Typical wind fluctuations and the resulting power infeed of offshore wind power plants – statistic approach supported by measurement

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Abstract-- **This paper describes the method of finding typical wind speed profiles for simulating the dynamic behavior of offshore wind power plants and the resulting power infeed of single wind turbine generators and the whole wind park. A good knowledge of the power infeed profile of single wind turbine generators and of big wind park clusters is essential for planning technically and economically optimized grid connections.**

To reach that goal the wind speed measurements of the German FINO1 platform are analyzed and statistically evaluated to find typical wind profiles for different seasons. A special algorithm is used to generate wind profiles for each wind turbine generator inside a park out of a typical wind profile for one position.

With these profiles the influence of wind direction and wind fluctuation on the best or worst averaging in terms of power infeed is investigated.

Index Terms-- **Offshore, wind park cluster, grid connection, typical wind speed profiles**

I. INTRODUCTION

These days the contract for the third high power link between offshore wind parks and the onshore grid in the area of the German North Sea has been announced using high voltage direct current technology (VSC HVDC). With that link 2000 megawatt of total transmission capacity will be installed until the year 2013. But a lot more offshore wind parks are planned in that area. Around 60 projects are in different planning stages, from the very beginning to commissioning phase. The distance to shoreline varies from 30 to more than 200 kilometers. A good knowledge of the power infeed profile of single wind turbine generators and of big offshore wind parks is essential for planning and operating of an economically and technically optimized grid connection.

To reach that goal long term wind speed measurements of the German research platform *FINO I* are analyzed and statistically evaluated to find characteristic wind speed profiles for the wind turbine generators. A special algorithm is used to generate out of these measurements profiles for all wind turbine generators of an offshore wind park. With these profiles the influence of wind direction and wind fluctuation on the best or worst averaging in terms of power infeed is investigated. In the last part of the paper a statistic approach for generation of typical wind speed profiles for different seasons and for a dedicated location is presented.

II. FINO I

FINO I is a research platform in the German North Sea and is located around 45 kilometers in the north of the Island Borkum. Since 2003 the platform supplies researchers among others with measurement data of wind speed in different heights, wind direction and air pressure. The wind speed is measured in the height of 33 meters and in the heights from 40 to 100 meters above sea level in steps of 10 meters. The wind direction is available in 33 and 90 meters.

For the work presented in this paper the above mentioned measurements of wind speed and direction of the years 2006 to 2009 in one second time steps are used, representing all in total more than $1.1 \cdot 10^9$ individual values. But after inspecting the datasets it was obvious that lots of the values are missing due to problems with sensors or the radio link. The range of the missing values is from some seconds to some days.

For example the spring of the year 2009 consists of around $7.95 \cdot 10^6$ seconds but only around $5.65 \cdot 10^6$ datasets are available (~71%) for the sensor in 90 meters height [3]. The longest duration between two missing datasets is 26 minutes and the average duration of complete measurement values is 3.5 seconds (Table 1).

	Spring of 2009
Available datasets	5647066
Maximum wind speed	29,08 m/s
Minimum wind speed	0,25 m/s
Missing values	29,0%
Maximum duration	00:26:02
Average duration	00:00:03.5

Table 1: Statistics of wind speed measurement in 90 meter height for spring 2009

To get time continuous wind speed profiles in a first step the gaps are filled with linear interpolated values. But the incorrectness of this method is acceptable only for small intervals of missing values. To use that method a suitable time frame with enough measurement values must be searched within the raw data array and then corrected. As an example see Figure 1.

For longer gaps the interpolation with spline functions is possible or the copy, scale and paste of neighbor data blocks [6]. The scaling has to be done in a way that the first value of the copied are fits to the last before the gap and same at the end of the copied are. In chapter III. only the linear interpolation is used because of the simplicity of the method which can be easily automated.

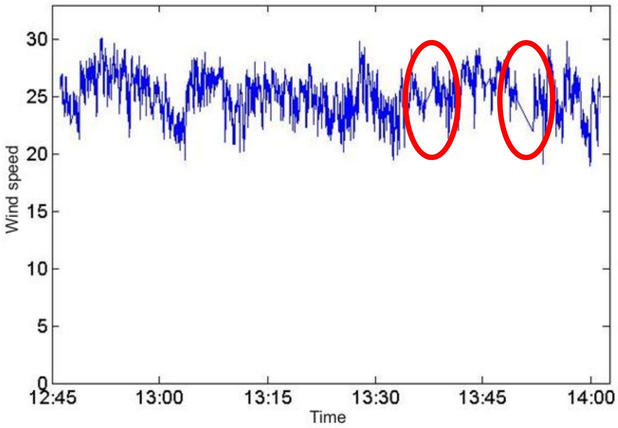

Figure 1: Example dataset with linear interpolated wind speed values

III. WIND SPEED MEASUREMENT AND OFFSHORE WIND PARK POWER INFEED

With the corrected wind speed profile one point within the wind park area is defined. But what to do with the other 79 wind turbine generators in a typical wind park?

To solve that problem three methods are investigated in this paper. First solution is to use the same wind speed profile for all wind turbine generators. Second way is to use the same profile for all generators but with a time delay between the locations. And finally a stochastic approach is applied.

A. Simultaneous wind speed profile

To get the accumulated power output of an offshore wind park all wind turbine generators get the same wind speed profile. Of course all wind turbine generators have the same power infeed and the offshore wind park power infeed is a simple multiplication of the number of wind turbine generators and the infeed of one of these. Figure 2 shows the power infeed of one wind turbine generator and Figure 3 the output of an offshore wind park with 80 wind turbine generators.

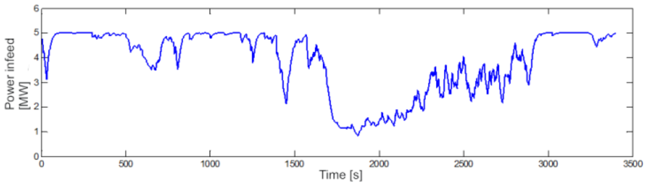

Figure 2: Power infeed of one generator

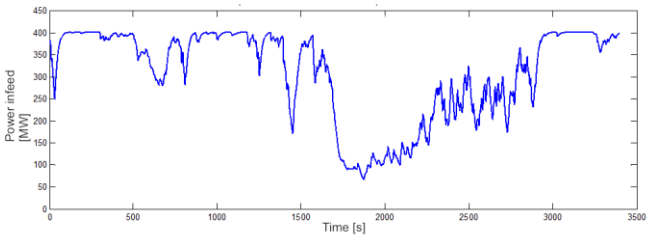

Figure 3: Power infeed of an offshore wind park with 80 wind turbine generators. Simultaneous wind speed profile

There is no balancing effect and no damping of fluctuations visible. Because of the wide area which is occupied by a real offshore wind park (more than 50 square kilometers) the simultaneous wind speed profile produces much too high fluctuations in the power output by neglecting the wind runtime between the wind turbine generators.

This very simple method may be good enough for very small wind parks with few wind turbine generators close together but not for average offshore wind parks in the North Sea. Another solution must be found.

B. Time delay wind speed profile

The assumption of the time delay wind speed profile method is that the wind blows with a constant direction within the park. The wind is assumed as a long lateral extended wave with constant strength along the wave. This wave moves with a constant speed of propagation v_W (mean wind speed of the used profile) through the offshore wind park (see Figure 4).

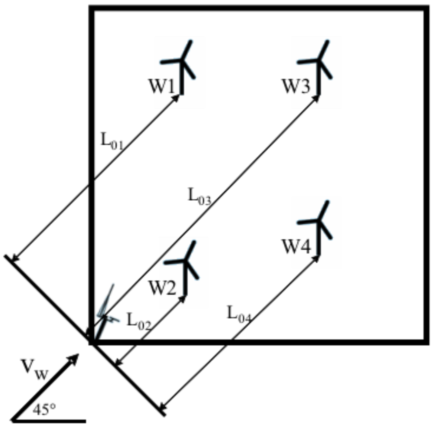

Figure 4: Location of the wind turbine generators and long lateral wind wave

Depending on the angle between the wind wave and the offshore wind park the length L_x between the wind wave's initial position and the wind turbine generator W_x varies (e.g. L_{01} and W_1). All wind turbine generators get the same wind profile but with a time delay ($t_{d,x}$) corresponding to the individual length L_x.

$$t_{d,x} = \frac{L_x}{v_W} \quad [s] \tag{1.1}$$

The result for an angle of 0° is shown in Figure 5. The smoothing effect of the short time gradients is clearly visible but the overall trend (compared with Figure 3) is still obvious. With the angle of 0° the worst case in terms of balancing is reached. Assumed a rectangular shape, all wind turbine generators in a row get the same wind speed profile and so have the same power output. Because of that fact this "frozen turbulence" method is not realistic for park scale investigations [5].

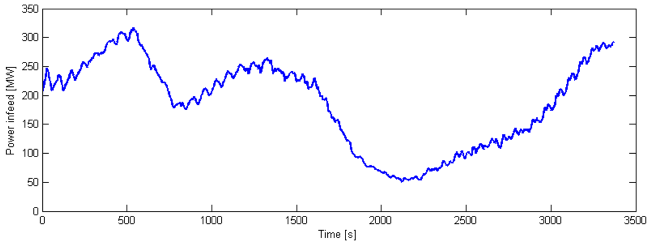

Figure 5: Power infeed for 0° and 80 wind turbine generators. Time delay wind speed profile

C. *Stochastic wind profile*

The stochastic wind speed profile method is an improvement of the time delay profile method. First the wake effect is added which describes the shadowing of wind turbine generators by others and second the local fluctuations are considered.

To get a stochastic wind profile four steps are necessary. First of all a floating mean value profile with a frame size of 60 seconds is generated out of the wind speed measurement table. Similar to the time delay method a special dataset of the floating mean wind speed profile for each wind turbine is generated depending on the angle between the wind wave and the offshore wind park and the position of the turbine within the park. Afterwards the influence of the wake effect according to the WAsP model (Wind Atlas Analysis and Application Program) of Risø National Laboratory is calculated for each generator. Equation (1.2) represents the model where v_0 is the free stream wind speed, v_{w0} is the multiplication of v_0 and a trust coefficient (which is determined for a specific wind turbine), r_{rot} is the rotor radius, x is the distance between the wind turbine generators and k_{wake} describes the wake decay. The constant k_{wake} is in different literature suggested a value between 0.04 and 0.08 [1][2].

$$v_w(x) = v_0 - (v_0 - v_{w0}) \cdot \left(\frac{r_{rot}}{r_{rot} + k_{wake} \cdot x} \right)^2 \tag{1.2}$$

Equation (1.3) gives the mean wind speed at hub height of a multiple, partly shadowed wind turbine rotor [4].

$$v_j(t) = v_{j0}(t) - \sqrt{\sum_{\substack{k=1 \\ k \neq j}} \frac{A_{Absch\_jk}}{A_{rot\_j}} \cdot \left(v_{w\_k}(x_{jk}, t) - v_{j0}(t)\right)^2} \tag{1.3}$$

$v_j(t)$: Mean wind speed at hub height

$v_{j0}(t)$: Free wind speed

$v_{w\_k}(x_{jk}, t)$: Shadowed wind speed

A_{rot_jk}: Free rotor area

A_{Absch_jk}: Shadowed rotor area

Finally a stochastic generated wind speed share is added to the time delayed floating mean value tables of the individual wind turbine generators which represents the local fluctuations. That stochastic part is generated by the density function based on a *Kaimal* spectrum [5] (equation (1.4)).

$$S_V(f) = u_*^2 \cdot \frac{\dfrac{F}{(\ln(\frac{h_{Turb}}{K_N}))^2 \cdot v_G}}{\left[1 + 1{,}5\left(\dfrac{F}{v_G} \cdot f\right)\right]^{\frac{5}{3}}} \tag{1.4}$$

h_{Turb}: Hub height

K_N: Surface roughness index

F: Turbulence index

v_G: Mean wind speed

$u_*^2 = 0.21 \cdot \sigma^2$: Mean variance oft the wind speed array

Figure 6 shows an example of a wind speed measurement and its floating mean value. Figure 7 represents the corresponding stochastic wind profile generated with the described method. The power output of an offshore wind park with 80 wind turbine generators is presented in Figure 8. Compared to the time delay method (Figure 5) the balancing effect is much better also for the 0° angle. The fluctuation of the power infeed decreases from around 1.52 MW/s to 0.21 MW/s (Figure 9). The reason is the superposition of the stochastic values for the turbulence share of the wind speed for all wind turbine generators in the same row of the offshore wind park instead the addition of the same profile (and so the same turbulences).

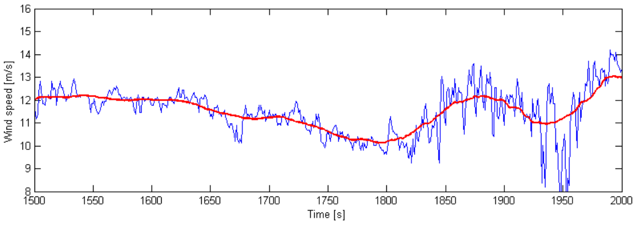

Figure 6: Example of a wind speed measurement and its floating mean value

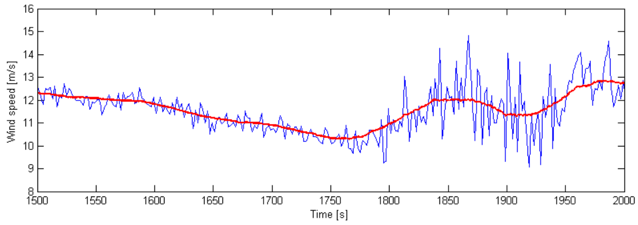

Figure 7: Example of a stochastic generated wind profile

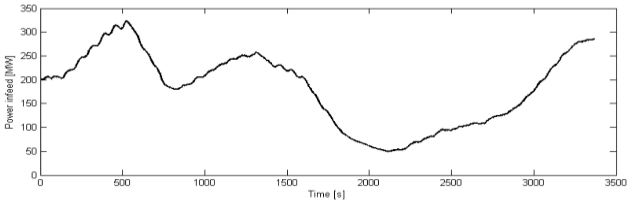

Figure 8: Power infeed for 0° and 80 wind turbine generators. Stochastic wind profile

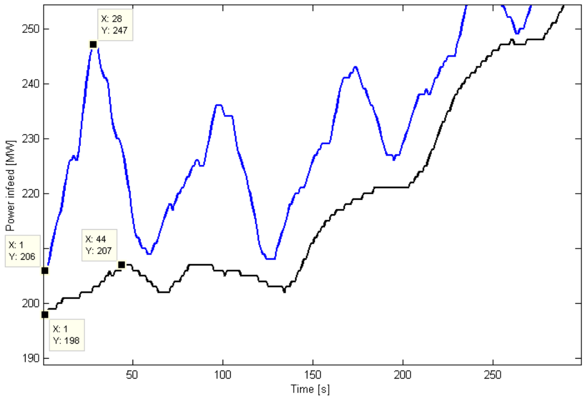

Figure 9: Power infeed for 0° and 80 wind turbine generators. Stochastic wind profile and time delay wind speed profile

With the method of stochastic wind profile generation a good and realistic way of getting wind speed profiles for a whole offshore wind park only by knowing the location of the wind turbine generators and having one single measurement location is described.

IV. TYPICAL OFFSHORE WIND SPEED PROFILES

The way mentioned in chapter II. to correct missing values in the measurement is only useful for small gaps. But the statistic evaluation shows numerous longer gaps in the *FINO I* data of 2006 to 2009. To solve that problem and to use the available measurements, typical generic wind speed profiles based on measurement for the location of *FINO I* should be generated. Profiles for the different seasons are necessary because of the big variation of wind speed and fluctuation during the year but only the results for spring are presented in this paper.

The first step to get typical generic wind profiles for dynamic research on wind turbine generators is the evaluation of the measurement data. Figure 10 shows the distribution of wind speed and its Weibull distribution (maximum at around 8.7 m/s) of the springs of 2006-2009 in 90 meter above sea level. The maximum measured wind speed is 31 m/s and the total number of measurement values of $21.47 \cdot 10^6$ is available. Out of that a mean wind speed was calculated with 9.45 m/s. Between 12% and 29% of the values (depending on the year) are missing. The longest period with complete data is 1 hour and 33 minutes but with an average length of around 8 seconds. For further investigations data blocks shorter than 5 seconds are not considered.

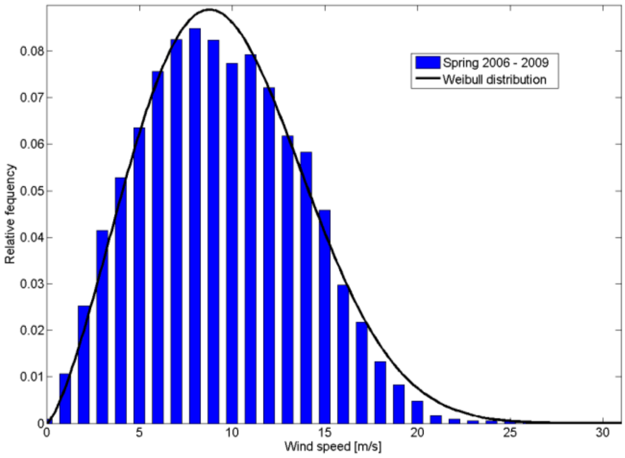

Figure 10: Wind speed distribution and its Weibull distribution of the springs of 2006-2009 in 90 meter.

The used blocks are divided into a mean wind speed and a turbulence part. Looking at the turbulence part of the wind speed (Figure 12) a significant accumulation in the range of ±0.2 m/s is visible.

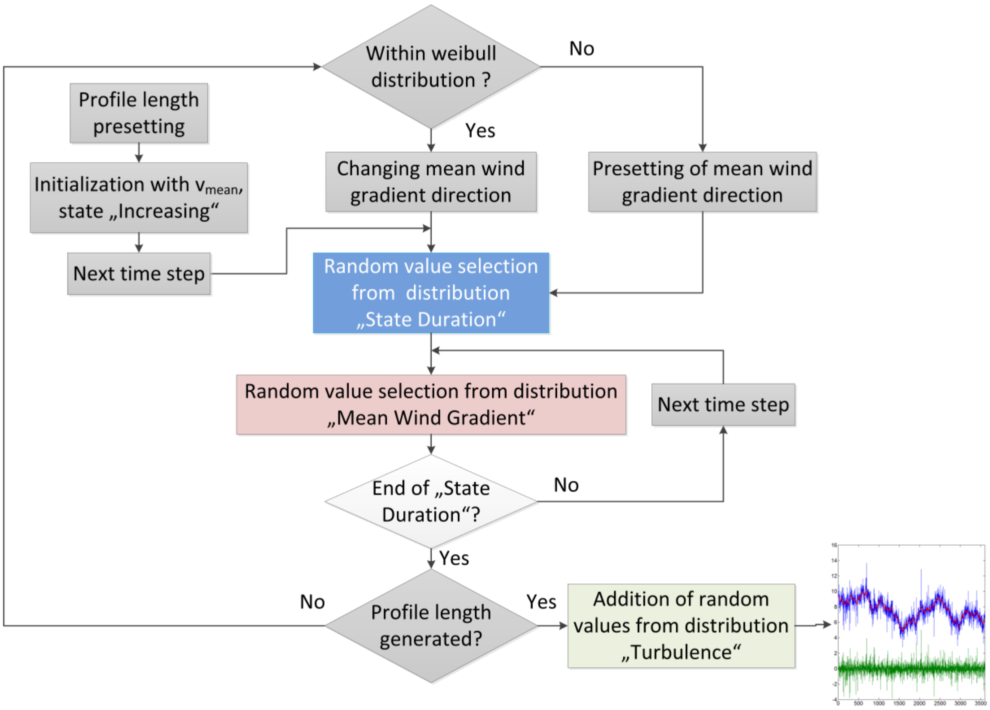

Figure 11: Method for generation of typical wind speed profiles

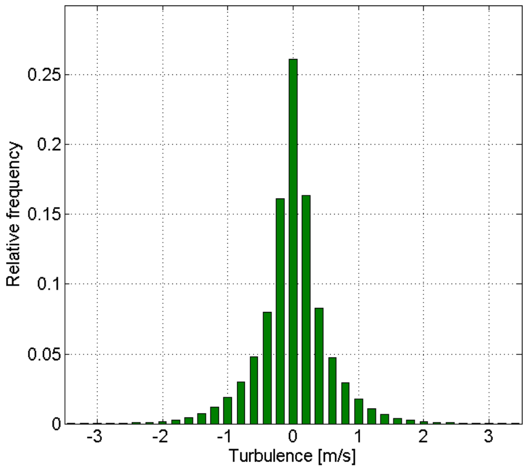

Figure 12: Distribution of the turbulence part

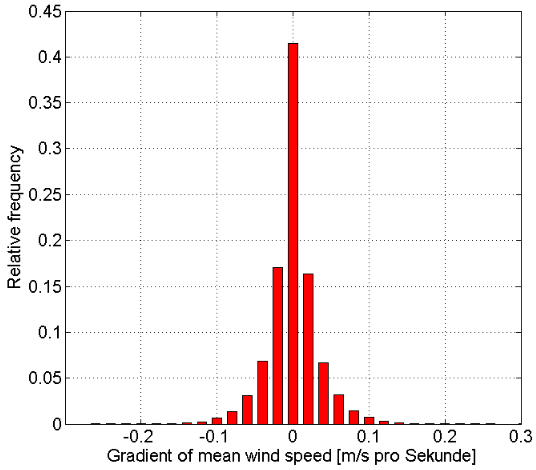

Figure 13: Distribution of the gradient of the mean wind speed

For the generation of typical profiles the gradient of the mean wind speed part is also interesting. Figure 13 shows the distribution of the gradient. Most values are in the range of ±0.02 m/s.

The last information that is needed is the duration of the rising or falling of the mean wind speed (state duration). Mostly the rising or falling times are three seconds and below. Longer periods have a probability less than 10% (Figure 14).

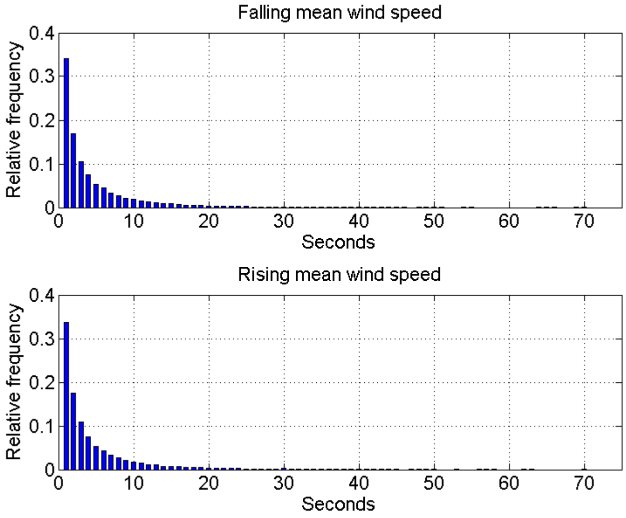

Figure 14: Distribution of the rise or falling time of the mean wind speed

To generate measurement based typical profiles the method is used which is pictured in Figure 11 and explained here:

- At first a desired profile length has to be defined (e.g. 20 minutes).
- As an initiation the first wind speed value in the new profile is preset with the mean value of all measurement data (here the data of all available springs).
- At the same time the state variable for the mean wind gradient is set to “increasing”. That means the second generated wind speed value is greater than the first.
- Next a random value of the state duration distribution is taken. The state duration tells how many of the following generated wind speed values have the same sign in there gradient. For example if the randomly chosen value is 5, then the wind speed profile rises for 5 seconds (because the state variable is set to “increasing”).
- Also a random value of the mean wind gradient distribution is chosen which defines the value for the gradient. So now the change and the direction of the wind speed from the actual and the next time step can be calculated. For that the wind speed result of previous time step of the new profile is taken and together with the gradient (direction and value) new amplitudes are calculated. This step repeats until the state duration (here in the example 5 seconds) is reached.
- If the predefined profile length is not yet reached, the generation goes on with a bandwidth check. The last new wind speed value is checked if it is within a band of 10% and 90% of the Weibull distribution for the measured wind speed. If so, the direction of the gradient is changed to the opposite direction and the generation goes on. If not, the direction is changed in a way that for the next loop the wind speed value goes back into the band.
- When the predefined profile length is reached a turbulence part needs to be added. For that, according to the profile length, random values for the turbulence part were generated in a way that the same distribution like the turbulence distribution of the measurement is reached.
- Finally the mean wind speed and the turbulence are added to a time continuous wind speed profile with the chosen length.

Figure 15 shows a generated wind profile with a length of 3400 seconds which represents a typical behavior for the location of the platform FINO I in terms of dynamic changes in wind speed.

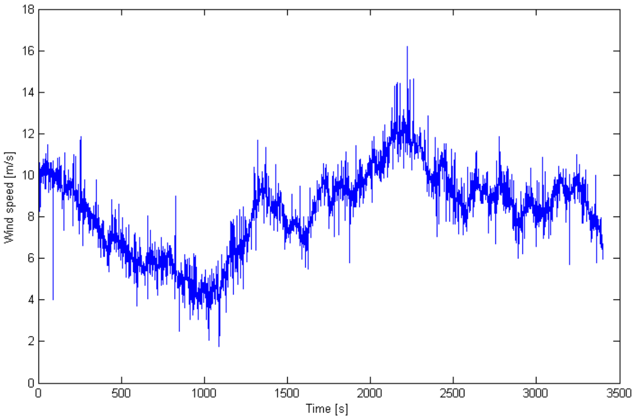

Figure 15: Typical generic wind profile.

V. CONCLUSION

The typical generic wind profiles generated with the procedure presented in this paper are suitable for studying network dynamics of the grid connection of offshore wind parks. Studies like observation of power fluctuations or voltage fluctuations in the offshore network or behavior during fault conditions can be carried out under a typical environment for a specific location.

After having generated the necessary typical wind speed profile for this location it must be transferred into a wind profile array consisting of single wind speed profiles for each wind turbine generator of an offshore wind park.

For this the method of stochastic wind profile generation is proposed. It is not a metrological methodology with the need of big climate models or supercomputers; it is a stochastic approach designed for an easy and fast calculation of the conditions within an average sized offshore wind park or a cluster of some offshore wind parks.

In near future the results of the model based on the *FINO I* measurements can be compared with the power infeed of the offshore wind park “*alpha ventus*” which is located right aside.

VI. REFERENCES

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VII. BIOGRAPHIES

Thomas Ahndorf received in 2004 his diploma in electrical power engineering and automation from the University of Applied Science in Karlsruhe, Germany. After this he started a postgraduate study also at the University of Applied Science in Karlsruhe and received his Master degree in Electrical Engineering in 2006 with distinction. Since 2006 Mr. Ahndorf worked at the Associated Institute of Power Transmission Systems of Technische Universität München as a Ph.D. student. His research is focused on the grid connection of large scale offshore wind power. Mr. Ahndorf is a member of the VDE

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