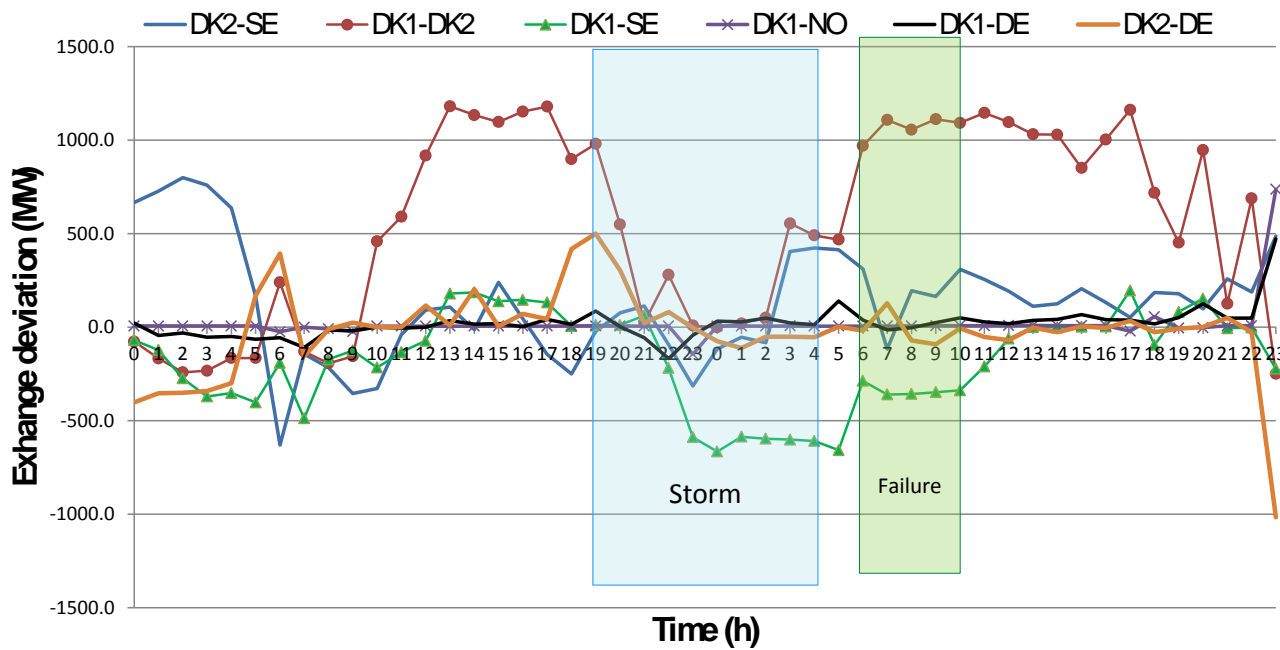
Figure 34. Deviation from Scheduled Trade

As illustrated in Figure 35, some correlation *seems to exist* between the decrease flow between DK1 and SE during hours 19 - Feb. 7th to 4 – Feb. 8th 2011 and the observed decrease in wind production in DK1. Furthermore, the volume of power flow change does not seem sufficient to keep balance in DK1.
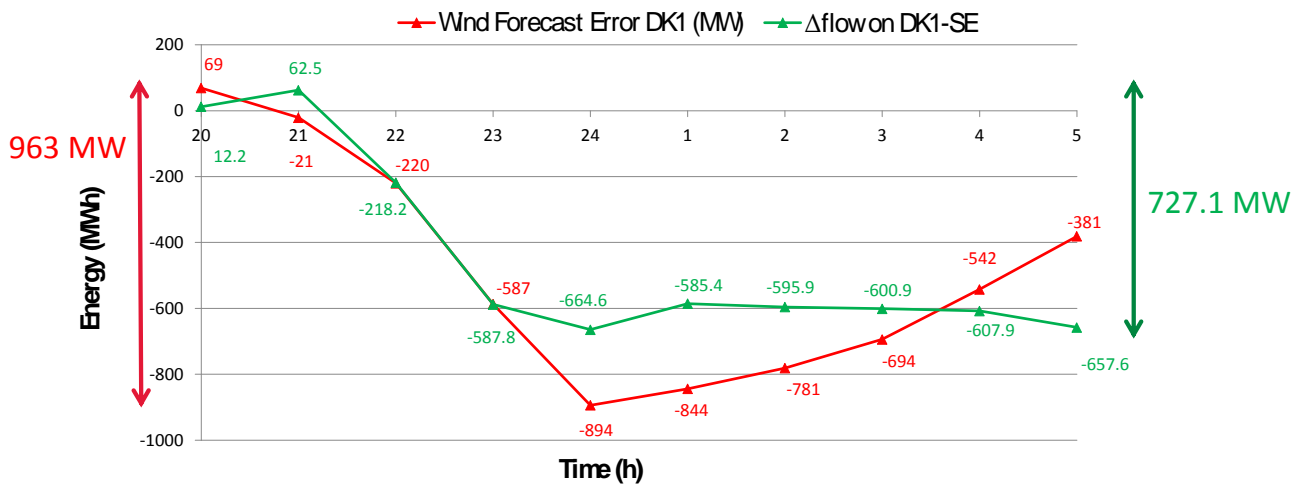

Figure 35. Plot of change in flow on DK1-SE and error in Wind Production

The recorded activated regulating power volumes during the storm passage and HVDC failure incidents are shown in Figure 36. It turns out that during the storm incident, upward regulating reserves both in DK1 and DK2 were activated while during HVDC failure downward regulating reserves were activated in DK1.
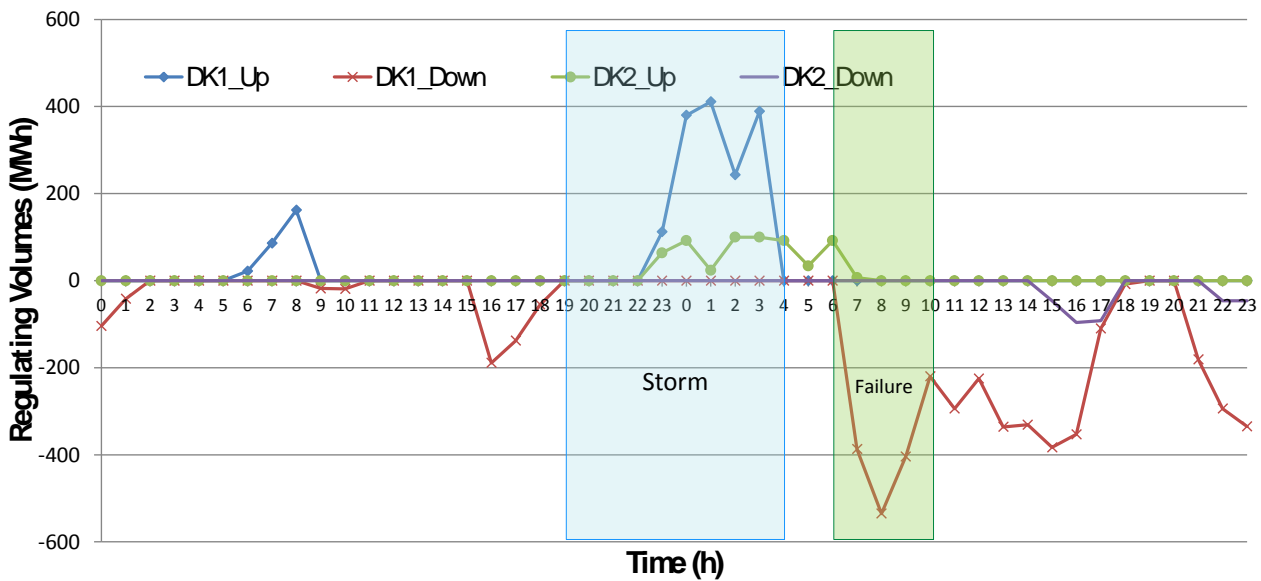

Figure 36. Activated Regulating Volumes (MWh)

Figure 37 compares the wind forecast error highlighted by the black curve and the deviation from scheduled trade against the activated regulating reserves in Denmark. During the storm incident, the negative wind forecast error was compensated by activated upward regulating reserves and import from Sweden. During the HVDC failure incident, the wind forecast error was nearly zero. However the scheduled export to Sweden was not possible due to the failure. Therefore, the Danish system ended with energy surplus since the units had been committed D-1 to export power to Sweden. Hence, the system balance was restored by activating downward regulating reserves within DK1.
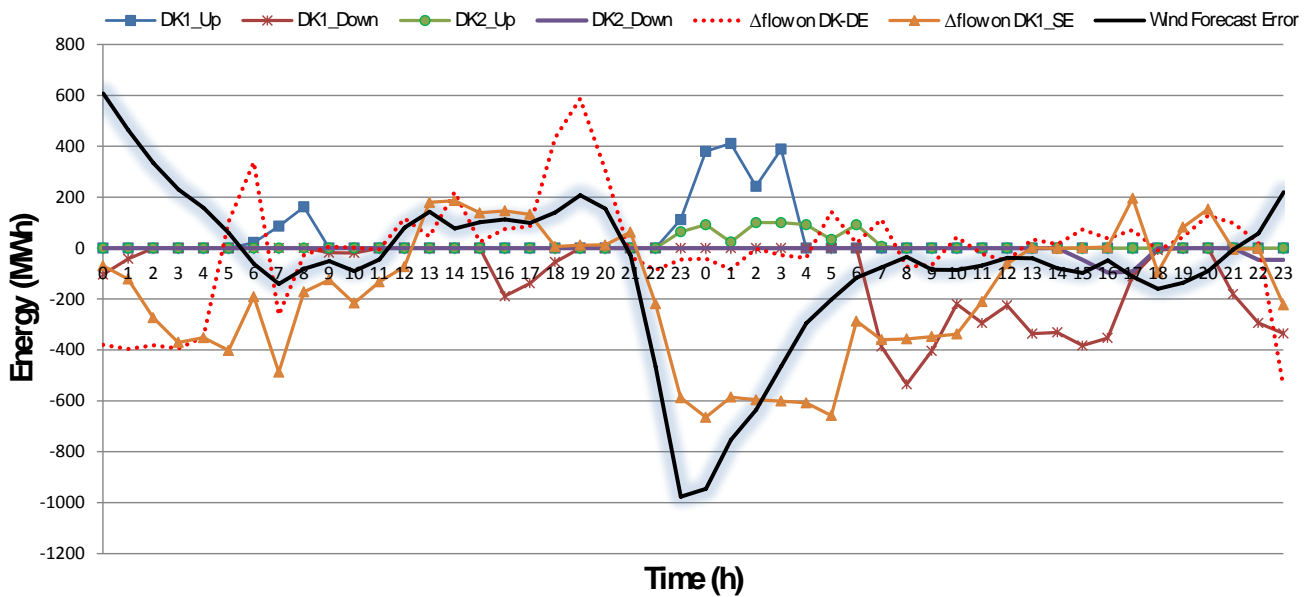
Figure 37. Activated Regulating Volumes (MWh) and Deviations from Scheduled Values

6.4 Frequency deviations during selected critical periods

The frequency of the power system describes the balance between electricity production and consumption. The better the balance, the smaller the frequency variation in the grid and therefore the better the electricity quality. The Nordic electricity grid (Finland, Sweden, Norway and Eastern Denmark) is synchronously interconnected, so the entire grid has the same frequency. In the inter-Nordic grid, the frequency is allowed to vary between 49.9 and 50.1 Hz, as normal operational frequency band by the Nordic TSOs [8]. To keep the frequency within operational guidelines, the TSOs' have frequency controlled reserves at their disposals. If the frequency of the grid is below the nominal value of 50 Hz, consumption is greater than production. Correspondingly, when the frequency is above the nominal value of 50 Hz, production is greater than consumption. If a power disturbance occurs within the system such that the frequency controlled reserves cannot compensate for the deviation fast enough, a frequency deviation outside the normal operational band (50 +/- 0.1 Hz) will occur.

In this part, we would like to investigate how the system frequency in the Nordic synchronous system and Western Denmark, synchronous with the Continental European system, behave for two selected critical periods. DK1 is synchronised with the Continental European synchronous system, and the Continental European system is much larger than the Nordic synchronous system. The more Generators and motors that are coupled to the power system, the more stored kinetic energy the system will have. Therefore, the

Continental system has more inertia than the Nordic system, which increases the robustness of the system in case of large frequency deviations. Thus, as will be shown later, the frequency in NO has been affected more than the frequency in DK1 during storm events. It can also be due to the unnecessary delays caused by the manual control in the Nordic system, whereas the automatic control system in Western Denmark reacted very fast on frequency deviations and therefore the frequency has not experienced such a large deviation as in the Nordic system.

As discussed previously the Regulating Power Market (NOIS) has proven its value through many years of successful operation. The simple but efficient design makes the NOIS a useful tool for the system operator to balance both contingencies and forecast errors, taking network congestions into account. On the negative side, the manual activation of reserves might cause unnecessary delays and a stressed situation for the system operator during critical contingencies. In order to improve the balancing task in the Nordic synchronous system, the Nordic TSOs (transmission system operators) have agreed on the implementation of automatic Load Frequency Control (LFC) in the Nordic synchronous system from 2013-2014. The status for the Nordic LFC is that by the end of 2012 100MW is running as part of a pilot project. During the spring of 2013 tests will be performed with both 200MW and 400MW running. The pilot project and the test will be evaluated at the end of 2013. The results so far show that the LFC improves the frequency quality in the Nordic area as expected.

We have chosen two events for further analysis which are highlighted by black boxes in Figure 38. The first period (**P1**) is between hours 22 to 23 (one hour) on February 7th and the next one (**P2**) is between hours 5:40 to 7:10 (one and half hours) on February 8th. During these two selected periods unexpected changes in the flow between the Nordic system and Western Danish system are observed. The first one is due to the effect of storm passage, and the second one is due to the failure of Konti-Skan link.
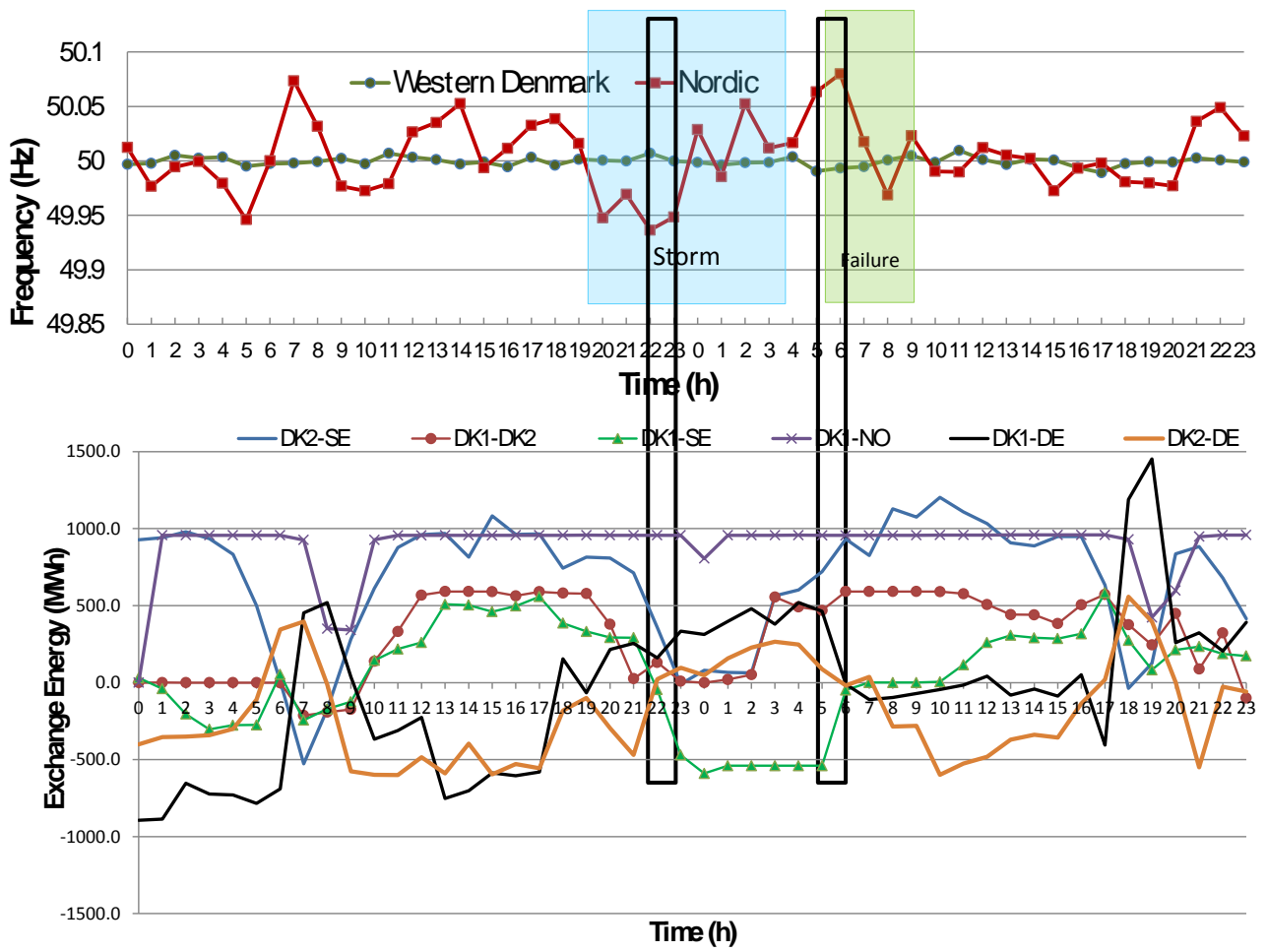
Figure 38. Two selected critical events **P1** and **P2**

Figure 39 shows the frequency deviation (minute resolution from Energinet.dk) in the Nordic system (NO) and Western Denmark (DK1) within four successive hours inside the storm. The flow on Konti-Skan is changed from 255 MW export from Western Denmark to 500 MW import during this period. The frequency in NO experienced large deviations, especially within **P1**, where the wind production in Western Danish system reached the minimum value according to Figure 29. The bandwidth for normal frequency operating excursion is highlighted by dashed green lines both for upper and lower thresholds. The period **P1** is marked by the black square. The frequency deviation exceeded the lower threshold of 49.9 Hz for 28 mins within **P1**.
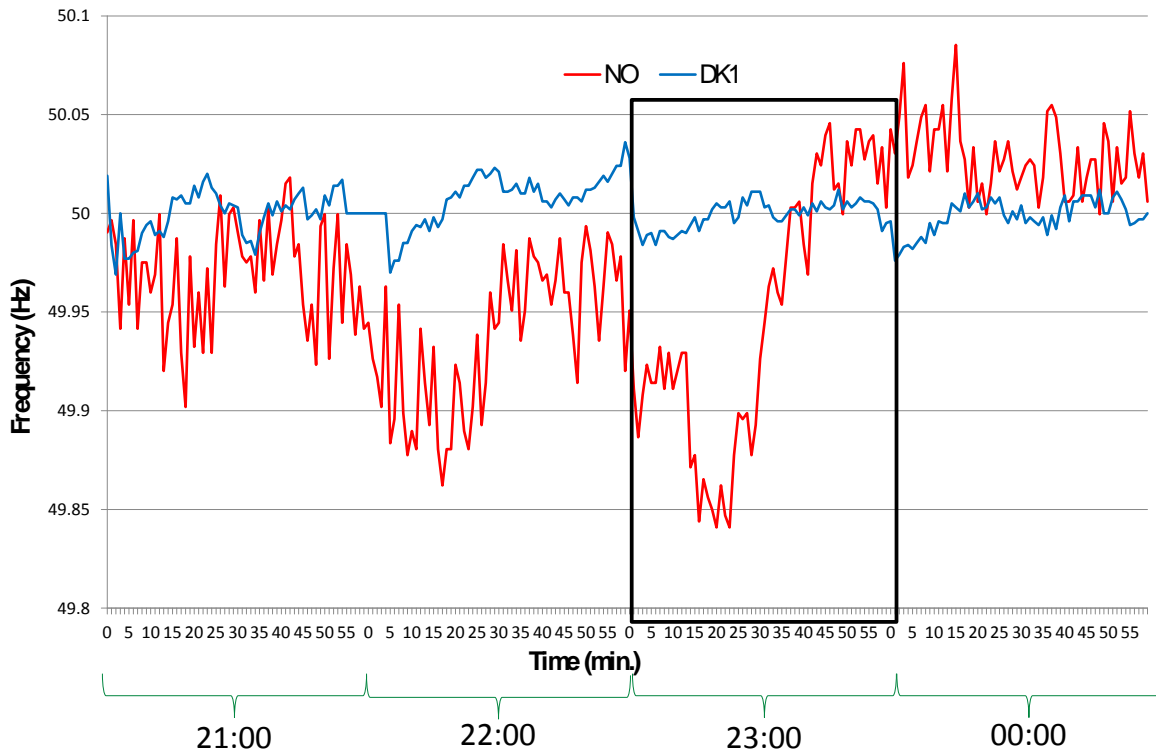
Figure 39. P1: Frequency deviations in storm event

Figure 40 illustrates the frequency in Western DK1 within **P1** period. It compares the minute values of frequency deviations against LFC control signals. It can be concluded from this figure that imbalance on the exchange of power between DK1 and Germany, which is caused by the wind production decrease in Denmark due to the storm, is observed (orange curve). This imbalance reflects the deviation from scheduled plan for export of power from DK1 to DE. The LFC in DK1 (green curve) reacts proportionally to the orange curve, which is one component of the control signal on exchange border between DK1 and Germany, called "Area Control Error (ACE) component for interchange", and not directly to imbalances across the HVDC links to the Nordic system.
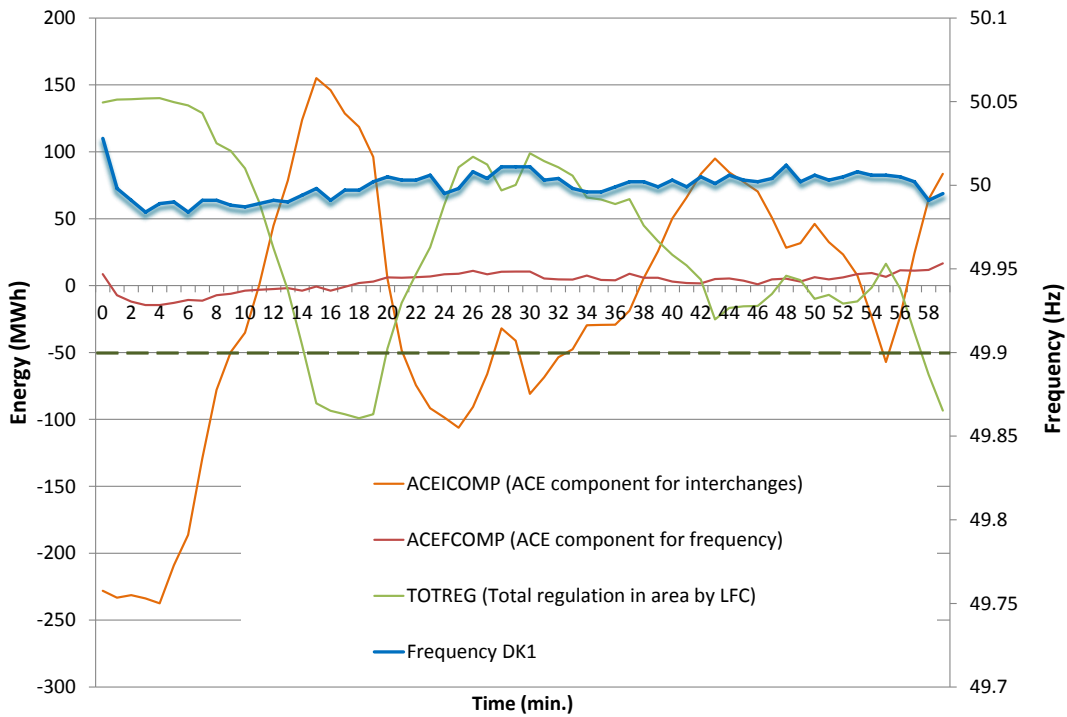
Figure 40. Frequency deviation versus LFC control signals in DK1 during P1 period

Figure 41 illustrates the frequency in NO within **P1** period. It compares the minute values of frequency deviations against flow exchange across Konti-Skan HVDC link. It can be concluded from this figure that the increased import from Sweden to DK1 causes the Nordic frequency (red curve in Figure 41) to go out of operational limits during the period 14 - 28 mins within P1. The frequency deviation trend in the Nordic system follows the exchange on Konti-Skan link (black curve).
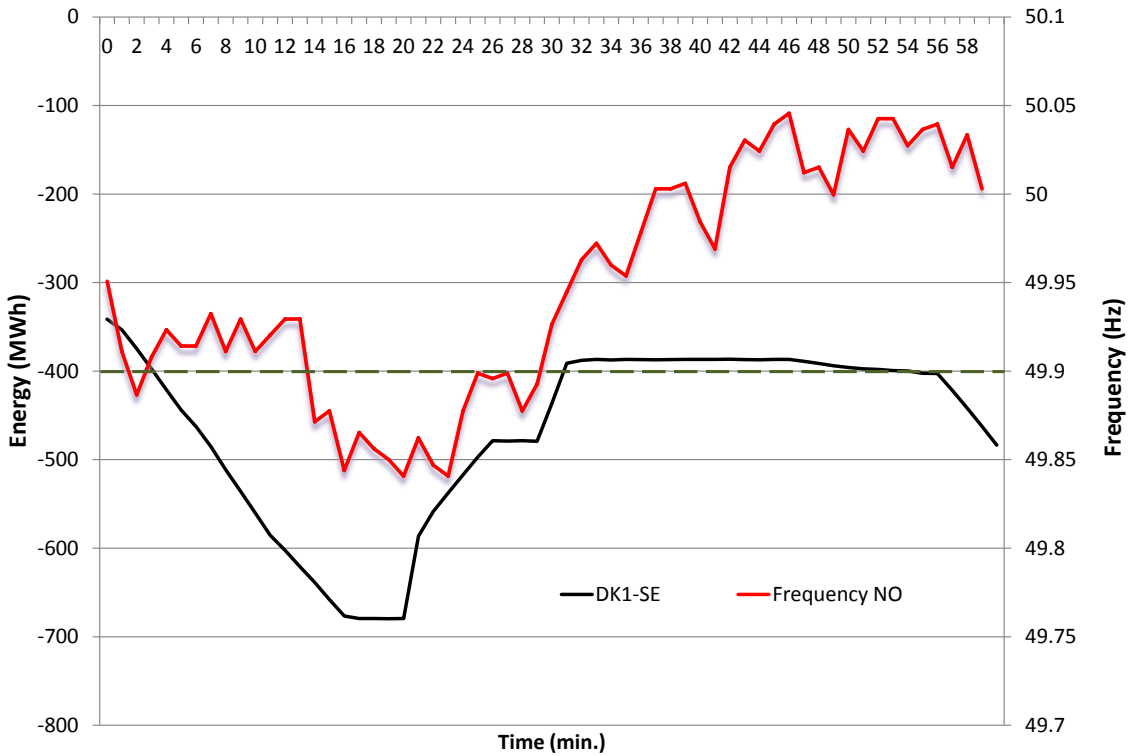
Figure 41. Frequency deviation versus exchange on Konti-Skan in NO during P1 period

Similar to Figure 39, Figure 42 depicts the frequency deviation in minutes for three successive hours directly before and during the HVDC failure. The frequency is depicted for both NO (red curve) and DK1 (blue curve). A window for one and half hours is selected when the frequency in the Nordic system presents a steady increasing trend. This increasing trend is caused by the failure in Konti-Skan link and during some minutes goes above the upper threshold for normal operational limits of 50.1 Hz (dotted green line).
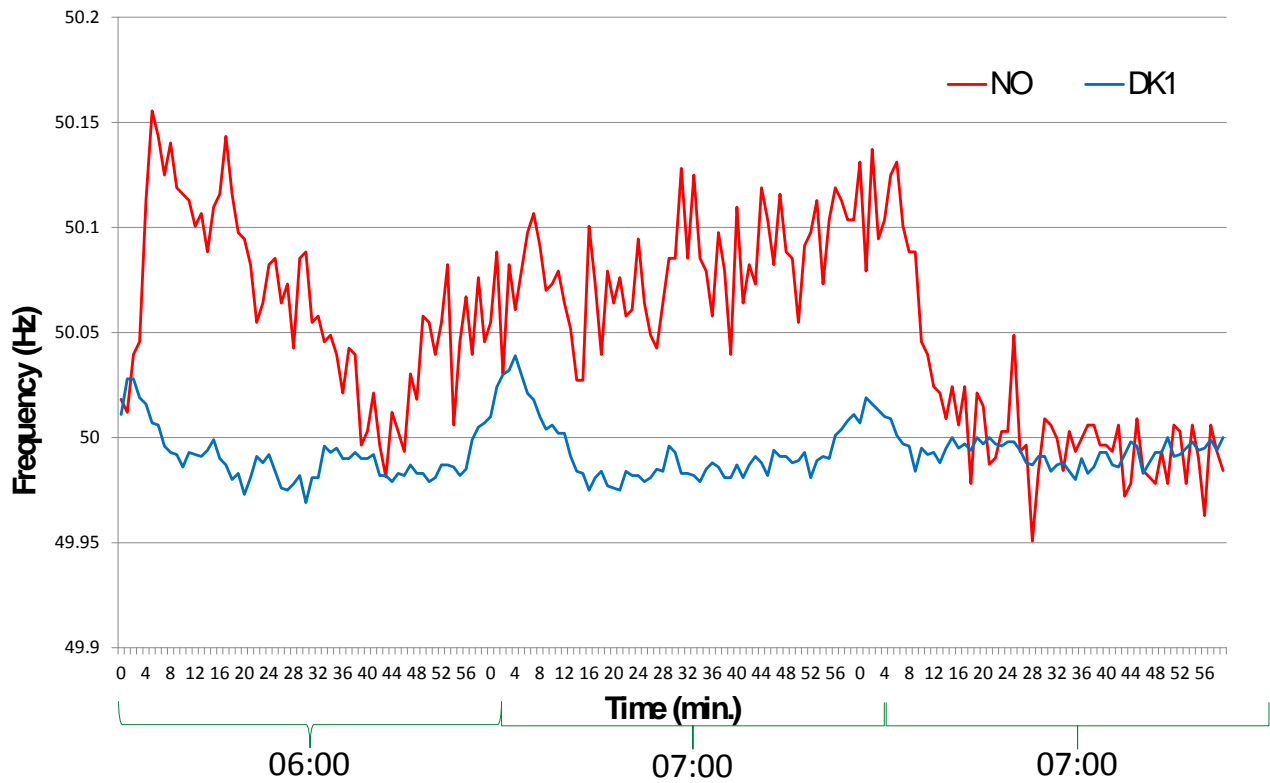
Figure 42. P2: Frequency deviations during Konti-Skan failure

Like above, the frequency in DK1 is compared with the LFC signals in DK1 in Figure 43. All the values are shown for **P2** period. The frequency in DK1 was not affected very much by the failure in Konti-Skan link. There is a small deviation directly at the failure time. It appears that the failure caused the exchange on the German border to increase rapidly (orange curve) and therefore caused this deviation in the frequency in DK1.
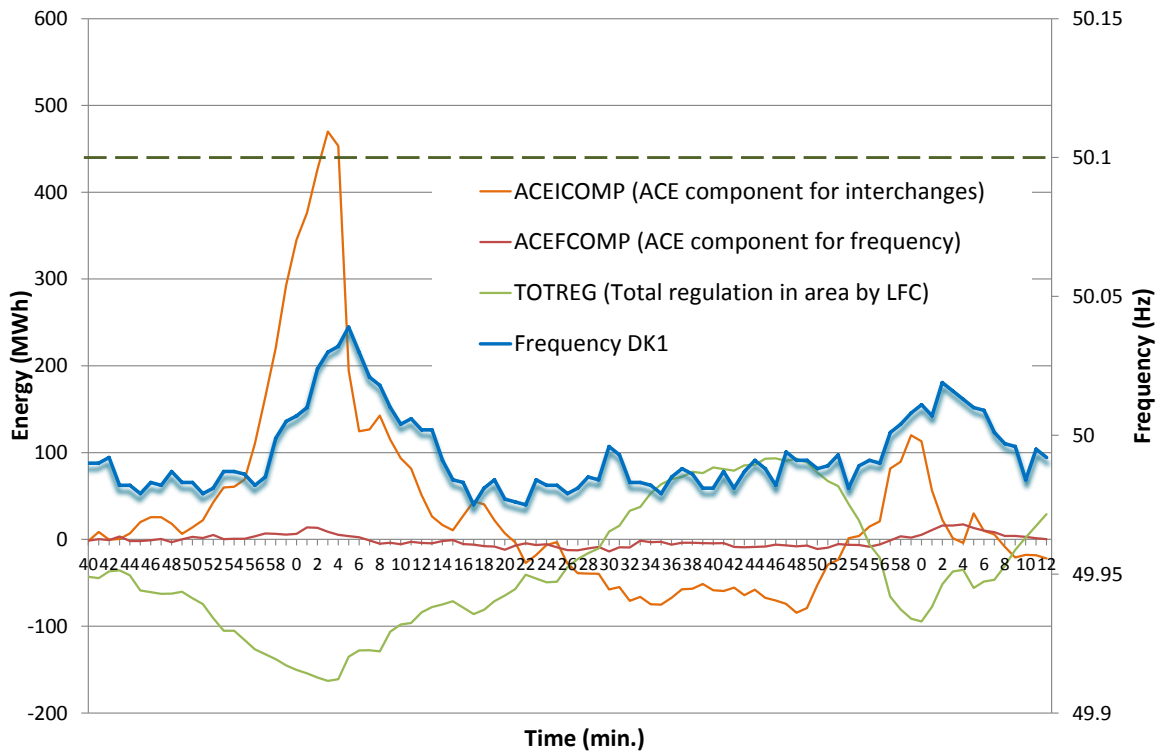
Figure 43. Frequency deviation versus LFC control signals in DK1 during P2 period

The frequency in NO is compared with flow across Konti-Skan within **P2** period in Figure 44. As depicted, the unexpected failure of Konti-Skan at minute 4 causes the frequency in NO to increase above the operational limit of 50.1 Hz throughout the period from minute 4 - 8(+1h).
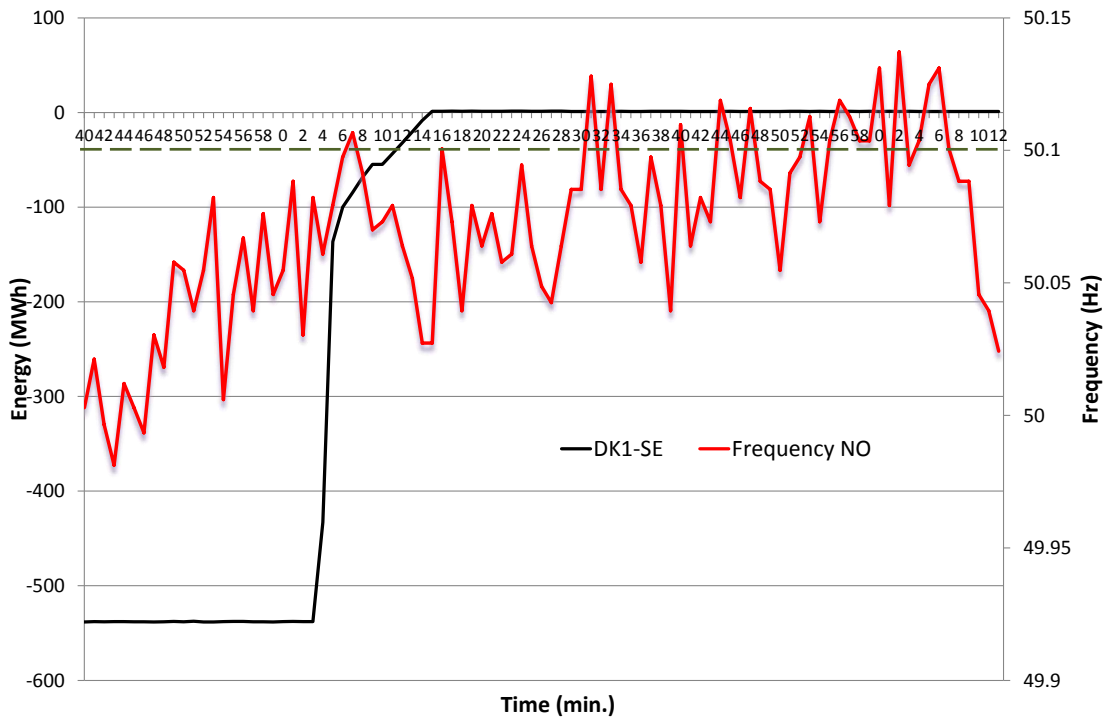
Figure 44. Frequency deviation in NO versus exchange across Konti-Skan link during P2 period

Figure 45 shows the frequency excursion against the planned and actual exchange energy between DK1 and the neighbouring countries in **P1** period. The exchange with Germany follows the planned values (the dashed blue curve shows the recorded values and light blue shows the planned exchange). The exchange between DK1 and Eastern Denmark (DK2) follows the planned exchange as well. However, both connections to Sweden and Norway contribute to support balancing in DK1 in **P1** period. The exchange across DK1-NO is reduced from 1000 MWh to 750 MWh. In addition, the exchange across DK1-SE changes from export to import towards DK1. The values change from 114 MWh (gray line) to -670 MWh (black cure). It seems that frequency excursion in NO is correlated with huge deviations on exchange across the DK1-SE link, Konti-Skan. Therefore, the increasing imported energy across Konti-Skan caused the frequency in NO to go out of operational limits at the beginning of **P1**.
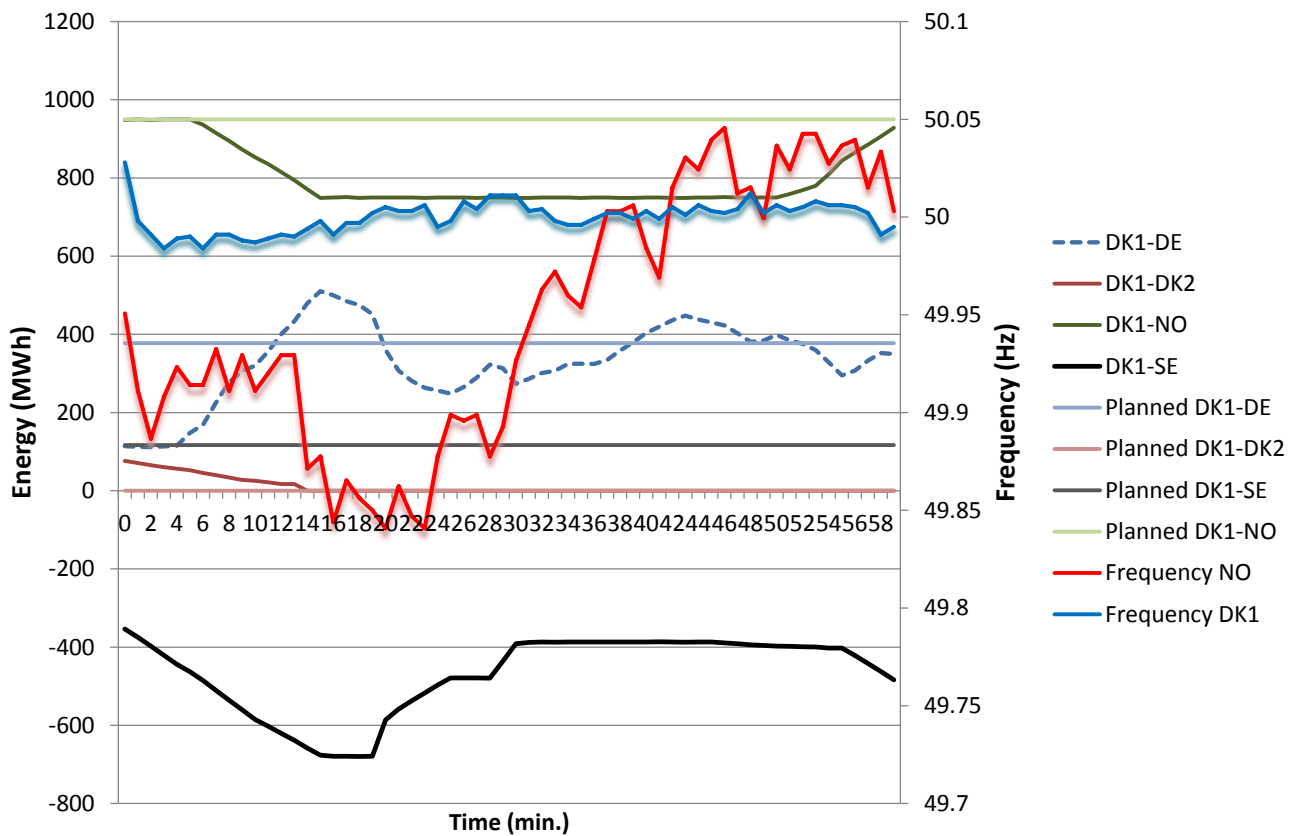
Figure 45. Frequency deviation versus exchange values during P1 period

Figure 46 shows the comparison between frequency excursion and exchange of energy between DK1 and the neighbouring countries in **P2** period. The exchange with Germany and Norway follows the planned values. However during failure, the interconnection between DK1 and DK2 was used to balance. As illustrated in Figure 46, the planned import from DK2 to DK1 is changed to export to DK2 after the unexpected failure in Konti-Skan.
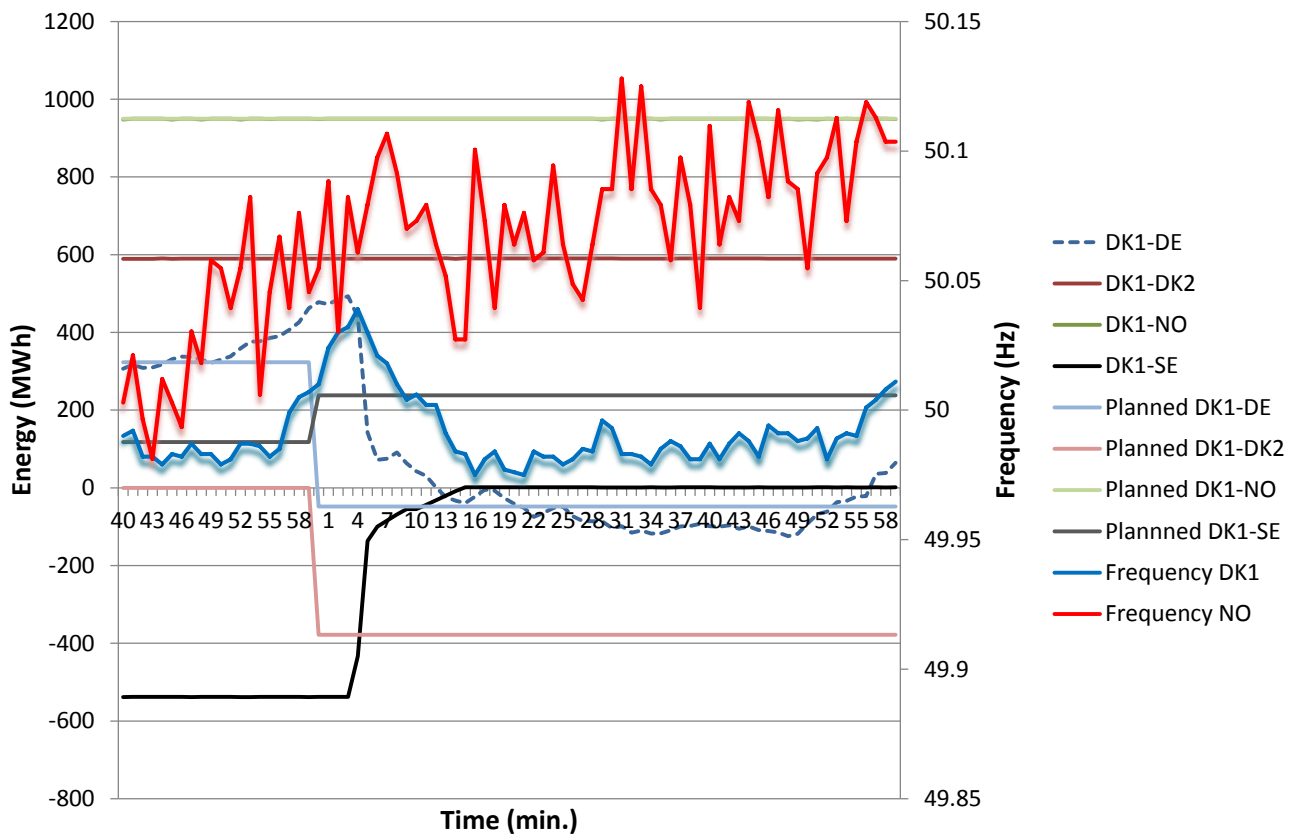
Figure 46. Frequency deviation versus exchange values during P2 period

7 Conclusions

During the duration of the project, several high wind speed events were recorded at HR2, with both HWSD and HWRT controllers. The analysis presented in this report has shown that when the wind turbines are equipped with HWRT, the wind power forecast error decreases with more than 50%. Similarly, the energy production during the high wind events increased with the HWRT controller compared to the HWSD controller although the amounts are negligible compared to the yearly production.

The storm front event on February 7th -8th, 2011 which was followed by the unexpected failure on HVDC line between Western Denmark and Sweden illustrates the consequences and challenges the power system faced/will face in the future when these events (will) occur. In both events, the measured exchange across HVDC interconnection is compared with the power flow at the border between Western Denmark and Germany. The measured values indicate that the large part of the imbalances caused by storm is compensated by exchanged balancing power, activated from the NOIS list, across Konti-Skan link. This shows the pivotal role of hydro power in the Nordic system to balance large wind power variations in Western Denmark especially

during the storm events. However, the frequency in the Nordic system experienced large deviations due to large deviation on exchange across Konti-Skan link. Furthermore, the failure in Konti-Skan link caused an increasing trend in the Nordic frequency and during some minutes frequency goes above the upper threshold for normal operational limits of 50.1 Hz. Comparing the frequency in the Nordic and the Western Danish system shows that the frequency in the Nordic system experienced larger deviations and this due to the following two reasons:

- Western Denmark is synchronised with the Continental European synchronous system, and Continental European system is much larger than the Nordic synchronous system. Therefore, Continental system has more inertia than the Nordic system.
- There are delays in the control signals caused by the manual control in the Nordic system, whereas the automatic control system in Western Denmark reacted very fast on frequency deviations. This has been improved since the Nordic LFC is running with 100MW and will improve further when the size increase.

In this report the focus has been on explaining the operational procedures that are important to understand how unexpected events are handled. When handling the system it is important both to have good forecasts of wind power production so that the wind power production can be anticipated as precise as possible and it is important to have access to enough automatic restoration reserves to restore balance. What the trade-off between these two types of reserves is an on-going discussion.

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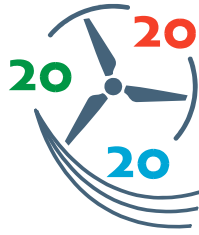
EC-GA nº   249812

Project full title: Transmission system operation with large penetration of Wind and other renewable Electricity sources
                      in Networks by means of innovative Tools and Integrated Energy Solutions

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