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Offshore Wind Power Prediction in Critical Weather Conditions

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Offshore wind power prediction in critical weather conditions

Nicolaos A. Cutululis, Nina K. Detlefsen, Poul Sørensen

***Abstract*—In critical weather conditions, when wind turbines or even whole wind farms are susceptible of shutting down, wind power production forecast is crucial. The performance of today's forecast systems in accurately predicting when a large wind farm is susceptible of shutting down due to extreme wind speeds is investigated in this paper. The analysis is done for Horns Rev 2 offshore wind farm, located on the west coast of Denmark. Historical forecasts, available at Energinet.dk, are compared to historical modelled data, resulted from meso-scale dynamical down-scaling of climate simulation. Finally, a case study, based on a storm event that occurred at Horns Rev 2 wind farm in November 2010 is presented.**

***Index Terms*—Wind farms, offshore, critical weather, prediction, extreme wind, wind power**

I. Introduction

WIND power is currently the most promising renewable technology and is expected to contribute significantly to achieving the "20-20-20" target set by EU - 20% reduction of greenhouse gases and 20% share of renewables by 2020 [1]. The development potential of wind power, especially offshore, is huge. For example, in Denmark only, the target is that wind power will supply approximately 50% of the electricity production by 2025. In order to achieve that, a large amount of offshore wind power, i.e. in the area of 2.5 GW, will be installed in North Sea, in sites that have been selected and published by the Danish Energy Authority [2].

The TWENTIES project (www.twenties-project.eu) aims at "demonstrating by early 2014 through real life, large scale demonstrations, the benefits and impacts of several critical technologies required to improve the pan-European transmission network, thus giving Europe a capability of responding to the increasing share of renewable in its energy mix by 2020 and beyond while keeping its present level of reliability performance" [3]. One of the demonstrations in Twenties is the Storm Management demonstration. The objective of this demonstration is: "The occurrence of storms will raise new challenges when it comes to secure operation of the whole European electric system with future large scale offshore wind power. With the present control schemes, storms will lead to sudden wind plant shut downs, which in turn is a threat to the whole system security, unless standby reserves are ready to take over power demands under very short notice. The challenge that this demonstration is addressing is to balance the wind power variability, operating the transmission grid securely during such storm conditions. The more specific objectives of the demonstration are to:

- Demonstrate secure power system control during storm passage, using hydro power plants in Norway to balance storm shut down of Horns Rev 2 wind farm in Denmark.
- Use existing forecast portfolio available to the TSO to monitor and plan the down regulation of large scale offshore wind power during storm passages.
- Provide more flexible wind turbine and wind farm control during storms." [3].

The ability of existing forecast tools to predict extreme wind periods at the Horns Rev 2 wind farm, located on the west coast of Denmark, Fig. 1, is analysed in this paper.

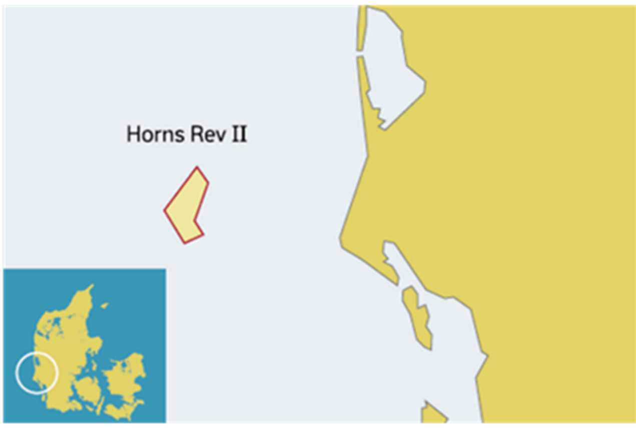

Fig. 1 Horns Rev 2 wind farm location

The idea is to assess the uncertainty in a way that will enable a planned wind farm shut down, which has a high reliability of not being "bypassed" by wind turbine protection. The performance of existing forecast tools has been analysed in many studies, but using performance indicators such as RMSE (root mean square error) and MAE (mean average error). These indicators are useful for normal

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operation, but much less relevant for storm forecasts. In this analysis, focus will be on predicting the time where the wind turbine will need to shut down to protect itself, e.g. the time where wind speed exceeds 25 m/s with the storm controller presently installed. At the same time, the planned shutdown should cost as little lost wind energy as possible. Therefore, the planned shut down time should be as close as possible to the time where the wind turbine itself would shut down, but still reliable.

For a secure operation of power systems, even when the share of energy produced by wind is not very significant, forecasting of wind power has become an indispensable tool. The Danish Transmission System Operator (TSO) Energinet.dk is no exception to that.

Energinet.dk, as TSO, is responsible for the transmission and permanent balance between production and consumption, even if it does not own or operate any generating or consuming facilities directly. All production and consumption entities plan their production or consumption and are obliged to send in detailed power schedules. These schedules are continuously updated.

Based on the power schedules Energinet.dk calculates the systems imbalance and can trade this in the regulating power market. If production facilities deviate from the schedules – which often is the case in a storm situation – Energinet.dk will experience a sudden imbalance that has to be taken care of, either by slow manual reserves or by automatic reserves. Energinet.dk has meteorological forecasts available and calculates its own wind power forecasts optimized to minimize the aggregated wind power imbalances. The forecast is updated every 5 minutes. Meteorological forecasts from DMI's Hirlam model are updated every 6 hours.

If a storm is forecasted correctly it will be possible to do a controlled action preventing severe imbalances. In this case there are several options for calling for this controlled action. The owner of the wind farm can choose to reduce power gradually before the storm or the TSO can call for a gradual reduction of power output. If the wind farm's output is reduced there will be some lost power. The challenge in this situation is to define the strategy for taking action (based on the forecast) in such a way that the lost power is minimized and the safety of the entire scaled future system is maintained. The forecasting of the storm is a crucial input to the management strategy for storm management. In this paper the results from the analysis of storm forecasts is presented.

When wind speed is becoming too strong, wind turbines are shutdown to prevent damage due to extreme mechanical loads. The typical power curve of a modern wind turbine is presented in Fig. 2. The wind turbine will shut down when the average wind speed reaches a certain value denoted V_4 in the Fig. 2. When the average wind speed drops below the shutdown value, the wind turbine starts again. To prevent frequent restarts and shutdowns, hysteresis is often applied, so that the wind turbine starts up only when the average wind speed reaches a value V_3 lower than the shutdown wind speed.

The typical value for which a wind turbine will initiate shut-down is when the 10-minute average nacelle anemometer wind speed reaches 25 m/s (V_4) and they will restart when the measured wind speed drops below 20 m/s (V_3).

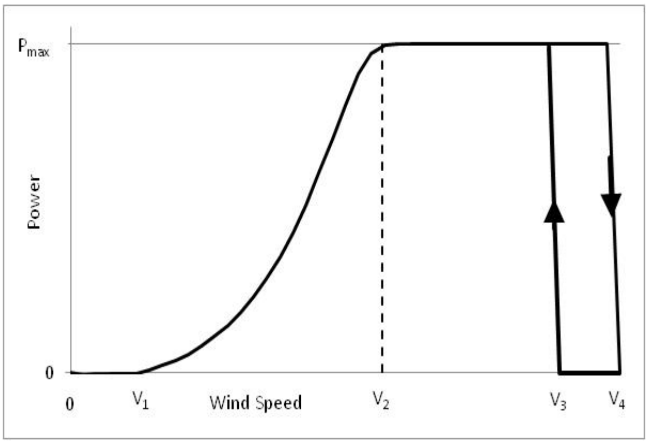

Fig. 2 Typical wind turbine power curve

Consequently, an extreme wind period (EWP) is defined to be the one in which the storm control is active and is considered to occur when the wind speed exceeds the cut-out speed and lasts until the wind speed drops below the cut-in speed.

The meteorological forecasts are given as the average value over an area defined by the grid points distance (15km spatial resolution for the meteorological forecast at Energinet.dk) and with hourly resolution. This means that the forecasted wind speed values will not give proper results if used for predicting when individual wind turbines will initiate shut-down due to large wind speed. Instead, they should be used to assess the ability to predict EWPs at wind farm level.

A question that arises naturally is what are the values that characterize an EWP when looking at a large offshore wind farm as a whole. This subject was analysed based on measurements coming from Nysted wind farm and the result was that most of EWP’s occur when the average wind speed over the whole wind farm is in the range [18(V_3) 22.5(V_4)] m/s. Therefore, this is the pair of wind speeds that, in the following, define a wind farm level EWP.

II. Historical Data Analysis

A. Historical modelled data

The meteorological data are generated by a climate simulation using the Weather Research and Forecasting (WRF) model and the dynamical downscaling technique developed by Hahmann et al [4], but using Newtonian relaxation terms toward the large-scale analysis (also known as grid or analysis nudging). Initial and boundary conditions and the gridded fields used in the nudging are taken from the NCEP reanalysis [5] at 2.5° × 2.5° resolution. The sea surface temperatures are obtained from the dataset of Reynolds et al [6] at 0.25° horizontal resolution and temporal resolution of 1 day. The simulation covers the period from January 1st 1999 to December 31st 2010 with hourly outputs. The model is run on an outer grid of spatial resolution of 45 km and a nested grid of 15km, respectively. The data from the inner domain, which covers most of Northern Europe, is used in this study. Additional details can be found in [7].

The historical modeled data are used due to the scarcity of consistent wind speed measurements, covering a period of time large enough to have a statistical relevance in the attempt of assessing the performance of forecasts to predict EWP. Before using this data, they were compared to measurements. The most consistent and lengthy data set available to the project partners comes from Nysted wind farm, located in the Baltic Sea [8]. The data consists of the 10-minutes average wind speeds recorded by the anemometers on the nacelle of the individual wind turbines. What is interesting in this context is the wind farm average wind speed. Therefore, the mean wind speed over the whole wind farm was computed as the average speed of all wind turbines in the wind farm. Further, the hourly mean wind speed was calculated and compared to the historical data. The data cover the period 2007 – 2010. The average wind speed, over the whole period, as well as the standard deviation for both measurements and historical modeled data are given in Table 1.

TABLE I
THE STATISTICS OF MEASURED AND HISTORICAL MODEL DATA

	Measurements	Historical
Average [m/s]	8.2	8.9
Standard deviation	3.34	4.25

The mean wind speed resulting from the down scaling of WRF data (the wind speed historical model data) is slightly higher than the one resulting from the averaging of the nacelle measurements. The variability of the time series is also different, with the historical data again having a larger standard deviation. The differences can be regarded as acceptable, especially if it is taken into account the fact that the measurements are from the wind turbine nacelle.

Fig. 3 shows measured versus historical model wind speed time series. There is an acceptable match between them. The duration curve of the error between the measured and the historical modelled wind farm mean wind speed is given in Fig. 4.

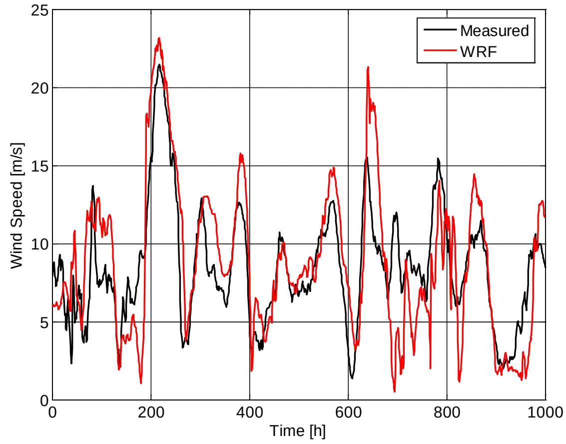

Fig. 3 Measured versus historical model data

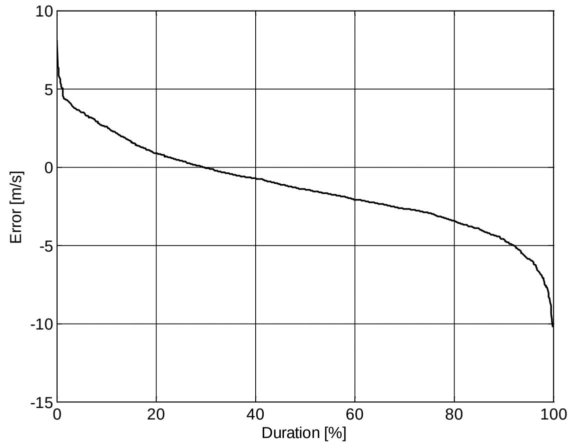

Fig. 4 Distribution of the error between measured and historical modelled wind farm mean speed

As expected, the error, which is defined as measured minus historical model, is positive only 30% of the time and negative about 70% of the time, thus historical model values are larger than the measured ones. One reason for this is that the available measurements are from the wind turbine nacelles, behind the rotor.

B. *Wind speed forecast errors*

The analysis of the ability of forecasting tools to predict storms at Horns Rev 2 offshore wind farm was done based on available data covering the time period February 2007 to November 2010 (45 months). The wind speed and direction are given at 100 meters height, with an hourly resolution. The yearly and the total number of forecasted EWP's versus the ones seen in the historical modeled wind speeds are given in Fig. 5. There seems to be a significant overestimation of the EWP by the forecast (33 forecast versus 19 resulting from the historical model data).

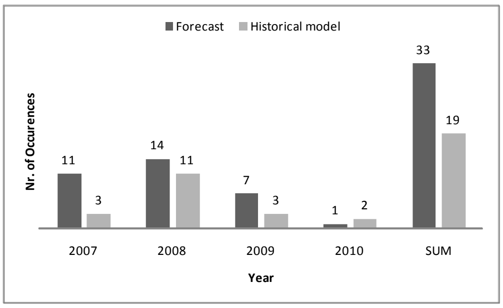

Fig. 5 EWP per year, 100 meters height wind speeds

Besides the frequency of the EWPs, it is also important to see the accuracy of the forecast. An accurate forecast, in this sense, is when an EWP did actually occur during the day that it was forecasted. The result of this analysis is given in Table 2, where it can be seen that of the 33 forecasted storms only 8 occurred and of the 19 that occurred only 8 was forecasted. The accuracy of the forecast is therefore rather poor, with less than 25% of the forecasted EWPs actually happening. Furthermore, it is observed that almost 60% of the EWPs that occurred were not forecasted at all.

TABLE II
ACCURACY OF FORECAST

Historical		Forecasted	Forecasted		Historical
Yes	No		Yes	No	
8	25	33	8	11	19
24%	**76%**	**100%**	**42%**	**58%**	**100%**

The wind speed forecast error is defined as the difference between forecasted and modeled wind speed, i.e. positive values of the forecast error means that the predicted wind speed is higher than the historical model wind speed. The duration curve of the wind speed forecast error, quantified during the predicted EWP, is given in Fig. 6, and marked as 100 meter. Data from 10 meters height are also available, but they are beyond the scope of this analysis. It can be concluded that there appears to be a systematic over estimation of the wind speed, as the forecast error is positive for around 70% of the time. The forecast error is situated in the range of ± 5 m/s for most of the time.

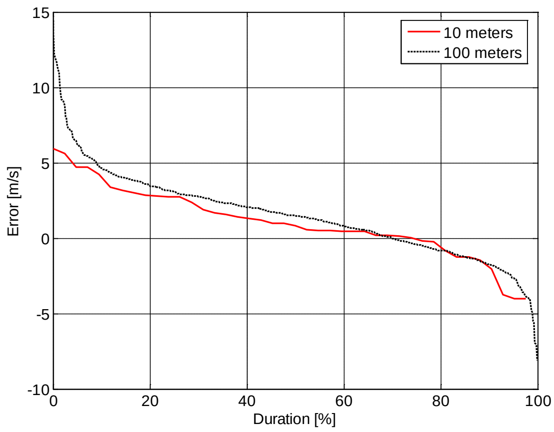

Fig. 6 Duration curves of the wind speed forecast errors

C. *Wind power forecast error*

For the operation of power systems, the most important part is wind power forecast. The typical way of obtaining wind power production from forecast wind speeds is by using a static model of the wind turbine, namely the power curve. Therefore, the available wind speeds, forecasted and historically modelled, were transformed in power using an aggregated wind farm power curve.

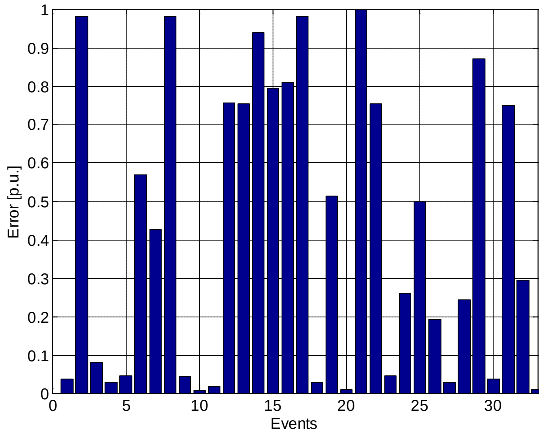

Fig. 7 Maximum absolute wind power error for each predicted EWP

The wind power forecast error, defined in a similar manner as the wind speed error, was quantified for each of the 33 forecasted EWP and the maximum absolute value, for each of them, is presented in Fig. 7.

The analysis shows that in most cases, the wind power forecast error is in the vicinity of 1 p.u. This means that TSO's will have to deal with sudden and unexpected (not forecasted) power losses of 1 p.u.

III. CASE STUDY

During a storm an EWPs was recorded in Horns Rev 2 on the afternoon-evening of November 11th, 2010.
The wind farm wind statistics of the wind speeds measured during the first period, from 16:00 to around 23:00 on November 11th, 2010, is shown in Fig. 8.

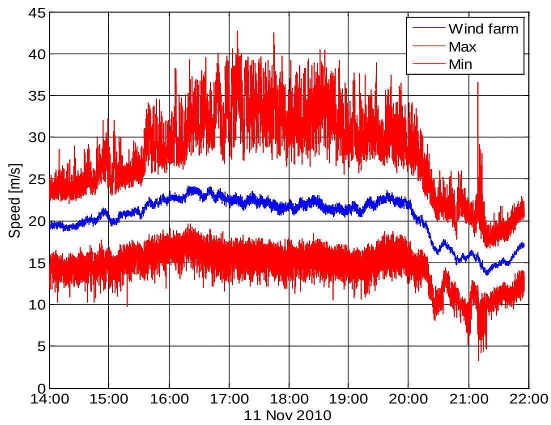

Fig. 8 Measured wind speeds during EWP

The sample time is 1 sec. and the wind speeds are measured on the individual wind turbine nacelle. The wind farm statistics are calculated as the mean value and minimum/maximum values of the 91 individual turbine wind speeds.

The first conclusion arising is that the average farm wind speed never exceeds 25 m/s, even if some of the wind turbines experience wind speeds well above 25 m/s for several hours. This shows that, when dealing with mean farm wind speeds, the hysteresis for individual wind turbines, i.e. [20 25] m/s, is not able to predict the wind farm behavior.

The wind speed forecast for November 11th is shown in Fig. 9. The measured wind speed is the mean value of the wind turbine wind speeds, similar to the one in Fig. 8, but with 1-minute sample. The forecast wind speed is the one available at Energinet.dk on November 10th at 12 AM and it is with 1-hour time step. It is easily observed that while the forecasted wind speed follows the measured one, its value never exceeds 22.5 m/s and thus it will not trigger the storm hysteresis.

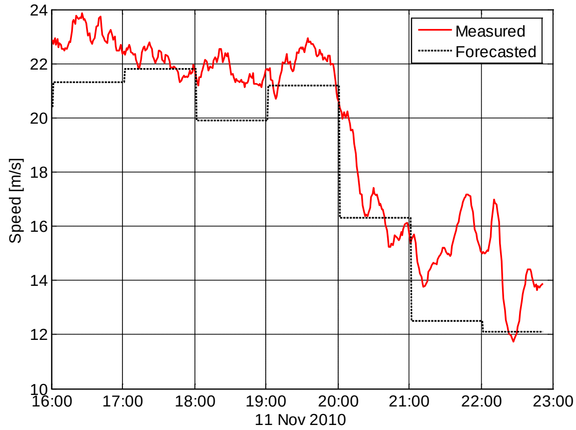

Fig. 9 Horns Rev 2 wind speed forecast for November 11th EWP

The power produced by Horns Rev 2 wind farm during November 11th EWP is shown in Fig. 10. The wind power production went from 1 p.u. to 0 in app. 55 minutes (16:17 – 17:22), which implies a ramp of app. -3.8 MW/min or -0.02 p.u./min. These values are not posing a big challenge in the operation of the West Denmark power system.

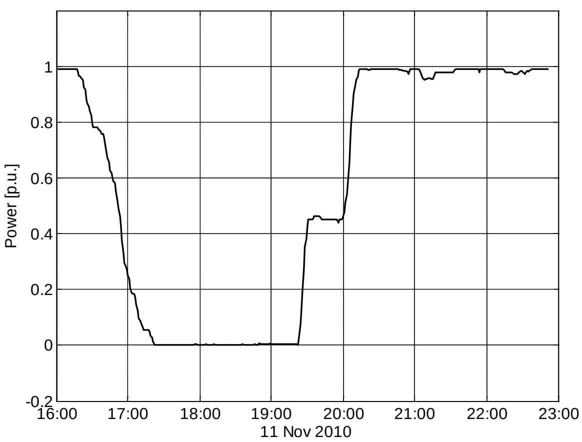

Fig. 10 Power produced by Horns Rev 2 wind farm during November 11th EWP

The wind power forecast, based on the online measurement data and running every 15 minutes, is shown in Fig. 11. The online wind power forecast has a 5-min resolution. Based on those forecasts, the control room operators will not have any prediction about the loss of wind power produced by Horns Rev 2.

The evolution of the wind power forecast error during the EWP is shown in Fig. 12. During the peak of the EWP, i.e. in the time interval 17:30 – 20:30 the error is going up to almost 1 p.u.

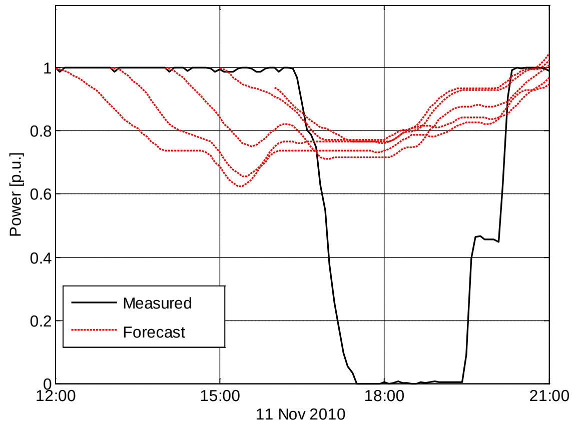

Fig. 11 Measured versus hourly intra-day forecast wind power

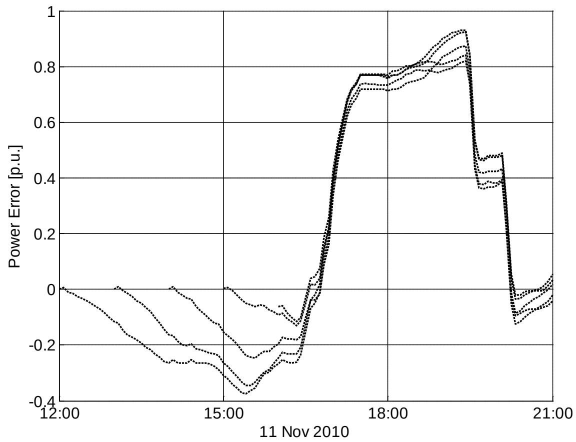

Fig. 12 Wind power forecast error during November 11th EWP

IV. Conclusions

The analysis presented in this paper aimed at assessing the capability of existing forecasting systems to predict EWP that would lead the whole wind farms to shut down in order to protect the wind turbines.

Some main conclusions arise from the work done. First of all, defining a so called “storm event” at a wind farm level is not trivial. For individual wind turbines, a “storm event” is very well defined and it has as a direct consequence the emergency shut-down of the wind turbine. The shut-down procedure is initiated when the 10-min average wind speed recorded by the anemometer on the wind turbine nacelle exceeds 25 m/s and the wind turbine remains stopped until the 10-min average wind speed reaches values below 20 m/s, thus leading to a so called wind speed hysteresis of [20 25] m/s. When dealing with wind farms, what is available is the wind speed forecast. This is usually given as the average wind speed over a grid area with a spatial resolution of several km, therefore using the wind turbine hysteresis is not feasible. From the analysis done, it came out that a hysteresis of [18 22.5] m/s, i.e. 10% lower than the wind turbine one, would be suitable when dealing with wind farms.

Even with this wind speed hysteresis, the ability of the forecast systems to predict when a wind farm will go from full production to zero is not very good. In general, the forecast seems to overestimate the EWP, with only 25% of the forecast EWPs having a correspondence in the model wind speed data. Furthermore, 60% of the EWP that could be indentified in the model data were not predicted by the forecasts. The same conclusions arise from the EWPs that occurred during the project period. Again, the wind speed forecasts are not able to predict that the wind farm will stop producing due to EWP.

When looking at the wind power production, the conclusions are similar. In both modelled and measured EWPs, the forecast wind power failed to predict the wind farm stopping. This could be, to some extent, due to the fact that the power curves used in Energinet.dk to transform wind speed in wind power are calibrated for wind speeds in the range of 5-10 m/s (the wind power optimisation range). In general, the extreme wind speed part of the power curve has not received much attention, partially because today, losing the power produced by an offshore wind farm, i.e. in the range of 200 MW, does not represent an important threat to secure operation of the power system.

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VI. Biographies

Nicolaos. A. Cutululis (M'06) was born in 1974. He received M. Sc. and Ph.D. in electrical engineering in 1998 and 2005. Since February 2005 he has been employed in Wind Energy Division of Risø DTU, currently as Senior Scientist. His main technical interest is integration of wind power into power systems, involving a variety of technical disciplines including integrated design, dynamic modeling and control of wind turbines and farms and wind fluctuation statistics.

Nina K. Detlefsen works in Systems Analysis at Energinet.dk. She studied operations research at the University of Aarhus, Denmark and the Norwegian University of Science and Technology. After working with research in decision support systems in agricultural sciences several years she joined the energy sector in 2006. Her special fields of interest include electric power systems, dispersed energy resources and modeling and optimizing energy system.

Poul E. Sørensen (M'04, SM'07 was born in 1958. He received M.Sc. in electrical engineering from the Technical University of Denmark in 1987. Since 1987 he has been employed in Wind Energy Division of Risø DTU, currently as Professor. His main technical interest is integration of wind power into power systems, including dynamic modeling and control of wind turbines and wind farms, power system control and stability, wind power fluctuations and forecast errors. He is convener of IEC working group preparing a new standard IEC 61400-27 Electrical Simulation Models for Wind Power Generation, and member of maintenance team of IEC 61400-21 on Measurement and Assessment of Power Quality of Gird Connected Wind Turbines. He is Editor for Wiley's journal Wind Energy.