DESCRIPTION OF VARYING OPERATIONAL CONDITIONS IN WIND TURBINES

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Summary

Vibrations of wind turbines strongly depends on the wind. For the purpose of wind turbines condition monitoring it is very important to understand the nature of the wind, especially its time variability. The paper investigates fundamental statistics of the wind and vibrations for four wind turbines in two wind farms. Seasonal and diurnal variations are presented and discussed. For both vibration and wind speed seasonal trends are clearly visible, particularly for mean values, but also for standard deviation. Variability of vibration and wind are compared using mean/std ratio. The results can be helpful to determine operational states of wind turbines. It can also help achieve comparable results of technical state assessment for different machines located in different locations.

Keywords: wind turbine, operational states variability, wind variability, vibration, monitoring.

OPIS ZMIENNOŚCI WARUNKÓW OPERACYJNYCH TURBIN WIATROWYCH

Streszczenie

Wibracje w turbinach wiatrowych zależą w znacznym stopniu od wiatru. Zrozumienie natury wiatru jako zjawiska, szczególnie jego zmienności, jest istotne dla skutecznej diagnostyki turbin wiatrowych. Artykuł opisuje podstawowe dane statystyczne prędkości wiatru oraz wibracji dla czterech turbin wiatrowych z dwóch różnych farm. Opisane są zmiany sezonowe i dzienne. Trendy sezonowe są widoczne zarówno w przypadku prędkości wiatru jak i poziomu wibracji, szczególnie w przypadku wartości średnich, ale także, do pewnego stopnia, dla odchyleń standardowych. Zmienności wibracji i prędkości wiatru są porównane przy pomocy współczynnika mean/std. Wyniki będą pomocne przy ustalaniu stanów operacyjnych turbin, a także przy ocenie stanu technicznego dla turbin zlokalizowanych w różnych lokacjach.

Słowa kluczowe: turbina wiatrowa, zmienność warunków operacyjnych, zmienność wiatru, wibracje, monitoring.

1. INTRODUCTION

Wind turbines are one of the most fastest growing branch of renewable energy sources. Wind energy resources in Poland are medium, but still not fully utilized [1].

According to the report prepared by Ministerstwo Gospodarki [2], until the year 2015 wind energy should become the major source of renewable energy. In 2030 wind farms capacity should reach 7867 MW in comparison to 976 MW in 2010. Those numbers prove, that wind turbines are considered as very important source of energy and great number of them might be expected to be built in the following years.

Wind turbine is a device that converts the kinetic energy stored in the air stream (wind) into the mechanical energy, which is afterwards converted into the electric power. Wind turbine machinery can be roughly divided into the mechanical (mechanical drive train) and electrical subsystems [3]. The first system consist mainly of generator (synchronous or asynchronous) sometimes followed by a frequency converter. Mechanical components are blades, bearing, blade pitch mechanism, gearbox and yaw system. Gearless systems are also available, e.g. by Enercon [4]. In such a designs, low speed generator followed by the inverter is used. The solution that tries to combine advantages of both types of drive trains has been presented by AREVA in MULTIBRID M5000 offshore plant, where single stage planetary gearbox is integrated with the generator [3, 5]. Both systems (mechanical and electrical) are controlled by the control unit.

In wind turbines two different methods of controlling the output power are commonly used [6]:

- Pitch control, where blades of the main rotor are able to change the pitch. This mechanism is also used as an additional braking mechanism.

- Stall control, where the blades have fixed pitch and in stronger winds part of energy causes the stall, which in turn causes the power to decrease.

The more popular method nowadays is the pitch control, where the speed constantly changes in order to maintain the highest possible efficiency. This cause smearing of lines in the vibration spectra, what brings the necessity of order tracking [6]. In stall controlled turbines the speed is much more stable over relatively long periods of time, and thus the smearing can be observed to a lesser extent [6].

The wind, which is basically movement of air masses in the atmosphere, is mainly caused by a heating of the earth surface by the sun, particularly by differences in solar energy absorption by different terrain types. The other two reasons of wind occurrence are Coriolis forces and air particles momentum. Wind is also affected by a surface friction, and the terrain shape [3]. Such a many factors that influence the behavior of the wind cause it to be a complicated and hardly predictable phenomenon. To predict wind on a given location, we have to take into consideration its global distribution, local low and high pressure areas and local terrain shape [3]. Variability of the wind is one of the most important arguments against wind energy utilization. It is thus especially important to possess as complete knowledge about this phenomenon as possible.

Wind speed is usually presented by two parameters – mean annual wind speed and wind speed frequency distribution. In order to characterize the wind speed in a given location, measurements taken over decades are necessary [3].

Wind speed variability is determined by two factors – latitude of the site and surrounding distribution of land and water. Wind speed has random and periodic components. The first one are mainly the wind speed turbulences, although mean wind speed changes randomly from year to year [3]. Periodic component are diurnal and seasonal wind speed changes. From the economical point of view the mean annual wind speed is the most significant information, although shorter changes are interested from the point of view of machinery diagnostics.

In the rotating machinery diagnostic, one of the measured quantities is level of vibrations, which are dependent, among others, on rotational speed of the shaft and power transmitted through the shaft. In wind turbine both load and shaft speed are directly related to the wind speed (are also dependent on the control type, i.e. stall or pitch). Thus the level of vibrations should be dependent on the wind speed. On the figure 1 the relation between vibration level measured on the component of drive train and wind speed is shown. Measurements of vibrations performed at different wind speeds might cause false evaluation of machinery state. In order to avoid such a situation, conditions in which vibrations are measured should be chosen carefully, and such an operating point evaluation is not possible without proper knowledge about operational conditions variability.

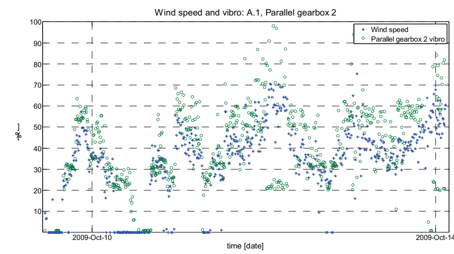

Fig. 1 Wind speed and vibrations on parallel gearbox of turbine A.1

The article is focused on the diagnostics of mechanical faults of rotating machinery (bearings, shaft, gearing). At first state of the art in wind turbine condition monitoring and wind variability are presented. The section is focused on different ways of wind variability assessment, mainly in the Europe but also in United States and Turkey. In the next section the statistical analysis of data from 4 wind turbines is presented, and on that basis seasonal trends are sought. Statistical analysis concerns both wind and driver-train vibration analysis. Examples of diurnal trend are also presented.

2. STATE OF THE ART

Some general information about wind turbine diagnostic can be found in [7 - 9]. Barszcz in [7] presents selection of diagnostic algorithms for wind turbines drive – train components. Problem of conditions variability is mentioned, along with its basic solution – order tracking. Thorough survey of condition monitoring (CMS) and fault detection (FDS) systems is presented in [8]. Beside vibration analysis also oil analysis, thermography, strain and acoustic (and more) are described. CMS and FDS of subsystems (rotor, pitch mechanism, gearboxes and bearings, electrical systems) are also reviewed.

Echavarria in [9] uses the German “250 MW Wind” test program database to investigate reliability wind turbines major components through several years. Report takes into consideration different turbines sizes (rated output power) and technology.

Example of new idea for wind turbine condition monitoring has been presented by Yang et. al in [10]. Faults are detected on the basis of generator output power and rotational speed, using continuous – wavelet – transform – based adaptive filters. Method is tested by detection mechanical unbalance and electrical asymmetry.

Wind variability is a complex topic and numerous publications brings the subject up. According to Hau [3] the most important for wind energy production are annual changes of mean wind speed, although diurnal, seasonal and even shorter changes occur. Exemplary data of annual variability are given in [3] (300kW wind turbine, north sea cost, years 1967 – 1997), which shows, that for most years power fluctuations from mean were less than 10%, although in some years they rises up to 15%. Description of annual changes can be found in works of Pryor[11] for Europe and Klink [12] for Minnesota.

Pryor in [11] focused on *historical variability of annual wind indices in Europe to provide a context for possible future scenarios, as well as possible tools for use in developing prognoses.* The analysis of inter – annual changes is conducted for Scandinavian and Baltic countries and also for whole continent. Inter - annual variability investigations and predictions are based on HadCM3 model. Klink [12] has investigated annual changes of wind speed on seven different sites in Minnesota. Beside the fact that mean annual wind speed have decreased in period from 1960s to mid 1990s, in each site different trends can be observed. The methods used in papers are described in the separate paragraph.

However, the current investigations are rather focused on seasonal, diurnal and hourly or even shorter changes. Holttinen in [13] presents data gathered from wind speed measurement in Nordic countries, along with comprehensive analysis of wind power variations. Several separate topics are in the field of his interest.

General conclusion states that *the hourly variations of large-scale wind power stay 91% - 94% of the time within +-5% of installed capacity in one country, and for the whole of the Nordic area 98% of the time.* Those data concern whole region, for single turbine/farm variability is higher. For single exemplary site (in Finland) standard deviation has been higher than mean value of wind power production (28.2% to 25.9%), while for the whole Nordic region this ratio was equal to 14.5% to 25.1%. In Europe standard deviations to mean ratio is 0.5 – 0.8 for 200km radius circle and 0.3 for >2000 km. The same conclusion might be drawn from correlation analysis – which is 0.7 for WT in distances less than 100km and below 0.5 for distances 200-500 km. For distributed geographically wind farms *the total production never reaches total installed capacity and hardly ever totally calm.*

Next subject brought up in [13] are trends in wind speed. Frequency distribution for single countries and whole Norway are given for each season, with conclusion that winter months are responsible for 110% to 150% of annual energy production. According to Hau [7] the diurnal trends can be rarely observed in Europe. Holttinen in [13] states, that such a patterns occurs when influence of sun dominates on weather front influence. Such a trend might be observed rather in the summer (in the Northern Europe). The more significant diurnal trend is observed in the southern part of Nordic area.

Another component of wind characteristics according to [13] are duration of calms, low winds and peaks, autocorrelation of wind power according to time lag (at 12h such a lag correlation becomes weak) and magnitude of variations for different time scales. For exemplary 103 MW wind farm those variations are: 4-7% of capacity in second, 10-14% in minute, 50-60% in an hour.

Apt [14] shows the turbine output in the form of power spectral density for both 1 sec and 1 hour samples. Data in [14] have been gathered from 4 wind farms for period of 4 years (2001 – 2004). *The measured output power is found to follow a Kolmogorov spectrum over more than four orders of magnitude, from 30 s to 2.6 days.* In [14] periodograms are used to present the PSD of output power, although no windowing or segments overlapping are used because no noticeable improvement in variant has been observed. *At frequencies between 2*10e-6 and 4*10e-2 the double logarithm plot of the spectrum is linear. At frequencies above 5*10e-2 the physical and electrical inertia of turbines appear to act as low pass filters.* Peaks in spectrum might be observed due to turbine blade passing. In [14] it is concluded that *Since wind is an intermittent resource, it must be matched with fill-in power sources from storage or generation if the power output of wind farms on a grid are correlated.*

Wan in [15] presents results of project undertaken by National Renewable Energy Laboratory *to record long-term, high – resolution (1Hz) wind power output data from large wind power plants in various regions.* Data have been gathered from 7 wind farms, the smallest 35 MW but most more than 100 MW capacity, with greatest distance between farms 1590 km (shortest 40 km). In the report coefficient of variance (COV, std/average) is frequently used to characterize the wind resource.

According to the data presented in [15] output power is less variable than wind speed. Wind power COV is generally higher than wind COV, although in some months they are almost equal.

The diurnal trends (the most strong in august, in winter almost not at all) and seasonal are mentioned in article. In the article the subject of aggregating wind turbines is also brought up (correlation between groups of turbines). *The range of 15-second correlation coefficients suggests that output powers from even nearby wind turbines are not related in short time frames. On the other hand, corr. Coeff. From 12-hour intervals are almost all close to 1.* [15]

Conclusions of [15]:

1. Short – term fluctuations of wind power plant are small – 0.1% for second data series, 1% for minute and 3% - 7% for hourly. No trends can be found in second – to – second fluctuations.
2. Output fluctuations are influenced mainly by the size of the wind power plants, more than by differences in turbine types and plant locations.
3. More wind plants connected to the system means output less volatile, although step changes in MW or kW will be even higher and calms are still possible.
4. Caution should be kept when simply scaling up wind power available from wind speed data from smaller wind power plant or single anemometer.

Petersen in [16] writes about the discipline known as wind power meteorology. According to the data presented in the article, in Northern Europe wind speed changes up to 30% from one decade to another might be expected and interannual variability up to 13%. Some laws and formulas concerning wind speed near surface are given (e.g. geostrophic drag law). Turbulence can be modeled by Kaimal spectra (atmosphere) and von Karman (rather wind channels).

Sinden in [17] investigate long-term wind patterns and their relationship to electricity demand in UK.

Giebel et. Al. [18] gives review of current methods of wind power prediction for single turbines, wind farms and whole regions, from few minutes up to a few days ahead. Ramp and variability forecasting are also in the scope of interest of researchers. Ramp forecasting has been first taken into consideration in 2006 in pilot project of the Alberta Electric System Operator, and variability *is only recently that it has come into the sight of researchers.*

Akpinar and Akpinar [19] and Celik [20] performed analysis of wind power in Turkey. Akpinar focuses on seasonal variations on 5 sites, using data gathered for 5 years. Celik studied data for year 1996 on one site, hourly values. Both papers used Weibull and Rayleigh distribution mainly. In [20] the first distribution is found to be more accurate (correlation coefficient 0.88). According to [19] '*c'* parameter of Weibull distribution is near the mean wind speed.

What is interesting for the purpose of this article are also statistical tools used to wind variability description in presented papers.

Pryor in [11] used only Min, Max, Mean and std values to investigate inter – annual variability, while Klink in [12] uses also percentiles and Weibull shape parameter and percentiles to characterize the Wind speed in Minnesota. Weibull distribution and Rayleigh distribution (which is the simpler version of Weibull) have been also used in [19] and [20] as main wind speed characteristic.

In [13] wind power production in Nordic countries is presented by: mean, median, std, std/mean, range, min and max. The data were gathered for 3 years (2000 – 2002). Wind power production is also presented in the form of frequency distribution. Another characteristics are calms, low wind and peaks, correlation between different farms (with different distances between them) and autocorrelation of wind speed (up to 12h time lag).

In [14] the output power of WTs have been investigated with PSD - periodograms (with eight segments, no overlapping and no windowing).

In [16] author focuses mainly on std/average coefficient in presented data and step changes – presented separately as positive and negative changes.

3. DESCRIPTIOM OF METHODOLOGY AND DATA

The dataset consist of wind speed, output power and vibrations measured by wind turbine monitoring system, which stores one value every 15 minutes. Data from 4 turbines, 3 placed in windpark A and 1 in windpark B, are presented. Measurements from A cover the period from 01.07.2009 to 24.08.2010, and from B from 01.09.2009 to 26.07.2010 (additionally with data from may 2009).

Data have not been collected during repairs and maintenance actions, what results in overall number of measurement points (single collected values) as presented in table 1. In case of A.3 the overall number of samples is higher than number of 15 minutes long periods. Such a situation is caused by sampling rate, which is not exactly equal to 15 minutes but vary significantly, so average sample is shorter than 15 minutes. It should be also noted that number of samples vary on different turbines and in different seasons. The influence of periods when turbine does not work is briefly presented in the next chapter.

Table 1 Number of samples for each turbine

	no. of 15 minutes periods	A.1	A.2	A.3
01.07.2009 to 24.08.2010	40320	34428	36846	41748
July, August, September	10058	12916	9178	11900
October, November, December	10058	7204	8919	10502
January, February, March	10058	5741	9218	9661
April, May, June	10058	8567	9531	9685

Dataset has been investigated using statistical tools – mean value, standard deviation and max value (min value in every case was equal to 0) and frequency distribution of the wind speed. Data are presented in table 4.1 and exemplary frequency distribution is presented on figure 4.3.

4. STATISTICAL DATA ANALYSIS

The statistical analysis of data are presented in the table 1. In Autumn and Winter the highest mean wind speed might be observed for A turbines, while in B only in the autumn the wind speed is considerably higher. The differences in mean wind speed between single turbines in A are relatively high. Situation is not so clear in case of standard deviation of wind speed. For both A.1 and A.2 (as well as for B) highest standard deviation occurs in winter and autumn, while for A.3 occurs in winter and spring. Some explanation of those facts might be found be inspection of wind speed plot for each turbines. Comparing figure 4.1 (A.3) with figure 4.2 (A.2) it can be seen, that on the latter January and match are months of the highest variance, while on A.3 May variance is very high additionally. However, in May the measurements on A.3 have been performed only for several days, and in those days wind speed seems to vary considerably. Probably if more data for May would be available, the variance will not be so high in this month and in whole spring. This example shows the necessity of comparison of measurement for more than 1 year what let to avoid such an anomalies.

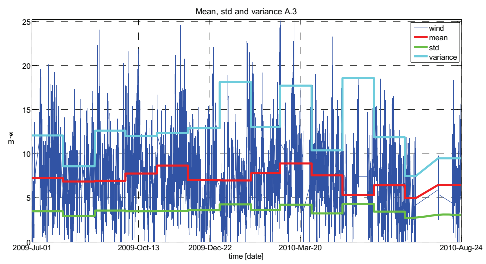

Fig. 4.1 Wind speed for A.3

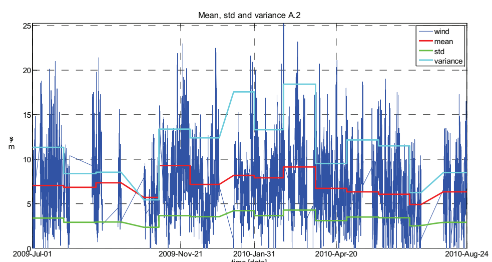

Fig. 4.2 Wind speed for A.2

Similar trend can be observed also in case of vibration measurement. In table 4.1 statistical analysis is presented – for A.1 and A.3 vibration measured on parallel gearbox is presented, for A.2 and B vibrations presented have been measured on generator. For A.1 and A.3 level of vibration is similar, while vibrations of A.2 generator are generally higher. The seasonal trend is even higher than in case of wind – for every turbine mean value of vibrations is higher in autumn and winter than in spring and summer. Situation is not so clear if vibrations standard deviation is taken into consideration.

Table 4.1 – statistical analysis

Season		Wind Turbine wind speed [m/s] / vibrations [g]			
		A.1 Parallel 1	**A.2** Generator 1	**A.3** Parallel 1	**B** Generator 1
Winter	**Prob***	6	6	5	7
	Max	24,9 / 0,699	25,3 / 1,164	25,2 / 0,425	24,5 / 0,690
	Mean	7,82 / 0,189	8,39 / 0,408	7,76 / 0,166	6,46 / 0,239
	Std	3,91 / 0,168	4,07 / 0,263	4,12 / 0,110	3,89 / 0,135
	Mean / std	2,00 / 1,123	2,06 / 1,55	1,88 / 1,51	2,25 / 1,77
Spring	**Prob***	6	6 / 8**	7	6
	Max	24,7 / 0,694	21,1 / 1,203	23,3 / 0,372	25,1 / 0,681
	Mean	6,47 / 0,144	6,38 / 0,269	6,560 / 0,139	6,46 / 0,152
	Std	3,33 / 0,129	3,33 / 0,291	3,74 / 0,093	3,53 / 0,122
	Mean / std	1,95 / 1,087	1,92 / 0,93	1,75 / 1,48	1,83 / 1,25
Summer	**Prob***	7	6 / 8	7	6
	Max	23,2 / 0,699	21,4 / 1,132	24,1 / 0,415	24,4 / 0,685
	Mean	6,24 / 0,130	6,58 / 0,362	6,804 / 0,148	6,21 / 0,136
	Std	3,60 / 0,110	3,11 / 0,248	3,29 / 0,095	3,54 / 0,115
	Mean / std	1,73 / 1,185	2,12 / 1,46	2,07 / 1,56	1,76 / 1,18
Autumn	**Prob***	7	7	7	6 / 8
	Max	23,6 / 0,693	23,0 / 1,231	24,6 / 0,416	25,4 / 0,696
	Mean	7,82 / 0,184	7,83 / 0,468	7,76 / 0,174	8,89 / 0,168
	Std	3,73 / 0,149	3,67 / 0,307	3,60 / 0,103	3,88 / 0,095
	Mean / std	2,10 / 1,241	2,13 / 1,53	2,16 / 1,69	2,29 / 1,77

* The wind speed value which probability of occurrence is the highest in given season
** There are two peaks

In order to compare variability of wind speed and vibrations amplitude, mean to std ratio has been calculated. The ratio is generally lower for vibrations, what means, that vibrations variability is even higher than variability of wind speed. In A turbines very weak seasonal effect can be observed, while in B ratio is considerably higher in autumn and winter.

On the figures 4.3a and 4.3b the exemplary histograms – for A.2 turbine in winter and spring, is shown. Histogram of summer is similar to histogram in spring, the same tendency can be observed in case of winter and autumn. The common feature of all histograms is higher probability of calms and low winds occurrence in summer and spring, as well as higher winds in autumn and winter.

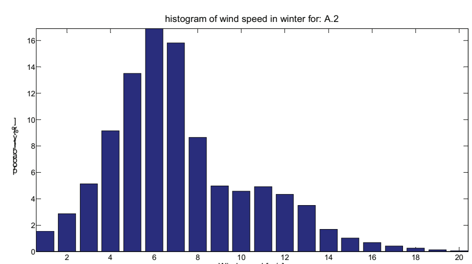

Fig. 4.3a Histogram of wind speed for A.2- winter

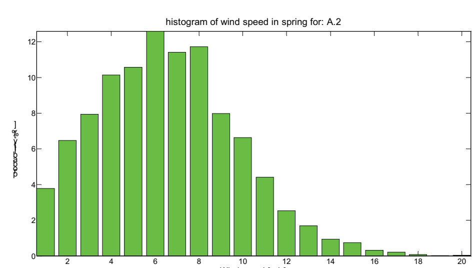

Fig. 4.3b Histogram of wind speed for A.2- spring

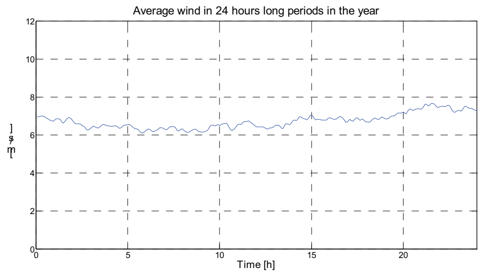

Fig. 4.4a Diurnal trend whole year A.3

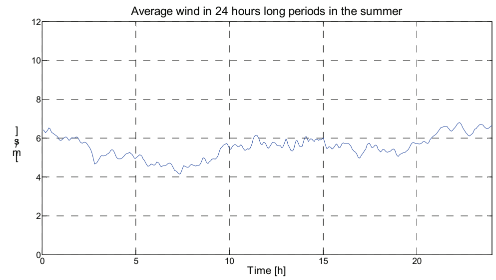

Fig.4.4b Diurnal trend May - September A.3

Diurnal trends have been sought in the data. Weak trends have been observed for turbines A.1 and A.2. The exemplary trend is shown in figures 4.4a and 4.4b (for A.3).In the summer and spring months (4.4a) the diurnal trend is more distinct, with two periods of higher wind – more visible in the night and less visible in the afternoon, but overall wind speed is smaller than in winter and fall months.

5. CONCLUSIONS

In the article the statistical analysis of variability of operational conditions is shown. Data consider both wind speed and vibration measured on drive-train of 4 wind turbines from 2 wind farms. It is clearly visible in the data, that mean wind speed is generally higher in the winter and autumn. The same trend, although not so distinct, might be observed in case of standard deviation of wind speed. For all turbines mean/std ratio is higher for wind speed than for vibration, so the latter variability is even higher than in case of wind speed. Probability distribution of wind speed is more steep in winter in autumn than in spring and summer, although in spring summer diurnal trend is much more distinct.

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