Improvement of the Power System Reliability by Prediction of Wind Power Generation

Kurt Rohrig[1], Bernhard Lange[2]

Abstract: The integration of wind farms into the electricity grid has become an important challenge for the utilization and control of electric power systems, because of the fluctuating and intermittent behaviour of wind power generation. Wind power predictions improve the economical and technical integration of large capacities of wind energy into the existing electricity grid. Trading, balancing, grid operation and safety increase the importance of forecasting electrical outputs from wind farms. Thus wind power forecast systems have to be integrated into the control room of the transmission system operator (TSO). Very high requirements of reliability and safety make this integration especially challenging.

The pooling of several large offshore wind farms into clusters in the GW range will make new options feasible for an optimized integration of wind power. The geographically distributed onshore wind farms will be aggregated to clusters, for the purpose of operating these wind farms as one large (virtual) wind power plant. For this purpose, a new structure, the wind farm cluster will be introduced. All wind farms, which are directly or indirectly connected to one transmission network node will be associated to one wind farm cluster. The wind farm cluster manager (WCM) assists the TSO by operating the cluster according to the requirements of the power transmission system. Non-controllable wind farms within a wind farm cluster are supported by controllable ones.

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I. INTRODUCTION

By the end of September 2006, more than 18,000 Wind Turbines (WTs) with an installed capacity of 19,500 MW generated approx. 22 TWh/year and supplied about 6.5% of the German electricity consumption [1], [2]. The targets of several countries of the European Union to increase the share of renewable energy production of the consumption to up to 40% [3] require a peak load contribution of 60%. This generation mix, dominated by Renewable Energy Sources (RES) leads to a continuous surplus in low demand periods (in the night). For wind power, these future scenarios expect temporal load coverage of more than 100 % [4]. Without new control options, these situations will effect system stability and run the risk of blackouts. To operate electricity systems with this high share of RES requires new operational strategies based on precise wind power forecasts and active contribution of Distributed Energy Resources (DER) to system reliability [5]. Without advanced and coordinated generation management, unexpected load flows will also appear frequently across borders, which requires an interoperability of the national grids.

The increasing penetration of wind energy in Germany, particularly in regions with low load has frequently direct impact on grid operation and congestion management. Special attention is to be put on the incorporation of the instantaneous and expected wind feed-in in the load flow calculations. The currently used forecast tools supply only one value per hour for wind power production for the entire control zone and/or the grid area. For the consideration of the wind feed-in for the load flow calculation however the exact values of in- and outfeed at each node of the high and extra-high voltage grid are required. Deviations between real and predicted wind power feed-in, particularly in high wind periods can cause extreme variations of the

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load flow and require a re-valuation of the entire grid condition.

Today, the network operators avoid congestions by curtailing wind power. This so called wind generation management will be improved by the use of tailored forecast systems – adapted to grid calculation tools.

II. TOOLS AND INFORMATION TO ASSIST MAINS OPERATION

Wind power forecast is an integral part of the electricity supply system in Germany. The Wind Power Management System (WPMS), developed by ISET, is used operationally by all German transmission system operators [6], [7]. The system consists of three parts:

- The determination of the instantaneous value of wind power feed-in, which performs an up-scaling of current measured power values at representative wind farms to the total wind power production in a grid area.
- The day-ahead forecast of the wind power production by means of artificial neural networks (ANN). This is based on input from a numerical weather prediction (NWP) model.
- The short-term forecast, which additionally employs online wind power measurements to continuously produce an improved forecast for up to 8 hours ahead.

For the determination of the instantaneous value and the short-term wind power forecast, representative wind farms or wind farm groups have to be determined and equipped with online measurement technology. For the day-ahead forecast, only historical time series of measured power output of the representative wind farms are needed. For these locations, forecasted meteorological data obtained from a numerical weather prediction (NWP) model are used as input [8], [9]. The resolution of the forecast and the forecast horizon depends on the NWP data used. In Germany, currently an hourly resolution and a forecast horizon of 3 days are in operation.

Artificial neural networks (ANN) are used to forecast the wind power generated by a wind farm from the predicted meteorological data of the NWP model. The ANNs are trained with NWP data and simultaneously measured wind farm power data from the past, in order to 'learn' the dependence of the power output on predicted wind speed and additional meteorological parameters (figure 1). The advantage of artificial neural networks over other calculation procedures is that it 'learns' connections and 'conjectures' results, also in the case of incomplete or contradictory input data [10]. Furthermore, the ANN can easily use additional meteorological data like air pressure or temperature to improve the accuracy of the forecasts. The deviation (Root Mean Square Error RMSE in percent of the installed capacity) between the (day ahead) predicted and actually occurring power for the control areas of the German TSOs in the operational forecast system currently is about 6% of the installed capacity. The forecast error for the total German grid amounts to about 5%.

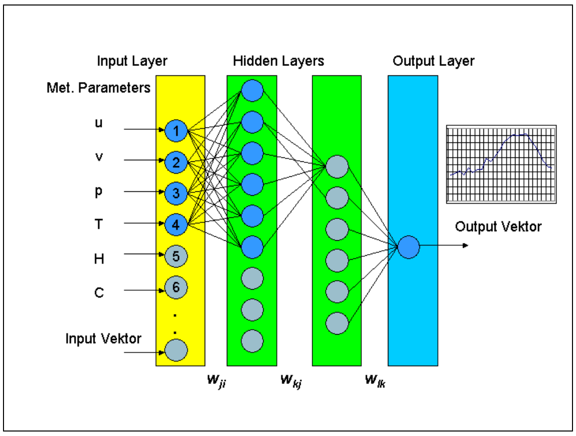

Fig. 1: Sketch of an artificial neural network (ANN) used for the wind power forecast

In addition to the forecast of the total output of the WTs for the next days, short-term (15-minutes to 8 hours) forecasts are the basis for an efficient and save power system management. Apart from the meteorological values such as wind speed, air pressure, temperature etc., online power measurements of representative wind farms are an important input for the short-term forecasts.

III. RECENT ADVANCES IN WIND POWER FORECASTING

Improved representation of the atmospheric boundary layer

The selection of the input parameters for the ANN is of crucial importance for the performance of the forecast. Wind velocity and wind direction are, of course, the most important parameters for the wind power forecast. However, with the neural network approach it is easily possible to incorporate additional parameters. The set of meteorological parameters used for the forecast has been improved to take into account the influence of atmospheric stability, especially for new turbines with high towers. This let to an important improvement in forecast accuracy. Most important was the inclusion of the predicted wind speed at 100 m height. As can be seen in figure 2 for the example of one German TSO control zone, the forecast error (RMSE in percent of installed capacity) was reduced by more than 20%. Two different numerical weather prediction models were used as input for the forecast, showing very similar results.

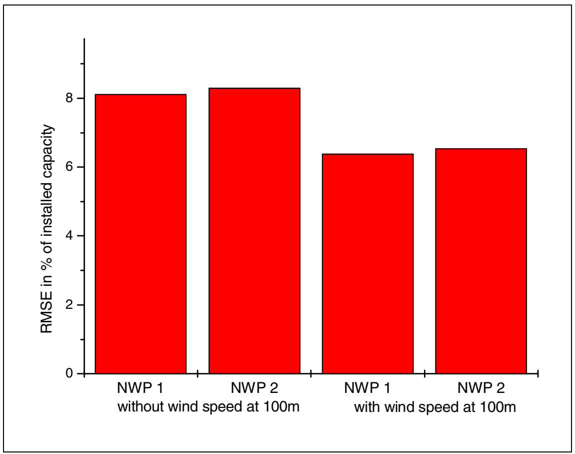

Fig. 2: Comparison of the wind power forecast accuracy for a control zone using forecasted wind speeds at 10 m and 100 m height as input parameter

Multi-model approach for forecasting methods

Day-ahead wind power forecasting by ANN as one method of artificial intelligence (AI) is used operationally by German TSOs. To improve the forecast ability, other types of AI-models were investigated in a comparative study. In detail these are mixture-of-experts (ME), nearest-neighbour search (NNS) combined with particle swarm optimization (PSO) and support vector machines (SVM). Additionally we build an ensemble from all models.

The ANN consists of nonlinear functions g which are combined by a series of weighted linear filters [11]. Here a neural network with one hidden layer was used, constituting the weight matrices A and a.

$$\hat{P}_t = g\left[\sum_{j=1}^{m} a_j g\left(\sum_{k=1}^{m} A_{jk} w_{kt}\right)\right] \quad (1)$$

The vector w_{kt} contains the input data from the numerical weather prediction model, i.e. k values of meteorological parameters at time t. $\hat{P}_t$ denotes the output value, i.e. the predicted power output of a wind farm at the time t.

The ME model is a construction of different 'expert' neural networks to tackle different regions of the data, and then uses an extra 'gating' network, which also sees the input values and weights the different experts corresponding to the input values [12].

The NNS [13] uses those observations in a historical NWP data set closest in input space to the actual input values to form the output. The used NNS method is based upon the construction of a common time delay vector of weather data from several prediction locations of the NWP and upon an iterative algorithm consisting of the NNS and a superior PSO for the selection of optimal input weather data [14].

The SVM maps the input data vectors w_t into a high-dimensional feature space by calculating convolutions of inner products using some so-called support vectors w_i of the input space.

$$f(w_t) = sign\left[\sum_{\text{sup port vectors}} P_i \alpha_i K(w_i, w_t) - b\right] \quad (2)$$

In general, support vector machines are learning machines using a convolution of an inner product K allowing the construction of non-linear decision functions in the input space, which are equivalent to linear decision functions in the feature space. In this feature space, an optimal separating hyper plane is constructed [15].

A comparative study between the different forecasting methods has been performed using power output measurements of 10 wind farms in the E.ON control zone and corresponding NWP prediction data for these points from the German weather service DWD. Data from September 2000 to July 2003 have been used. Figure 3 shows the comparison of the mean RMSE for the 10 wind farms. It can be seen that the support vector machine yields the best results in this case. Also, a simple ensemble approach has been tested by averaging the outputs of the models studied. As can be seen in figure 3, even this simple ensemble improves the forecast accuracy compared to the results of the single ensemble members.

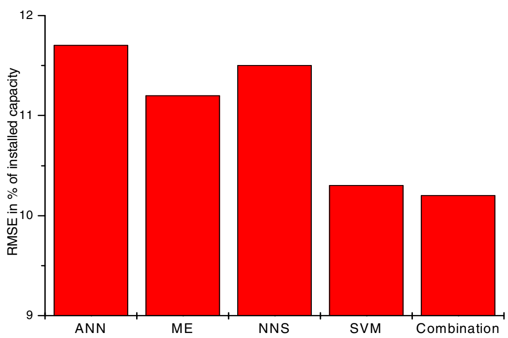

Fig. 3: Comparison of the mean RMSE of a wind power forecast for a group of single wind farms obtained with different AI methods and with a combination of all methods

Multi-model approach for numerical weather forecast models

An investigation points out the influence of merging different NWP models on the accuracy of the wind power forecast. Three different NWP models have been used for a day-ahead wind power forecast for Germany. All models have been used with the WPMS (based on the ANN method). The training of the networks has been performed with data of more than one year. A concurrent data set of seven months (April – October) has been used for the comparison.

The RMSE in percent of the installed capacity of the three models are shown in figure 4. It can be seen that the differences between the models are small. Additionally, a simple combination of the three models has been tested by averaging their forecasts. It can be seen that even this simple approach improves the forecast accuracy very significantly compared to the results of the single models. The resulting RMSE for the combined model for Germany is 4,7%.

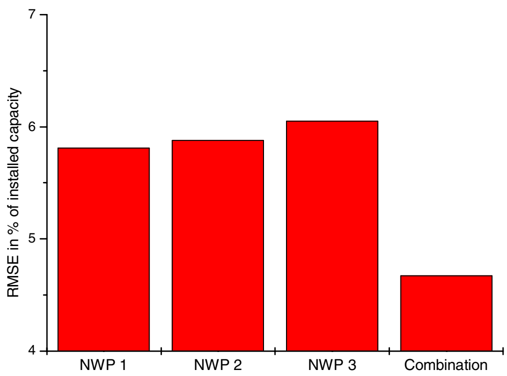

Fig. 4: Comparison of the mean RMSE of a wind power forecast for Germany obtained with the WPMS with input data from three different NWP models and with a combination of these models

Prediction of the forecast uncertainty

In addition to the wind power forecast itself, it is important to have knowledge of uncertainties of this forecast. A statistical method has been used to predict not only the power output, but also an upper and lower limit for the forecast accuracy for each time step (figure 5). The statistical method is based on the determination of the forecast uncertainty for each representative wind farm depending on wind speed and wind direction. The total uncertainty is then calculated from the uncertainty estimations of all representative wind farms.

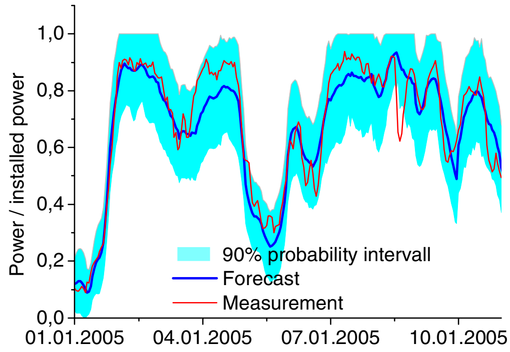

Fig. 5: Example time series of the forecasted power output and its 90% probability interval compared with real production values

IV. EXTENDED OPERATIONAL CONTROL FOR LARGE WIND FARMS

According to the German Federal Government's planning, the share of renewable energies in German electricity consumption should increase to 12,5 % by 2010 and to 20 % by 2020, of which the majority will be expected as wind energy. The conventional power production in the electrical power system will be reduced at times with high wind power feed-in. Today, conventional power plants are needed to supply ancillary services for grid management. In the future, wind farms will have to provide a part of these ancillary services, such as the supply of reactive and balancing power. Modern WTs have extended functions capable to contribute to operational grid management [16], e.g.:

- Reactive power feed-in (desired value of default reactive power or default power factor) depending on the WTs ability of reactive power provision and the wind conditions.
- Generation Management (limitation of maximum active power feed-in), which controls and regulates the power feed-in to the grid connection node.

A single WT operates as an autonomous system, but for additional functions a high-level Power Management System (PMS) is necessary. The PMS operates and manages a wind farm, which may consist of several single wind turbines. By using this PMS, the following management strategies can be applied:

- Reactive power provision (desired value of default reactive power or default power factor) with a usual setting range like conventional-power-station, independent of the wind conditions
- Schedule setting to follow a given schedule for the wind farm depending on the wind (power)

V. WIND FARM CLUSTER MANAGEMENT

The pooling of several large wind farms into clusters will make new options feasible for an optimised integration of intermittent generation into electricity supply systems. The geographically distributed onshore wind farms will be aggregated to clusters, for the purpose of operating these wind farms as one large (virtual) wind power plant [17]. For this purpose, a new structure, the wind farm cluster, will be introduced. All wind farms, which are directly or indirectly connected to one transmission network node, will be associated to one wind farm cluster. The WCM aids the TSO by operating the cluster according to the requirements of the power transmission system. Non-controllable wind farms within a wind farm cluster are supported by controllable ones. The following operational control strategies to support a reliable grid operation are feasible:

1. Reduction of gradients to minimize ramp rates
2. Supply of reactive power with a usual setting range like a conventional-power-station
3. Generation Management which controls and regulates the feed-in for the whole wind farm cluster
4. Supply of negative and positive reserve power for the balancing between wind power prediction and wind power generation
5. Congestion Management by limitation of wind power output
6. Generation schedule of wind power feed-in to achieve a reliable scheduling

The first four strategies have aspects relating both to operation control for single wind farms and to energy management of a whole cluster. For example, even if a wind farm is able to supply balancing power, by taking advantage of the smoothing effect in a cluster of distributed wind farms the reliability, which is needed for balancing power, is increasing substantially. However, it is still depending on the wind forecast and its uncertainties. Some of these strategies use the same basic functions e.g. the limitation of power output. The control strategies can be realised by using the four WCM operating modes:

1. Active Power Limitation (which combines the strategies “Reduction of gradients”, “Generation Management” and “Congestion Management”)
2. Supply of Reactive Power
3. Supply of Balancing Power
4. Scheduling

The WCM can be located in the TSO’s grid control centre. The existing control-system could be used to manage the data flow. The WCM receives the measured values from the wind farms. The desired values will be sent from the WCM to the several PMS’s.

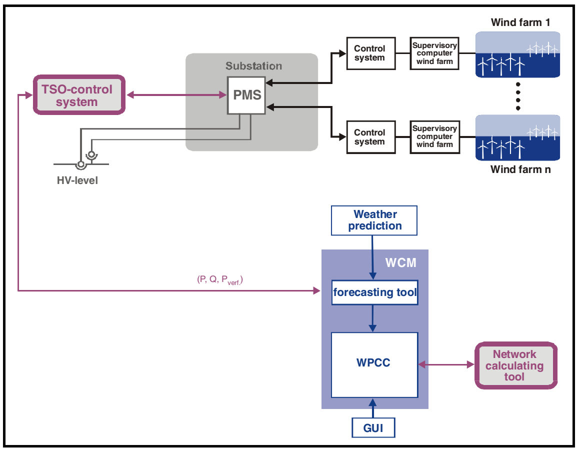

Fig. 6: Data flow between WCM, PMS and the TSO control system

For the operation modes different planning intervals need to be considered. At the previous day (after receiving the meterological weather forecast) a day-ahead-prediction is computed. By using the forecast as a provisional wind generation schedule, the TSO can calculate the power flow in his grid and thus detect possible congestions. The tool also provides a confidence interval for the forecast uncertainty [18]. This allows a first estimation of the balancing power needed for the cluster.

If necessary, the WCM executes calculations to implement the TSO's requirements for the cluster, e.g. if the TSO wants the whole cluster to follow a given schedule, the WCM computes generation schedules for each single wind farm, to ensure that the aggregation of all wind farms in the cluster achieves the requirements for the cluster.

Assuming a 100 % accuracy of wind power prediction will be achieved, this schedule could be followed by the wind farms. The day-ahead prediction is used as an initial estimation of wind power generation. During operation, a short-term prediction using current measured data to obtain a more accurate forecast in the range of 4 hours is executed. The WCM gets the current feed-in-values from the TSO’s control system every 15 minutes. With this information it predicts the future generation for the next point in time up to a time horizon of four hours and then re-computes the generation schedule for every single wind farm under consideration of the cluster constraints.

Active Power Limitation

By the operation mode "Active Power Limitation" the WCM ensures that the active power output for the whole cluster is kept under a certain limit. In this case the active power feed-in of the wind farms has to be reduced.

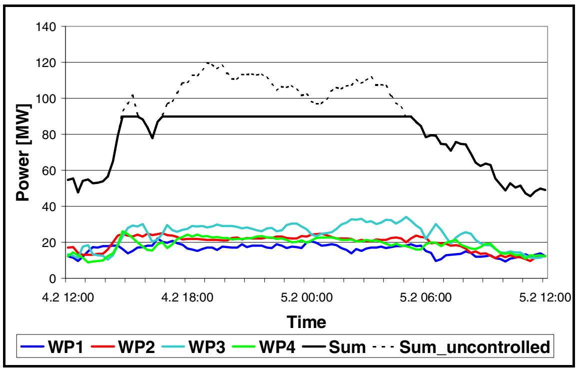

Fig. 7: Active power limitation in a cluster with four wind farms

Figure 7 shows an example with four wind farms ("WP1" – "WP4") and a total power limitation for the cluster of 90 MW. Without limitation of active power, the predicted maximum cluster feed-in in this example is about 120 MW ("Sum_uncontrolled"). If this would lead to congestion, the TSO has to limit the wind power feed-in of the whole cluster during a specific time period. The WCM now computes a schedule for all four wind farms, so that the sum of the output does not exceed the required value of 90 MW ("Sum").

Supply of Reactive Power

The operation mode "Supply of Reactive Power" can be used to provide a desired value of reactive power. In this case for each wind farm the information is needed, whether and to what extent reactive power can be supplied. For wind farms, which cannot supply a variable amount of reactive power, a forecast of its reactive power demand or generation is needed. With this information the WCM is able to determine the respective reactive power of each wind farm and to transfer the set points to the PMS.

If the wind farm is not directly connected to the power transmission system, the supply of reactive power for onshore wind farms is difficult. The WCM operates the wind farms according to the requirements of the power transmission system, but in this case the regulation of the reactive power is done by the respective Distribution System Operator. Thus the supply of reactive power by the WCM is only sensible for wind farms, which are directly connected to the transmission system. This is usually the case for offshore and large onshore wind farms.

Supply of Balancing Power

By the operating mode "Supply of Balancing Power" the WCM shall provide negative and positive reserve power for the balancing between wind power prediction and wind power generation in the whole TSO control area. In the future, in order to provide balancing power for load variations or power plant failures, WTs have to meet the TSOs pre-qualification rules for balancing power.

The supply of negative balancing power can be easily done by curtailing the output of the wind farm. To supply positive balancing power, the wind farm can be curtailed first and provide the difference between the curtailed and the un-curtailed wind power output as positive balancing power. In this operating mode the active power feed-in of the wind farms is reduced.

Because it is not possible to compute a wind power prediction with an accuracy of 100 %, a confidence interval to estimate the error between actual and predicted feed-in is necessary. The lower level of the confidence interval is the value for wind generation, which will be available with high probability. Since the requirement for availability of balancing power is very high, instead of the forecasted value the lower level of the confidence interval must be taken as reference level for supply of balancing power. If the cluster now curtails its feed-in below this level, the difference between computed feed-in and lower level of the confidence interval can be provided as positive balancing power. However, it has to be pointed out that it is still necessary to analyse whether it is possible that wind farms can provide balancing power with respect to the TSOs pre-qualification rules and the high requirements especially in view of availability and reliability.

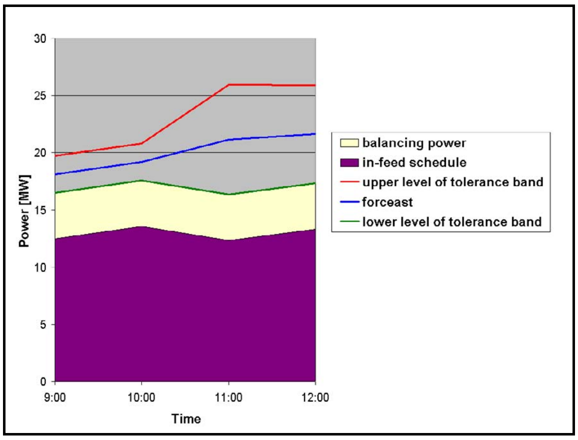

Fig. 8: Example for wind farm with balancing power after short term prediction

Figure 8 shows an example for a computed wind generation schedule based on the 4 hour short term prediction with a provided positive balancing power of 4 MW. The computed feed-in power can be provided at the same time as negative balancing power. The schedule for the cluster feed-in is then used as set point in the operating mode "Active Power Limitation". If the balancing power is not needed, the cluster runs through its computed schedule. If balancing power is needed, the feed-in of the cluster can be increased or decreased according to the need of positive or negative balancing power.

Scheduling

Aim of this operation mode is to follow a given schedule for wind farm clusters. This is done by taking advantage of the smoothing effect. The schedule must consider the given weather situation and particularly the wind conditions, e.g. the schedule can't be higher than the predicted wind power generation.

VI. CONCLUSIONS

As the wind power capacity grows fast in Germany and many other countries, forecast accuracy becomes increasingly important. However, it can also be expected that the increase in forecasting accuracy can be maintained in the future. A number of improvements such as the development of operational ensemble model systems, new generation of NWP models with more frequent updates of the weather predictions and methods for the combination of different forecasting methods are expected. Especially for short-term wind power forecasting, the additional use of online wind measurement data [19] has the potential for a new role of forecasts in mains control. Forecast accuracy is only one of the challenges for wind power forecasting systems of the future. Additionally, the scope of systems will have to be extended to meet future challenges:

- Wind power forecast in the offshore environment has the potential to become more reliable than on land, if specific offshore forecast models are developed.
- Improved forecasts for short time horizons will be needed for grid reliability.
- Prediction of the probability distribution of the forecasting error and reduction of events with large errors give the opportunity to reduce the reserve capacity for balancing wind power forecast errors.
- Forecasts in high spatial resolution for each grid node of the high voltage grid will be needed for high wind power penetration to tackle the problem of congestion management.

Considering the increasing number of wind farms in electrical power systems and the upcoming erection of offshore wind farms, an intelligent management tool for wind power generation becomes more important. Besides new operational controls for single wind farms, a high-level energy-management is also necessary.

By pooling of wind farms to so called wind farm clusters, the WCM, developed in a German research and development project, is able to coordinate the geographically distributed wind farms and represent it as one (virtual) wind power plant for the system operators purposes. The developed WCM simplifies the controlling of large number of WTs in electrical power system as one unit.

VII. ACKNOWLEDGEMENT

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Dr. Kurt Rohrig is head of ISET's R&D Division Information and Energy Economy. Dr. Rohrig worked with ISET since 1991 and has been the scientist-in-charge for projects handling the real time calculation and prediction of wind power for large supply areas – operated in co-operation with large power transmission utilities. The computer models and approaches, developed in frame of his work are in operation at all German transmission system operators with high wind power penetration. He is member of IEEE PES and representative of ISET in CIGRE C6. Furthermore, Dr. Rohrig is head of the thematic network "Energy and Communication" which consists of 12 partners of industry, universities and research institutes.

Dr. Bernhard Lange is head of Information and Prediction Systems of the R&D Division Information and Energy Economy at ISET. He is a physicist with MSc from the University of Oldenburg. After graduating he worked in Denmark with Risø National Laboratory and Wind World A/S. 1998 to 2002 he prepared his PhD about offshore wind power meteorology at Risø National Laboratory and University of Oldenburg. His main research interests for the last 10 years are wind power meteorology and wind farm modelling.