Control Reserve Provision with Wind Power Plants

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Abstract— **Under current framework conditions wind turbines are not able to participate in control reserve markets, though they are contributing an increasing share of the electricity in the power system. For this reason, the Fraunhofer IWES led the two-year project called "control reserve provision with wind farms" together with Enercon, Energiequelle, Amprion and TenneT, in order to investigate a possible participation of wind turbines in balancing reserve markets. The objectives of the project were to define a method for the bid creation in the market and a proof method for the delivery of control reserve by wind turbines. Alongside the associated information and communications technology solutions had to be developed. This paper will show the results from this project.**

The amount of control reserve that can be offered with a defined security can be determined with the help of probabilistic forecasts. Different strategies to offer control reserve on the market have an impact on the achievable potentials. In addition, a proof method using the available active power signal was developed. This allows the provision of control reserve relative to the available active power signal and reduces energy losses. The proof method implemented currently is based on sschedules and would cause energy losses for wind farms. In a field test the proof method using the available active was demonstrated.

The project concludes that the delivery of control reserve with wind turbines is technically possible for the proof method using the schedule. The determination of the available active power however is still not accurate enough. The project proved that significant economic potentials can be accessed with changes of the market regulations and if wind farms opt to offer negative balancing reserves with the proof method available active power.

Keywords-component; control reserve, wind farms, tertiary reserve, available active power, balance control, probabilistic forecast, ancillary services

I. INTRODUCTION

As part of the energy revolution more than 25% of the electricity consumed in Germany was generated by renewable energy sources. This energy is mainly provided by wind farms and photovoltaic systems. For this reason, it is increasingly necessary that these generators provide ancillary services. The reform of the Renewable Energy Sources Act (EEG) in 2012 grants renewable energy sources the possibility to participate in markets [1]. This explicitly includes the participation in the markets for the provision of ancillary services. In this context control reserve has been delivered successfully from biogas plants. So far wind farms have not provided control reserve. This is mainly due to the regulations for the control reserve markets not yet adapted to allow such participation.

In order to change this, the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) worked together wind the wind turbine manufacturer Enercon, the wind farm operator Energiequelle and the transmission system operators Amprion and TenneT in a project called “Control reserve provision with wind farms”. In this project a method was developed to provide control reserve with wind farms in Germany. Two main aspects were the development of bidding strategies that fit to the market scheme and the development of a proof method that facilitates the needs of fluctuating RES. The technical feasibility of the newly developed detection method has been shown conclusively in a field test [2].

II. OFFER CREATION FOR THE MARKET

The participation of wind farms on the control reserve market requires that wind turbines provide the service with the same reliability as existing providers. Market participants guarantee a reliability of their offer of 100%. This means that they always have to deliver control reserve when they are dispatched. This requirement, however, cannot be met by any technical system. Based on experience of the transmission system operators (TSOs), reliability for the provision of control reserve was set to 99.994% in the project thus ensuring that the current actual reliability of the market participants is not violated.

A. Probabilistic Forecast

The calculation of reliability levels for offers aims to quantify uncertainty, so that it can be guaranteed that the offered control reserve is below the quantity in 0.006% of the cases on dispatch. Probabilistic forecasts are a tool to determine the reliability of forecasts of wind farms and of controllable systems. Probabilistic forecasts link the forecasted power value with a probability, which allows the determination for likeliness for exceeding or falling short of this forecasted power value. These forecasts provide the power value of a wind farm or a wind farm pool which will be reached or exceeded with a specified probability. A reliability of 99.994% means that the power value will be achieved or exceeded with a probability of 99.994% of this

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value. In 0.006% of the cases it would fall short of this value accordingly. In the project three methods to calculate probabilistic forecasts for wind farms and a method for calculating the probabilistic forecast of controllable generation were used. These have been used to calculate the offers for the control reserve markets. At this point the three ways to create probabilistic wind power forecasts are presented.

1) Kernel density estimation

With the aid of a kernel density estimator it is possible to calculate the probability density distribution of a stochastic variable building upon previously measured value pairs. This allows the mapping of values in relationship to each other. In contrast to a histogram the kernel density estimation provides a continuous probability distribution. The most important elements of the kernel density estimation are the cores, which can be various probability functions, such as a Gaussian function [3]. Each sample value of a time series is replaced by one of the cores. The probability distribution is the result of the summation of all cores. By a scaling of the kernels it is guaranteed that the result of summation gives the density of a probability measure.

In the case of the probabilistic day-ahead forecast a 2-dimensioniale probability distribution is formed out of the forecasted values and the corresponding forecast errors. One dimension is the day-ahead forecast; the other dimension is the forecast error observed in the given time series. Based on the day-ahead forecast, the probabilistic forecast can be calculated using the kernel density estimation. The last step consists of truncating this forecast for each time step to the levels of reliability desired.

2) Quantile Regression

For the creation of bids the offer of control reserve from wind turbines, the method of quantile regression can also be used. This method delivers power values, or mathematically described quantiles that are exceeded with a predetermined probability as a result. By doing so the risk that these thresholds are exceeded is known and the reliability of the offered control reserve can be quantified. The values of the quantiles generally depend on other independent variables such as wind power forecasts, the predicted wind speed and wind direction. Mathematically, this problem is a quantile regression, which assigns the independent variables a quantile. Since the relationship between wind speed and performance for wind turbines is nonlinear, a nonlinear quantile regression must be used. For the quantile regression artificial neural networks are used in this project. This helps to map the quantiles in a general nonlinear relationship depending on their multivariate input variables.

The procedure of a probabilistic forecast is as follows: Based on historical time series a neural network for the quantiles is trained. Then, this network may compute quantiles with new and independent data to create bids for the control reserve market. The input variables for the artificial neural network are the forecasted wind speed of a numerical weather prediction model, the forecast wind direction and the actual measured performance. For the day-ahead forecast the actual feed-in power is irrelevant and can be omitted.

3) Physical-statistic Model

The previous methods were statistical models (so-called black box models). Another approach for creating probabilistic forecasts is the introduction of a physical model that is already based on previously known physical considerations. Here, performance curves of wind turbines, models for the shadowing of the turbines and the description of the landscape roughness and other factors can be used. The usage of physical models requires a large set of input variables. Obtaining certain information can prove difficult in practice. Therefore often physical and statistical methods are combined to combine advantages of both. On the one hand existing information can be used to increase accuracy; on the other hand, unknown information can be integrated with statistical methods in order to increase forecasting accuracy. For deterministic wind power forecasts this method is used successfully.

The following describes a method of this approach which combines the mathematical description of the wind speed, the forecast error and the description of the wind farm. These various factors are analysed separately. The assumption for the creation of the forecast is that the uncertainty of the forecast mainly comes from the uncertainty of forecasts of wind speed. This error is easier to describe, if it has not yet been converted into the corresponding wind farm power value. The error can be divided into a systematic error and a random error. The systematic error arises for example from the coarse resolution of the landscape or of a not very exact parameterization of the weather model. The systematic deviations are identified and balanced. Only random dependencies that result from the mistakes of the weather forecast remain. These can be described best with a logistic error distribution of the wind speed error for the given wind farms. It is useful to apply the error distribution on the wind speed, because the conversion of wind speed into a power value is non-linear and thus generates additional errors. The wind speed is easier to describe with error distributions than the wind power values. The conversion into a power value occurs as the last step. The wind farms used in the project allow for the matching of the measured velocities of the nacelle anemometer with the predicted wind speeds.

B. Offering Strategies

The forecast uncertainty of wind energy can be included into the calculation of offers for the control reserve markets. In order to guarantee the required reliability different strategies can be chosen. The wind farm could be fully collateralized by controllable systems, only partially or not at all.

1) Full collateralization

The strategy full collateralization is a rule of thumb for providers, so that these can take advantage of pooling between wind farms and controllable systems without having to calculate probabilistic forecasts for the latter. The rule says that if the wind park pool is part of a pool with controllable systems, the service offered by the wind park pool with a reliability of 99.8% needs to be secured with n-2 or at least 20% of the offered reserve in order to achieve a reliability of the pool of 99.994%. An example for a pool using the strategy full collateralization is a wind farm pool combined with five gas turbine plants. Each gas turbine has a reliability of 99.8% which can be provided in the case of a non-fulfilment of the wind turbines.

2) Part collateral

The full collateralization with n-2 has the disadvantage that the entire control reserve offered by wind farms must be secured by a pool of controllable generators. Partial collateral could be a more precise solution for wind farm pools. This links the probabilistic forecasts of controllable generation and the wind park pools. The result of this is an offer equally reliable as with the strategy full collateral.

The combination of the different characteristics of the probabilistic forecasts results in a pooling effect. This leads to the fact that a joint offering of the wind farms and the controllable generation pool is able to provide more capacity than in the case when both pools are offered individually yet keeping the level of reliability. The reason is that the probability of failure of controllable generation has discrete probability values for the different operating conditions (normal operation, partial failure, total failure), while the forecast errors of wind turbines have a continuous probability distribution. The offer of the pool is calculated with the probabilistic forecast of the wind farms and then convoluted with the probabilistic offer of the controllable generation. Ultimately the reliability for the pool of 99.994% can be reached.

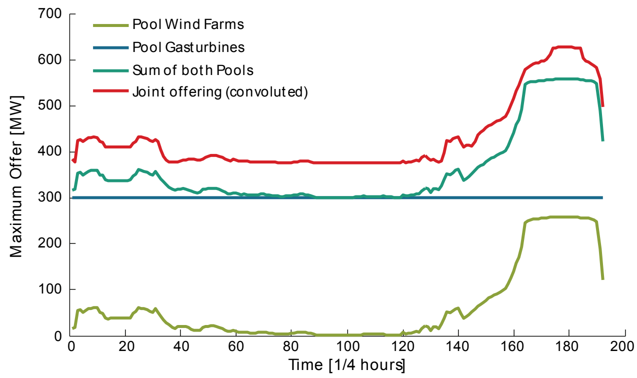

Figure 1. Pooling of a day-head forecast of wind farms of 1 GW and a 1 GW pool of five gas turbines in total

Previous figure shows the result of the combination of a wind farm pool with a capacity of 1000 MW and a pool of five gas power plants, each capable of providing 200 MW control reserve. The wind farm pool forecast is based on the day-ahead forecast. The blue line in the graph shows the individual offer of the gas turbine pool (blue line), the individual offer of the wind farm pool (light green line), the sum of both offers (dark green line) and the offering of the common of the pool of wind farms and gas power plants as a convolution of both individual offers (red line) for the time span of two days. Due to the aforementioned pooling effects the control reserve increases significantly through the convolution of offers, even in times with no offerable capacity from the wind farm pool. Pooling effects decrease if an intraday forecast of wind farm pool is combined with the gas turbines, since the forecast characteristic of intraday forecast is more similar to the discrete forecast of the gas turbines.

3) No collateral

The offering with a partial collateralisation requires the participation of controllable generators in the pool. The strategy with no collateral requires no pooling with such units and still guarantees the reliability of 99.994%. In order to reach this level of reliability only the probabilistic forecast of the wind farm pool is used.

C. Potentials for the delivery of control reserve

1) Potentials for offering control reserve with a 30 GW wind farm pool

In the figure below the offer potentials for the entire German wind farm pool are shown for various levels of reliability. These numbers have been created using the kernel density estimator approach, as mentioned above. The available data for the creation of the forecast covers several years, providing a representative set of data [4]. The reliability of 99.994% is calculated based on this data. The rated power of the wind farm pool is 30 GW, which represents almost the entirety of wind farms in Germany in the year 2012. The following graph shows the ordered duration curve of possible capacities in MW for different levels of reliabilities.

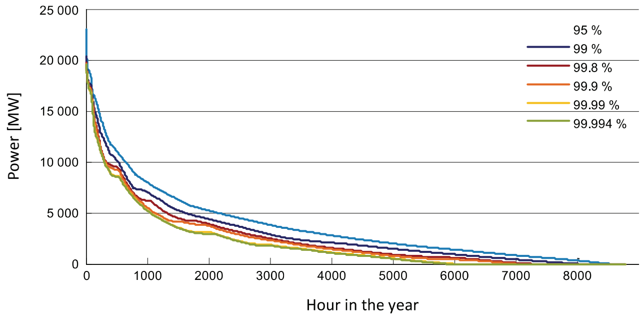

Figure 2. Sorted hourly duration curve of potentials for the control reserve market with different levels of reliability for the 30 GW wind farm pool

The potential for offering control reserve with wind farm pools decreases with increasing reliability and increasing product lengths (impact of product length not shown here). The potential for offering control reserve with a 30 GW wind farm pool in 2012 with a product length of 1 h and a reliability of 95% is 29.8 TWh. When a product length of 1 h and a reliability of 99.994% is applied the potential supply decreases to 16.7 TWh. Averaged over the year, this would correspond to a power of 1.9 GW (6.3% of the installed power rating). If the product length extended to four hours or 24 hours the potential decreases to 14.7 TWh (product length 4 h) and 7.3 TWh (product length 24 h) at the same level of reliability.

At the time of reporting the TSOs in Germany tender a negative tertiary control reserve of about 2,500 MW. The calculated potentials of a 30 GW wind farm pool at a reliability of 99.994% could satisfy the demand entirely in 1,500 hours of the year. In more than 3,500 hours at least 100 MW could be contributed. In about 5000 hours a year, the 30 GW wind pool does not contribute to the control reserve supply.

2) Testing the reliability of the offer with a short-term forecast

The reliability can be increased when using short-term forecasts, such as the 1 h intraday forecasts. It can also be used to prevent possible violations of the offer. This can be seen in the figure below, which is the only time of the year where the offer would have been violated, based on a probabilistic day-ahead forecast with a reliability of 99.994%,. This would have happened in the period of the 25th of December 2012 from 00:00 to 04:00 where the orange area is just above the red line. This would have been a violation of the offer and the offered control reserve would not have been entirely available. This violation is well within the limitations of the 99.994%. Only a small part of the offer would not have been supplied. In addition to this the non-fulfilment would have been detected by using the probabilistic 1 h intraday forecast for the same reliability. Countermeasures could have been taken. The use of probabilistic intraday forecasts is therefore a way to increase the reliability of supply.

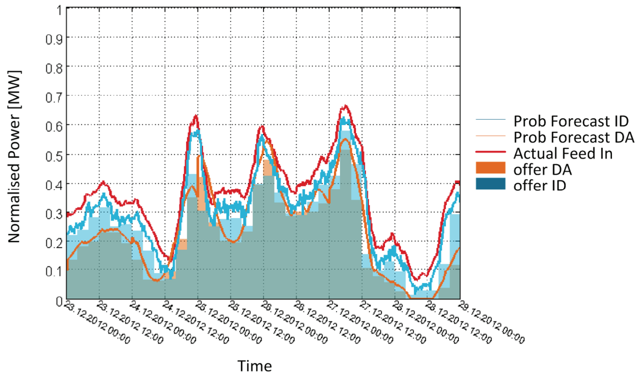

Figure 3. Probabilistic day-ahead forecast (orange), probabilistic 1 h intraday forecast (blue), day-ahead block potential (orange blocks), intraday potential (blue blocks) and actual feed-in (red)

III. Proof Method for the Delivery of Control Reserve

In the project, two different proof methods for the delivery of control reserve have been assessed. The first method is called the method "schedule" whereas the second method is called "available active power". The first option uses the balance responsible party's schedule to prove the delivery of control reserve. This proof method is done by comparing the actual feed-in to the previously announced schedule which was sent to the TSO. This proof mechanism is currently applied for the delivery of control reserve. An alternative possibility to prove the delivery of control reserve of wind farms is using the available active power signal. This signal is the power that would have been produced if the wind farm would not have been curtailed to comply with a schedule. The latter proof method was developed in the project.

A. *Proof method "schedule"*

In the proof method "schedule" the wind turbine is curtailed to a predefined value which is then used as the reference value for the down regulation. The difference between the curtailed value and the actual feed-in is then the proof that the control reserve has been delivered. This method is suitable for controllable generation as they can manage to generate power to a predefined schedule. For wind turbines, with their volatile feed-in, the application of this method would mean that they would have to be curtailed in order to be able to produce along the schedule with a high reliability. This would lead to energy losses and therefore would be environmentally and economically disadvantageous.

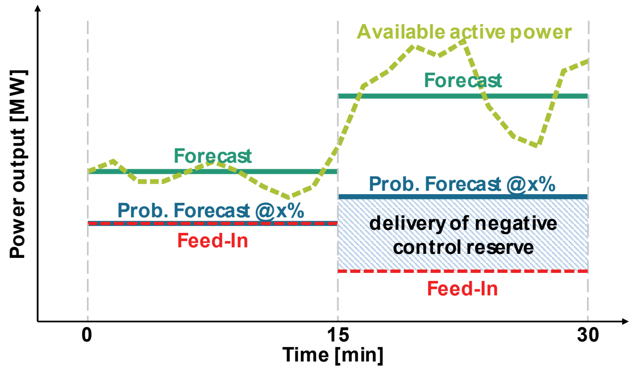

Figure 4. Proof of control reserve under the mechanism "schedule"

The illustration above shows the provision of negative control reserve by a wind farm with the proof method "schedule" applied. The method, however, can also be applied to positive control reserve provision. The illustration shows two quarter of an hour. The green line is the power feed-in of the wind farm pool without curtailment. In the first quarter of an hour the control reserve is ready to be dispatched by the wind farm pool, but no control reserve is actually dispatched. The wind farm pool is operated along the schedule (blue line) generating energy losses through curtailment. The losses are the area between the blue line and the green line. Without down-regulation the wind farm pool would have generated the red line indicated which was the previously defined as a schedule. In the second quarter of an hour control reserve is dispatched from the wind farm pool. In this case, the schedule is used as a reference for the proof of delivery of control reserve. The difference between the schedule and the feed-in must equal the contracted offer.

B. *Proof method "available active power"*

The proof method "available active power" uses the available active power signal as a reference for the down-regulation when control reserve is dispatched. The difference between the available active signal and the actual feed-in must equal the contracted control reserve. The available active power is the power, which would have been produced by the wind farm pool, if it had not been curtailed. In the first quarter-of-an hour, when the wind farm pool is ready to deliver control reserve, the wind farm pool would run unthrottled. When the negative control reserve is dispatched the wind farm pool is operated along the red line. The red line is the available active power minus the contracted control reserve. Energy losses only occur when the wind farm pool is curtailed. Thus the method "available active power" minimizes energy losses.

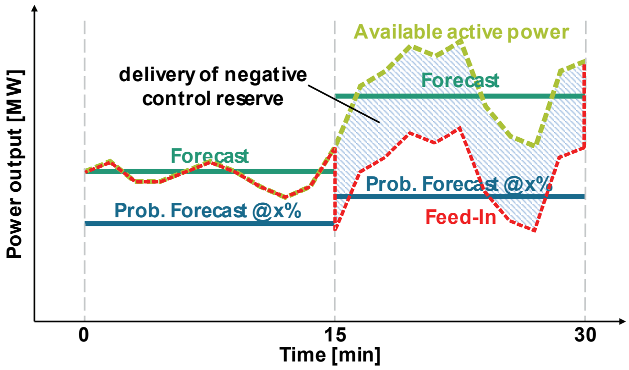

Figure 5. Proof of control reserve under the mechanism "available active power"

The illustration above shows the control reserve provision of a wind farm pool with the proof method "available active power". In the first quarter of an hour the negative control reserve is available but not dispatched. Here the wind farm pool is producing according to the available active power signal. In the second quarter of an hour a dispatch of negative control power is performed. The wind farm pool is down-regulated relative to available active power signal.

IV. Field Test

A field test to demonstrate the control reserve provision from wind farm pools was carried out in the project. The field test was performed with two wind farms of the project partners Energiequelle and Enercon, with a rated power of 40 MW. These wind farms were connected to the virtual power plant at the Fraunhofer IWES, forming a wind farm pool. The aim of the field was, to show the technical feasibility of the provision of control reserve using the proof method "available active power" for the first time.

The field test consisted of three phases. In the first phase of the wind farm provides control reserve in symmetrical band of ± 3 MW. That means that the wind farm is curtailed by 3 MW to be able to provide +3 MW positive reserves as well as 3 MW of negative reserves. The wind farm pool is tested for full activation into both directions. In the second phase the wind farm pool follows real frequency signal, thus demonstrating the provision of primary control reserve. Test conditions are adapted and the ±20 mHz dead band is removed. Fully activation equals frequency deviation of ±50 mHz instead of ±200 mHz as in the real world. Control reserve is activated according to the frequency signal. In the third phase, first a complete activation of positive control reserve is followed by a complete activation of negative control reserve finalized by making the contracted capacity available again. Phases two and three are adaptations of the sample protocols for pre-qualification for the control reserve provision in Germany.

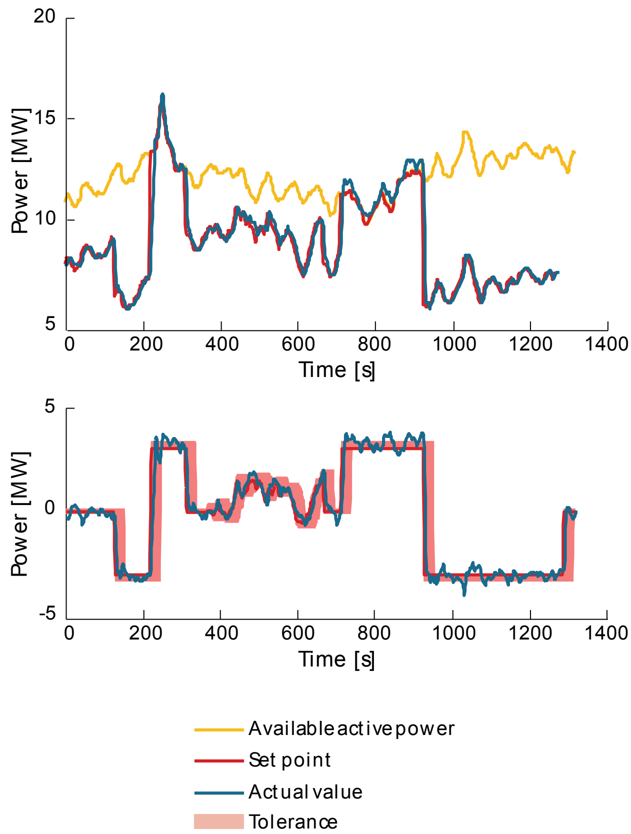

Figure 6. Field test results for one wind farm

The following diagram shows the field test results for one of the two wind farms. In the upper part of the figure the course of the available active power signal (yellow line), the set point (red line) and the actual value of the wind farm (blue line) is shown. The set point is obtained from the available active power signal minus the contracted positive control reserve plus the dispatched amount of control reserve. In the lower part of the figure the set point (red line); the actual value (blue) and the tolerance can be seen (read area). The tolerance is derived from the requirements for the provision of primary control reserve in Germany.

It can be seen that the power lies partly above the available active power. This is partly due to the fact that in this field test, the calculated available active power signal was reduced to account for calculation uncertainty. This was done to prevent the available active power to be overestimated and thus guaranteed that the positive control reserve can be fully activated.

Furthermore, it can be seen that the wind farm is very responsive to changes of production values and has no problems to follow the set points within the time limit of 30 seconds that are required for the provision of primary control reserve. Despite that one can see that there is a lag between receiving the new set points and the change of power output. This can lead to control issues which may put may delivered power outside of the tolerance area. Technical feasibility to provide control reserve under the current framework conditions is not given on a firm wind farm level. Through the pooling of several wind farms, however, stochastic fluctuations can be reduced the significantly.

The application for the tertiary market leads to the usage of minute mean values. Mean values for one minute compensate most of these fluctuations so that the actual values for the delivery almost lie within the tolerance range. It can be concluded that technological feasibility is given on the wind farm level for the tertiary control. However, determination of the available active power is not yet possible to accurate enough for secondary control reserve markets and requires further research.

V. CONCLUSION

In the project "control energy by wind turbines", a concept was introduced, control performance can provide with the wind turbines. It was shown how wind turbines control power with the same reliability as current provider can offer. Then the potentials were identified. In high wind feed, wind turbines can cover a large part of the required control performance. In addition, a new proof method for the provision of balancing power was developed by wind turbines, which minimizes the loss of the primary energy wind. This method was first demonstrated in a field test.

The results show that under the current framework conditions wind farm pools are not yet ready to provide control reserve in the German markets. The economics of the provision of control reserve are dependent on the framework conditions. The economics have been discussed extensively in [5].

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