Available Active Power Estimation of Wind Power Plants with 3-Second Data

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***Abstract*—The Available Active Power of wind power plants is an important figure which is taking on an ever greater importance with increasing shares of wind in the electricity systems, in particular for the provision of operating reserve. In this paper we present four methods for the estimation of the Available Active Power and compare these methods by testing them with time series from a real wind power plant with different time resolutions. Thereby we especially address the challenge of estimating the Available Active Power in a three second resolution.**

Available Active Power; AAP; Wind Power Plants; Operating Reserve; Balancing; 3-Second Data; Wind Integration

I. INTRODUCTION

The Available Active Power (AAP) is the power a wind power plant could produce if it has not been curtailed. It is an important figure for the integration of wind into the electricity grid, especially for high shares of wind energy. Based on the AAP the compensation payments for wind power plant owners in the case of curtailments due to grid congestions can be calculated. When wind power plants are curtailed the AAP delivers important information for the preparation of short term forecasts. Another application of the AAP is the future provision of operating reserve by wind power plants. This paper focuses on the latter.

In the research project *Regelenergie durch Windkraftanlagen* (*Operating Reserve by wind power plants)* the AAP is used to proof the delivery of operating reserve. During the provision of negative operating reserve the wind power plant feeds in its AAP. When the wind power plant delivers negative operating reserve the demanded balancing power is subtracted from the AAP to get the new feed in value (Fig. 1).

In [1] we tested different methods to estimate the AAP with data averaged over 10 minutes. However the provision and delivery of secondary and tertiary reserve requires data with time resolutions of three seconds respectively one minute. In this paper we compare four of these methods with 3-Second, 1-Minute and 10-Minute data. First we will give an overview about the differences between the different resolved data. Then the four methods are presented and the results are compared and discussed. Finally we will give an outlook how we are going to improve the AAP for three second and one minute intervals.

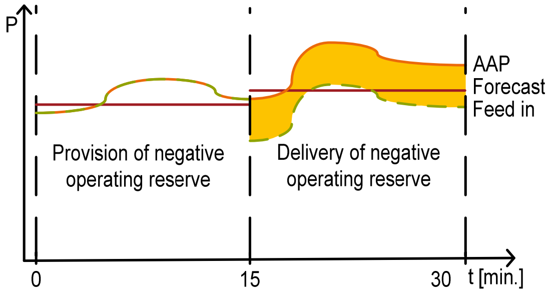

Figure 1. Proof of the delivery of negative control reserve

II. DATA AND MODELS

A. Data Base

All calculations in this paper are based on historical data measured from a wind power plant located in Brandenburg, Eastern Germany. It consists of 18 wind turbines with a nominal power of 2065 kW each. The next wind power plants are a few kilometers away so that the analyzed wind power plant is not affected from their wakes.

Additionally to the static data like nominal power, rotor diameter, hub height, position, power curve etc. the nacelle anemometer wind speed, nacelle position, wind direction relative to the nacelle position and power of each wind turbine were measured during April 8th and June 30th 2013.

The historical data was measured approximately every three seconds. As it is not possible to measure the data exactly every three seconds due to communication and IT reasons the measured values are interpolated to intervals of three seconds.

After that the different time series are divided into one minute respectively ten minute intervals and averaged over these intervals. As the time series are fragmented due to communication reasons only those ten minute intervals are selected where all data (wind speed, wind direction and power of all wind turbines) are available for more than 75% of the time. The one minute and three second interval time series are also derived from these selected intervals.

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B. Comparison of 10-Minute, 1-Minute and 3-Second Data

Wind speed, power and wind direction fluctuate highly in reality, whereby the wind speed is the most crucial factor for the produced power. Figure 2. shows the wind speed and the power of one wind turbine measured in three second intervals. It can be seen that the power follows the wind speed in a way but does not fluctuate that highly and is more constant. This is due to the fact that the inertia of the system acts as a low-pass filter. That means that the oscillations of the wind are dampened. Another reason is that the measurement of the wind is done very selective only at one point namely at the nacelle anemometer, whereas the power results from the average wind speed over the swept rotor area.

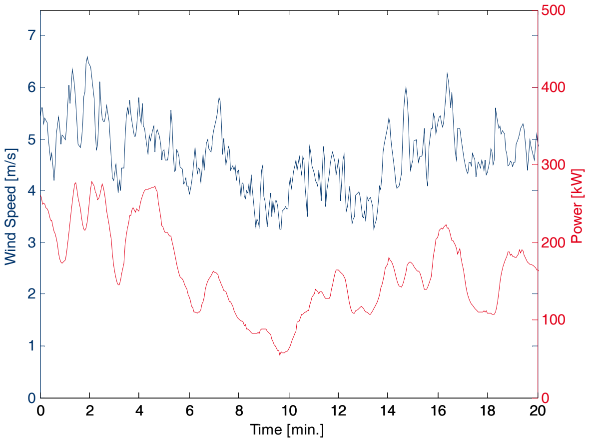

Figure 2. Wind speed and power of one wind turbine measured in three second intervalls

But not only wind speed and power of a single wind turbine fluctuate highly, there are also great differences from one wind turbine to the other within a wind power plant. Figure 3. that there is nearly no correlation between the power output of one wind turbine to the other wind turbines' outputs. While one wind turbine operates at its nominal power other turbines produce only a fifth or even less.

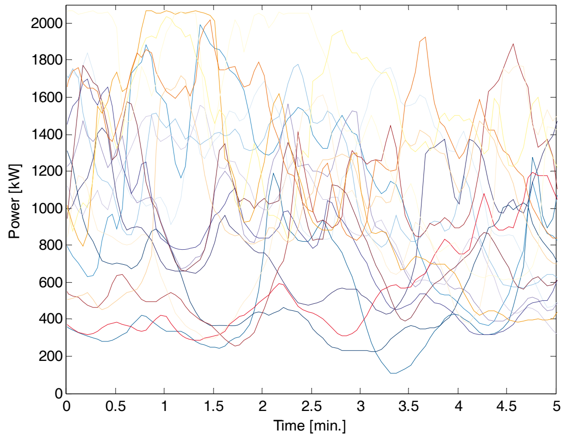

Figure 3. Power output of all 18 wind turbines in a three second resolution

Averaging the three second data to one or ten minute intervals leads to the effect that outliers compensate each other which means that the time series are smoothed out (Figure 4. .

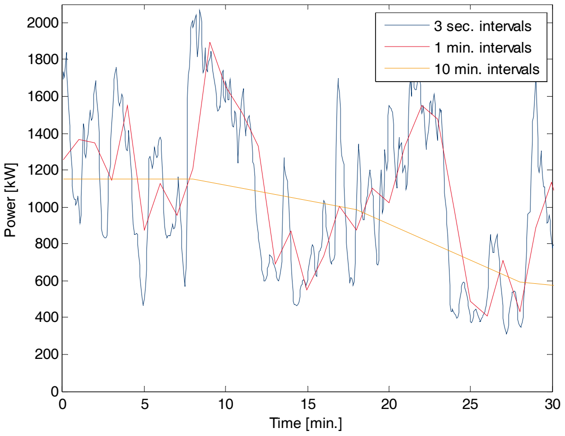

Figure 4. Power output of one wind turbine averaged over three second, one minute and ten minute intervals

C. Models

In the following we present the four methods that are tested with the different time resolution time series. These four methods are already described in [1].

1) Last measured value

The approach of the last measured value method is straight forward. Here the AAP is estimated with the last measured power output before the curtailment (Figure 5.). This method implicitly assumes that the wind conditions do not change over the whole curtailment period.

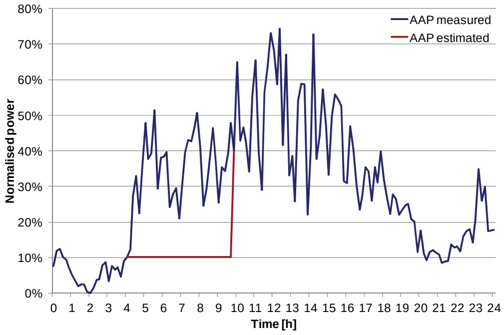

Figure 5. Schematic representation of the last measured value method for a curtailment of six hours

For this method the power output of the wind power plant right before the curtailment is the only information required.

2) Site-specific power curve

The site-specific power curve method uses a site-specific power curve and the nacelle anemometer wind speed of each wind turbine to calculate the single turbine's AAP. These AAPs are then summed up to the wind power plant's AAP.

For the calculation of the site-specific power curve historical data of the wind turbine's power output and the measured nacelle anemometer wind speed is needed. Then the local regression model method LOESS is applied (Figure 6.) to these data to get the power curve that assigns a power output to every wind speed. During the curtailment the measured nacelle anemometer wind speed is used to look up the AAP with the help of the power curve. The period during that the historical data is measured should be as long as possible so that most wind conditions are covered and proper results are ensured.

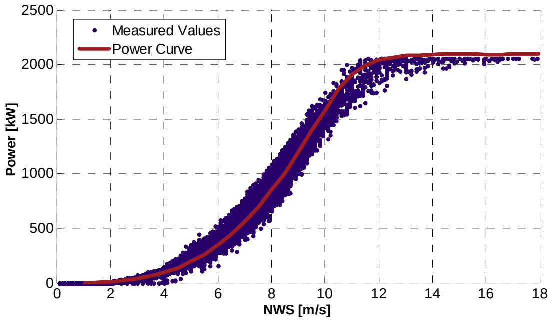

Figure 6. Measured values and power curve of single wind turbine

3) *Reference wind turbine*

The reference wind turbine method uses the relation between one turbine's power output and the other turbines' power output under a certain wind direction. During the curtailment the power output of the reference wind turbine that is neither curtailed nor affected by wakes of the other wind turbines is used to estimate the AAP of the other wind turbines. These AAPs are then summed up to the wind power plant's AAP. The reference wind turbine is selected depending on the wind direction.

To find the relation between the wind turbines' power output depending on the wind direction historical data of the measured power outputs and nacelle anemometer wind speeds is required. Here the general rule applies again that the more data the better the results. With this data and the help of artificial neural networks the relation between the power output of each wind turbine, the averaged wind direction of all wind turbines and the power output of every other wind turbine is derived. During the curtailment the measured nacelle anemometer wind speed and produced power of the reference wind turbine and the averaged wind direction is needed.

4) *Physical model*

For the correct calculation of the AAP during curtailment periods the physical model tries to reflect the wake effects' influence from other turbines as well as from the own rotor on the measured nacelle anemometer wind speed. The idea is basically the same as in Eisen [2] but we additionally implemented the nacelle anemometer wind speed correction. As the model is relatively simple no detailed wind turbine model is needed.

For the modelling of the wind power plant static data like wind turbines' positions, hub heights, rotor diameters, and power curves are needed. To correct the nacelle anemometer wind speed measurement historical time series of the nacelle anemometer wind speed and power output of every wind turbine is needed.

In Figure 7. the proceeding of this method can be seen. First the measured nacelle anemometer wind speed is corrected to the wind speed in front of the rotor. After that the corrected wind speed is put in the inverse wake model of the wind farm with the current cT-Values that result from the curtailment.

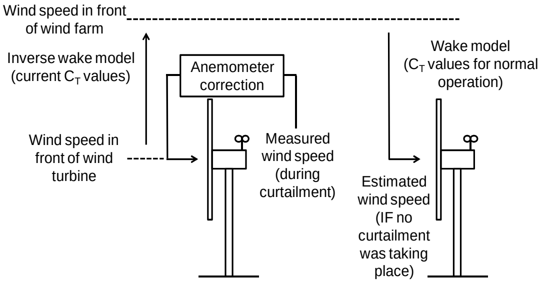

Figure 7. Proceeding of the physical model (following [2])

The free wind speed in front of the wind farm as result of the previous calculations is then used as input for the wake model that is now parameterized with the cT-values for normal operation. The resulting wind speeds in front of each wind turbine and the power curves are then used to estimate the single AAPs that are again summed up to the wind power plant's AAP.

a) *Wake modeling*

During curtailment, less energy is extracted from the wind, thus changing the wake effects within the park. To avoid overestimation of the available active power, it is crucial to incorporate the changes in wakes in the model. For ten minute data it is possible to use either an implicit wake consideration, as with the reference model, or to directly estimating the effects as with the physical model.

The physical model is based on the Jensen model [3] assuming conservation of momentum within a cylindrical volume around the turbine. Jensen considered the wake to expand linearly, with a factor α.

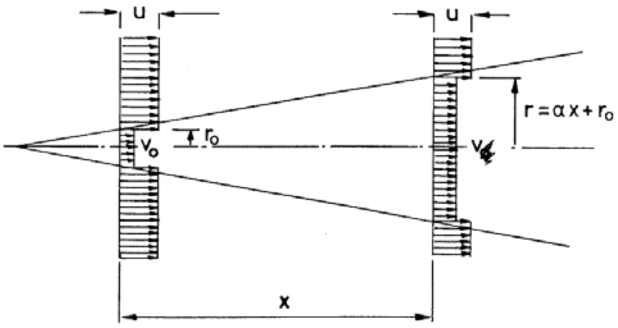

Figure 8. Schematic illustration of the Jensen Model (Source: [3])

To conserve momentum, the velocity at distance x within the cylinder has to fulfill

$$r_0^2 v_0 + (r^2 - r_0^2)u = rv \tag{1}$$

Substituting $r = \alpha x + r_0$ and with the axial induction factor $a = 1 - v_0/u$ one finds

$$v = u\left(1 - 2a\left(\frac{r_0}{r_0 + kx}\right)^2\right) \tag{2}$$

The actuator disk model states, that $c_t = 4a(1-a)$ [4] such that for $a < \frac{1}{2}$ one gets $a = \frac{1}{2}(1 - \sqrt{1 - c_t})$ and the wake effect indeed decreases for a curtailed wind turbine with lower c_t. Other more detailed models exist [5] but the Jensen model is sufficient for understanding the challenges arising when 3-second-data is used.

D. *Challenges of 3-second-data*

1) *Turbine model*

In order to accurately simulate the output of a wind turbine for given wind conditions, the inertia of the system needs to be taken into account instead of directly applying the c_p-curve. Advanced models are used for analyzing transient stability of wind turbines [6][7], their impact on grid stability[8] as well as for developing control strategies [9]. Moreover models have been used for understanding the behavior of wind turbines [10][11]. The complexity of the model varies accordingly to the complexity of the turbine and the accuracy requirements on the simulation. In general n masses can be simulated each connected via a gearbox and a spring. A dashbox is used for linear damping [12]. For transient stability analysis, up to six-mass models are used [7] incorporating each wing as well as each part of the drive train as a separated mass. On the other side, lumped models with one mass combining the inertia of rotor drive train as well as generator are also used [10][11]. For the Enercon E-82 turbine, such a lumped model is sufficient. Since no gearbox is used, all parts rotate with the same angular momentum. The inaccuracies inflicted by simulating the drive train with infinite stiffness, can be neglected for they should not be relevant for the considered time-scale.

Let J be the moment of inertia of the turbine. Given an angular momentum ω the rotational energy of the system is

$$\mathrm{E_{rot}} = \frac{1}{2}\,\mathrm{J}\,\omega^2 \qquad (3)$$

The rotation is thus depending on the rotational energy such that

$$J\frac{d\omega}{dt} = \frac{dE_{rot}}{dt}. \qquad (4)$$

The temporal change of kinetic energy is

$$\frac{dE_{rot}}{dt} = T(\lambda)\cdot\omega - \frac{1}{\eta}P_{el}(\omega) - P_{diss}(\omega) \qquad (5)$$

with η as the energy conversion efficiency of the generator. If the c_p-curve of the turbine is known, this can be rewritten as

$$\frac{dE_{rot}}{dt} = \frac{1}{2}c_p(\alpha,\lambda)\rho U_\infty^3\pi R^2 - \frac{1}{\eta(\omega)}P_{el}(\omega). \qquad (6)$$

Here ρ is the density of the fluid, U_∞ is the fluid velocity far in front of the turbine and R is the radius of the turbine rotor. The value λ is the tip speed velocity and α the pitch angle. The dissipative energy-lost is implicitly accounted for via $\eta(\omega)$. An analysis of $\eta(\omega)$ would be possible if one could find events, where the wind velocity suddenly drops to low values close to zero such that $U_\infty^3 \approx 0$. In this case,

$$\eta(\omega_0) = \left.\frac{P_{el}(\omega_0)}{J\frac{d\omega}{dt}}\right|_{\omega_0} \qquad (7)$$

Based on this one-mass-model, the c_p-curve can be estimated, if not provided by the manufacturer. For this, one first calculates the time-series:

$$c_p(t) = \frac{2}{\rho U_\infty^3\pi R^2}\left(J\frac{d\omega(t)}{dt} + \frac{1}{\eta(\omega)}P_{el}(t)\right). \qquad (8)$$

Then, a look-up matrix can be created filled with the corresponding (α,λ)values. If no information on the pitch angle is available, simply deriving a simple $c_p(\lambda)$-curve will not be successful. First evaluations of the data have shown, that the variance of $c_p(\lambda)$ for a fixed λ is too large. For this, other strategies will have to be developed. One approach would be to derive a $c_p(U_\infty)$curve. First results are promising. Another possibility would include a model of the pitch-angle dynamics themselves, where the optimal $\alpha(\lambda)$strategy corresponds to fix points in the $\lambda - \alpha$ domain. In both cases the model would be restricted to the uncurtailed condition. Nevertheless, for calculating the AAP this is sufficient.

2) *Wake-Field-Propagation*

Modelling the wind turbine using the blade element theory shows that the thrust-coefficient is depending on the tip-speed ratio [4]. Because of the turbines inertia, and fluctuating wind conditions, this ratio is varying. To incorporate these variations into the wake model, the propagation of the wake field has to be known. The estimation of the temporal difference between two turbines is part of a current research project and will be added to our wake-modeling soon.

E. *Error Calculation*

The error of the estimated AAP is calculated by the normalized root mean square error (nRMSE) with the calculated available active power AAP, measured power P and the installed capacity $\mathrm{P_{nom}}$:

$$nRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(AAP_i - P_i)^2}{n}}}{P_{nom}} \qquad (9)$$

III. Results and Discussion

TABLE I. shows the Results for the different methods and averaged time series. What all methods have in common is that the error increases with shorter average intervals. However the rate of increase differs. For the last measurement method the nRMSE increases from 13.26 % to 13.85 % which corresponds to an increase of 4.5 %. For the site specific power curve method and the reference wind turbine method the increase is 116.9 % respectively 68.9 %, whereas the increase of the physical model's nRMSE is again quite small with 1.8 %.

TABLE I. nRMSE for the Different Methods and Averaged Time Series

	10 min.	***1 min.***	***3 sec.***
Last Measurement*	13.26 %	13.71 %	13.85 %
Site-specific Power Curve	1.54 %	2.20 %	3.34 %
Reference Wind Turbine	3.15 %	4.29 %	5.32 %
Physical Model	2.79 %	2.80 %	2.84 %

* Curtailment duration: two hours

The longer the onset of the curtailment is ago, the higher the chance that the average wind condition has changed.

This fact leads to the rapid increase of the estimation error if the last measured value model is used (Figure 9. . The fact that the errors are less depending on the temporal resolution is a result of the averaging during the calculation, either done for calculating the intervals, or during the calculation of the average error.

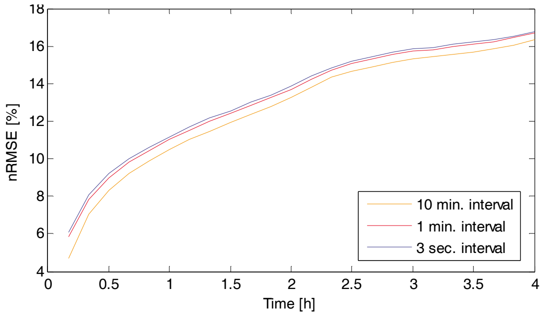

Figure 9. nRMSE of last measurement method over the duration of curtailment and for different average intervals

The increase of the site-specific power curve method's nRMSE can be explained by Figure 10. The greater the average interval the smaller the scattering of the points representing the power output at a specific wind speed. As this is a power curve method that estimates the AAP via a power curve that is only a line the deviations of the three second data can be much greater than for the 3 second intervals.

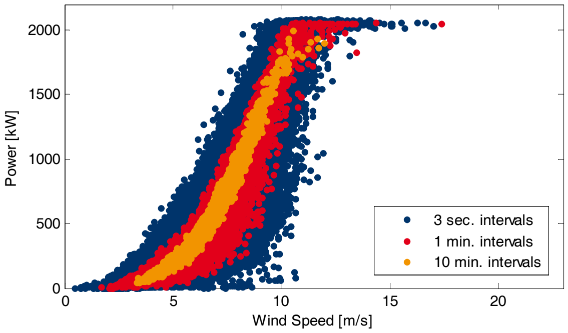

Figure 10. Power over wind speed of one wind turbine for time series with different average intervals

The explanation of the behavior of the reference wind turbine method's nRMSE is also easy. Considering Figure 3. it is quite obvious that it is nearly impossible to conclude from one turbine's power output to the other's with three second data, although there are some balancing effects between the single wind turbines of one wind power plant when the sum of all power outputs is considered. This is much easier with data averaged over ten minutes as here the temporal fluctuations of the single wind turbine are already balanced out.

The inaccuracies of the site specific curve model are mainly a result of its inability to account for the dynamical behavior of the wind turbine. Since the physical model calculates the free flow velocity as an average of the estimated free flow velocity of all turbines, this value is less fluctuating. Whereas this reduction of information is not necessary and thus increasing the error for the 10-minute case, for the 3-second case it suppresses noise such that the physical model's error is increasing slower than that of the site specific curve.

IV. CONCLUSION AND OUTLOOK

Four models for determining the AAP have been tested for their ability to correctly estimate the AAP on different time scales. It has been shown, that, compared to 10-minute-data, high time resolutions add new challenges to the task. Based on the measured data, temporal as well as spatial fluctuations have been shown, that increase the difficulty of the task. Of the evaluated models, the site-specific power curve as well as the physical model were able to estimate the park-output on a three second scale with a nRMSE below 4%. Nevertheless, both models do not take the dynamics of the wind-turbines into account. A physical model of the turbines dynamic for simple gearless turbines has been proposed. Its effect on the accuracy of the AAP-estimation has yet to be shown. Up to now, the effects of wake-changes due to curtailment have not been considered. As shown in [1], these effects are significant, such that taking them into account will be crucial for any model to be successful. Of the above examined models, only the physical model is capable of considering the changes in wake. Improving the model by incorporating the turbines dynamics as well as the wake-dynamics within the park will be part of future research.

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