THREE-DIMENSIONAL REPRESENTATION OF DIAGNOSTIC FEATURES IN APPLICATION TO WIND TURBINES

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Summary

Wind turbine condition monitoring is essential task in the process of maintaining machine operation at the optimal level. It is related to ensuring the profitability of investment and the provision of security in the environment of the turbine. However, the working conditions of turbine associated with non-stationary nature of the stimulus which is wind, impede the correct diagnosis of the machine. In addition, a multitude of parameters adversely affects the clarity of predictions and setting alarm thresholds. In the article, the authors evaluate the impact of power generator and bearing rotational speed on the root-mean-square (RMS) value received on the generator bearing. The study was performed in various dynamic states of the bearing: the intact and after discovery of damage. It was possible due to long term monitoring of the system and further analysis of the RMS as a function of power and rotational speed. For this purpose the method that bases on calculation of arithmetic mean of the data in the segments corresponding to the chosen ranges of both rotational speed and generator output power. Results are presented in the form of three-dimensional charts, which allow assessing the impact of parameters on the estimator. As observed, a greater impact on the RMS has the power which reveals as more dynamic changes of RMS to the fluctuation of power. The variation of rotational speed does not affect RMS so rapidly. This was confirmed by an analysis of the slope the function obtained by linear regression. Therefore, it might lead to the conclusion that operational state of wind turbines should be assessed due to generated power level not in respect to rotational speed.

Keywords: wind turbine, vibration analysis, non-stationary operation, damage detection

TRÓJWYMIAROWA REPREZENTACJA PARAMETRÓW DIAGNOSTYCZNYCH W ZASTOSOWANIU DO TURBIN WIATROWYCH

Streszczenie

Monitorowanie stanu pracy turbiny wiatrowej jest niezbędnym zadaniem w procesie utrzymania pracy maszyny na optymalnym poziomie. Jest to związane zarówno z utrzymaniem rentowności inwestycji jak i zapewniania bezpieczeństwa w otoczeniu pracy turbiny. Jednakże warunki pracy turbiny związane z niestacjonarnym charakterem czynnika pobudzającego, jakim jest wiatr, utrudniają poprawną diagnozę stanu maszyny. Dodatkowo mnogość parametrów wpływa niekorzystnie na klarowność prognozy i ustawienie progów alarmowych. W artykule autorzy oceniają wpływ mocy generatora i prędkości obrotowej łożyska generatora na zmianę wartości skutecznej (RMS) wibracji otrzymanej na łożysku generatora. Obserwacja została poczyniona w dwóch stanach dynamicznych łożyska: w stanie nieuszkodzonym oraz po stwierdzeniu uszkodzenia. Umożliwiła to długoczasowa obserwacja turbiny pod kątem ww. parametrów, a następnie analiza zależności RMS w funkcji mocy i prędkości obrotowej. W tym celu zaproponowano metodę polegającą na obliczaniu średniej arytmetycznej wartości RMS w segmentach odpowiadającym wybranym zakresom prędkości obrotowej i mocy generatora. Wyniki przedstawiono w postaci trójwymiarowych wykresów, które pozwalają na ocenę wpływu parametrów na estymator. Jak zaobserwowano, większy wpływ na RMS ma parametr mocy generatora, co objawia się bardziej dynamiczną zmianą RMS w odniesieniu do zmiany mocy. Wahania prędkości obrotowej nie wpływają na estymator tak gwałtownie. Zostało to potwierdzone analizą współczynników kierunkowych funkcji otrzymanej przy pomocy regresji liniowej. Może to prowadzić do wniosku, że stan działania turbin wiatrowych powinien być oceniany ze względu na generowany poziom mocy a nie z powodu prędkości obrotowej.

Słowa kluczowe: turbiny wiatrowe, analiza drgań, zmienne warunki eksploatacyjne, wykrywanie uszkodzeń

1. INTRODUCTION

Over the last few years wind power is becoming an important sector of the energy industry. Therefore more and more attention is paid to the aspect of operation maintenance of the wind power generating machinery [1-4]. It does not only enable to limit the possible breakdown cost and time of repair, but in addition it provides higher productivity of the machinery [5].

Because of the fact that wind turbines work under non-stationary wind behaviour [6], thus the analysis of vibration-based diagnostic features might be misleading. Since load-dependent excitation of the system affects vibration-based features, it is proposed in [7-8] to use feature-load representation to present distribution of features against the operating conditions. As has been presented it provides better effectiveness in classification of data than simple statistical feature processing.

The issue of fault detection of bearings operating in non-stationary conditions has been widely investigated in the recent time. Many diagnostic techniques has been employed for this issue, including wavelets, the envelope analysis, adaptive filters and exploiting cyclostationarity of vibrations [9-11], etc. Unfortunately methods listed above are not applicable to the data acquired by online monitoring system. The offline processing for multidimensional features has been investigated in [12-13] and may include data processing using Principal Component Analysis, data projection technique, outliers analysis, etc. However, due to the economic reasons building of advanced feature extracting module for online processing is not economically justified and is expected to be simplified. Such difficulty occurs not only for wind turbines, but also in many fields where rotating machinery is employed, e.g. mining, marine or aviation industries. It is important to remember that condition monitoring on this field has yet found complete solutions and still needs improvement.

Therefore the main aim of this paper is to present the analysis of the influence of operation parameters on the vibration estimators on the example of root-mean-square (RMS) as it is in authors’ opinion the most general analysis. For this purpose the power and rotational speed are investigated in two stages of the lifetime of the generator bearing: before and after recognition of fault. It was possible due to long term monitoring of the system. Such analysis can suggest the limiting of operation parameters used for observation of damage.

The paper is organized as follows. After the introductory part the investigated wind turbine design is briefly described along with placement of sensors used for the research. Next, the methodology of the investigation is explained step by step and presented in figures. The results of the research are described in the further section and followed by the conclusions.

2. INVESTIGATED WIND TURBINE

For the purpose of investigation, the commonly used turbine with nominal power of 1500 kW was selected. The turbine has two nominal states of operation which depend on the wind speed – except for the nominal operational mode it also is enabled to work on, so called, the “low” gear that corresponds to 1000 kW of generator output power.

In Fig. 1 one may find a kinematic system of the analysed wind turbine. The main rotor is driven by three blades and supported by the main bearing. It passes the torque to the planetary gearbox. Second bearing supporting the rotor is incorporated into the gearbox. The planetary gear has three planets, which are driven by the planet carrier. The planets transmit the torque to the sun gear, in the same time increasing the rotational speed. The sun shaft passes the torque from the planetary gear to the two-stage parallel gear. The parallel gear contains three shafts: the slow shaft clutched to the sun shaft, the intermediate shaft and the high speed shaft, which drives the generator. The generator produces AC current of a varying frequency. This current is converted first into DC power and then into AC current of frequency equal to the grid frequency. Electric transformations are performed by the controller at the base of the tower. The transmission chain changes the rotational speed from about 25 RPM on the main rotor to about 1800 RPM at the generator. In the considered case a diagnosed object is a bearing in electric power generator of a wind turbine.

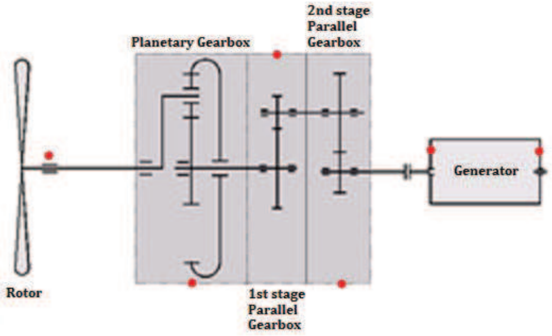


Fig. 1 Kinematic scheme of the analysed wind turbine with location of vibration sensors (red dots)

Typical requirement for wind turbine drive-train condition monitoring systems is to measure vibrations with six measurement channels that each covers separate area of drive-train [14]. Namely: main bearing, planetary gearbox, 1st stage of parallel gearbox, 2nd stage of parallel gearbox, front of the generator and back of the generator.

Additional required measurement covers rotational speed in order to asses acquired vibration data to proper operational state. In majority of condition monitoring systems dedicated for wind turbines value of generated power is measured as well as a supporting feature.

3. METHODOLOGY

The main objective of this paper is to present the vibration estimator – RMS as a two dimensional function of power and rotational speed. It is the authors' belief that such representation will provide better understanding of the influence of those parameters on these vibration-based features.

Presented study is performed for the wind turbine generator bearing in two different technical conditions: the undamaged and with advanced outer race fault. Data used in described investigation was obtained from industrial condition monitoring system operating on commercial wind-farm. Presented measurements were carried out on the described turbine for over six months (from 25th September 2009 to 7th April 2010), which resulted in 28575 samples for each parameter (RMS of vibration, RPM and generator).

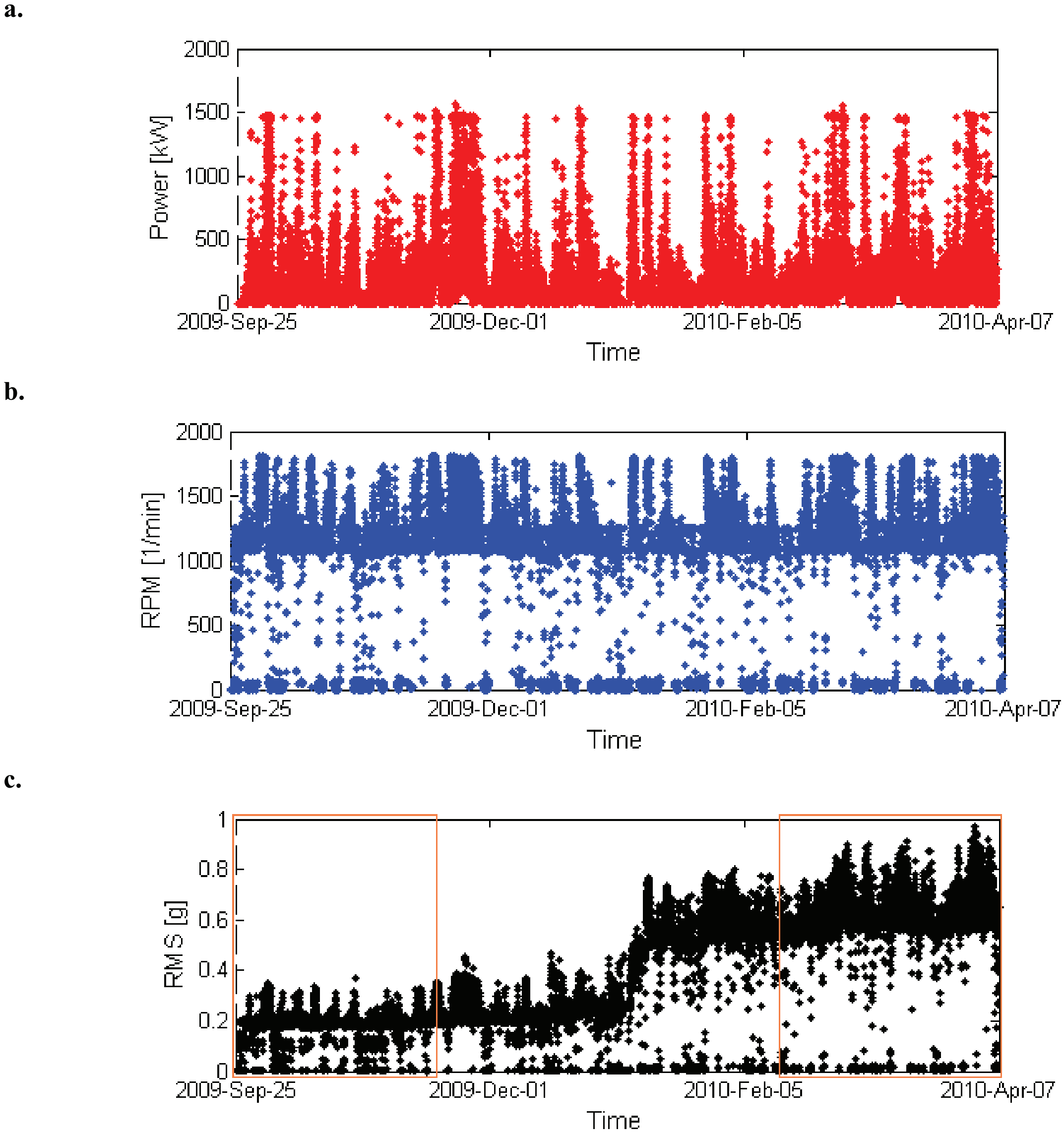


Fig. 2 Measurements acquired by condition monitoring system presented against number of samples: a. power, b. rotational speed (RPM), c. root-mean-square (RMS) with marked regions of undamaged and damaged bearing output power).

In Fig. 2a-c one may find plots of parameters in different, time-varying operating conditions. In Fig. 2c one may notice development of the fault of the bearing as increasing RMS value of the signal. The two sets taken for further investigation consisted of first and last 6000 samples of the total samples (for undamaged and damaged bearing, respectively). Selected regions are marked in Fig. 2c. RMS data used in presented case study was acquired for the wind turbine operating with rotational speed from 1050 RPM to 1800 RPM. Additionally, range of analysed data was limited to values corresponding to generator output power between 200 and 1500 kW. Such preselection of data for analysis was dictated by the amount of data available in database and it is the result of the operational character of the most industrial wind turbines.

In Fig. 3 and 4 one may find RMS in function of power and rotational speed, respectively. It is presented in two conditions of the generator bearing. In Fig. 3a and b it can be seen how often turbine was operating with its nominal power.

For each parameter the observer notice a large scatter of data, nevertheless the scatter of RMS in function of RPM is greater than in function of power. Furthermore the change in energy signal in

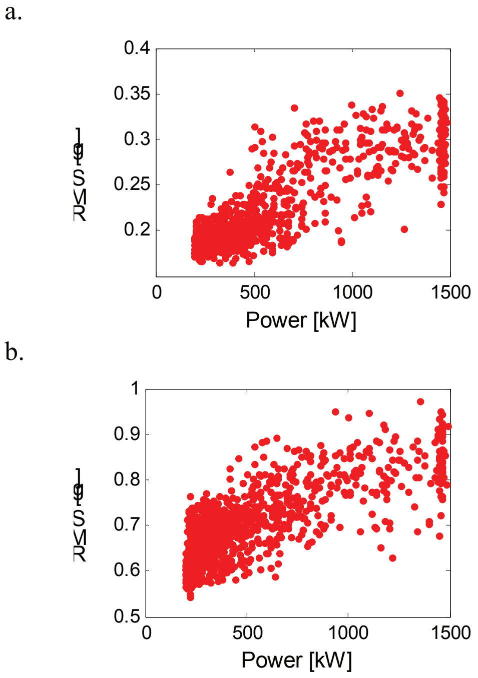


Fig. 3 RMS in relation to power for bearing: a. undamaged, b. damaged relation to the power is greater than for RPM

It is important to remember that the vibration estimators depend on two parameters, therefore those parameters should be considered together when analysing the fluctuation of RMS. Such three-dimensional analysis allows observers to assess the impact of the operational parameters. As observed, the RMS might be understood as a function of two variables: power and RPM (only if we consider different values of RMS for the same coordinates as their mean). Therefore, there is a possibility to create a structure from points with three variables: power, RPM and RMS. The motivation for this action comes from the fact that RMS can be compared to the energy of the measured signal, and thus be treated as the damage indicator. Since it is related to generator output power and RPM, the three-dimensional plot of these parameters would illustrate the influence of power and rotational speed on the damage diagnosis.

In order to present scattered RMS data as a three- dimensional surface that could be clear to analyse the authors wish to propose the method that bases on calculation of arithmetic mean of the data in the segments corresponding to chosen ranges of both rotational speed and generator output power.

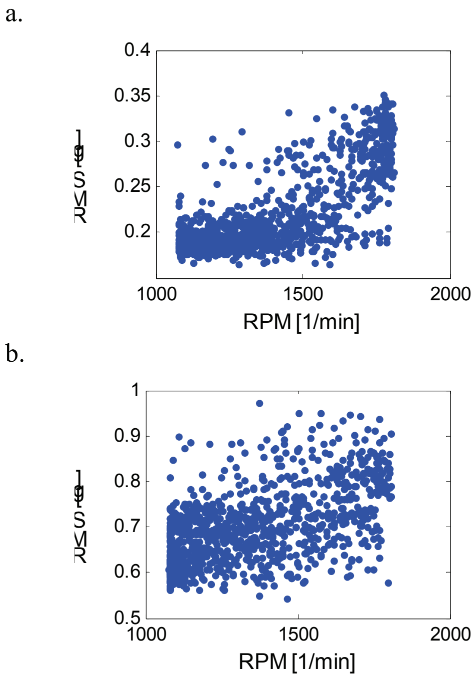


Fig. 4 RMS in relation to rotational speed (RPM) for bearing: a. undamaged, b. damaged

Mean value of RMS calculated for chosen segment is given by:

$$RMS_{\Delta RPM}^{\Delta P}(P,RPM)=\frac{1}{n}\sum_{n=1}^{n}RMS_{RPM'}^{P'}(n), \tag{1}$$

$$P'\subset\left\{P-{}^{\Delta P}\!/_{2},\,P+{}^{\Delta P}\!/_{2}\right\}, \tag{2}$$

$$RPM'\subset\left\{RPM-{}^{\Delta RPM}\!/_{2},\,RPM+{}^{\Delta RPM}\!/_{2}\right\}. \tag{3}$$

where P stands for *Power*. ΔP and ΔRPM are range-widths power and rotational speed respectively $RMS_{RPM'}^{P'}(n)$ is the n^{th} RMS sample corresponding to the range of power P' and the range of rotational speed RMS'.

For presented study ΔP was equal to 200 kW while ΔRPM was equal to 100 RPM.

To better understand the behavior of the estimator, the RMS charts of power or RPM for two permanent, fixed values of each operating parameter are presented. The constant values are equal to 500 and 1300 [kW] of power and 1300 and 1600 RPM of rotational speed. Then, using linear regression straight lines were plotted. The slopes of the lines were recorded in the Table 1. Furthermore, the variation was obtained to give information about spread of the data.

4. RESULTS OF EXPERIMENT

The Fig. 5 and 6 show the relationship between the RMS and both power and RPM for bearing without and with damage, respectively. Please note that results for two cases are presented in different scales. However in order to better reveal the changes of RMS axes on both plots were scaled to cover the same range of feature variation (0.3g). The one may notice, the change is more abrupt for the state of damage. As observed, the greater impact on RMS has the power which is disclosed by more dynamic changes of RMS in relation to the power variation. The fluctuation of RPM does not affect RMS so intensely. It can even be assumed, that in the case presented in Fig. 5 for low power estimations, RMS is almost constant in relation to RPM. On the other hand, relatively dynamic changes of RMS in relation to power can be noticed. As generator output power increases, RMS value also increase rapidly. For both cases (Fig 5 and 6) it can be noticed that up to 1000 kW average RMS value increase almost linearly which confirms results presented in [7]. Additionally, for rotational speed values around 1400 RPM slight increase of RMS estimation can be noticed (especially for higher power values. It might be the result of local resonance of the system.

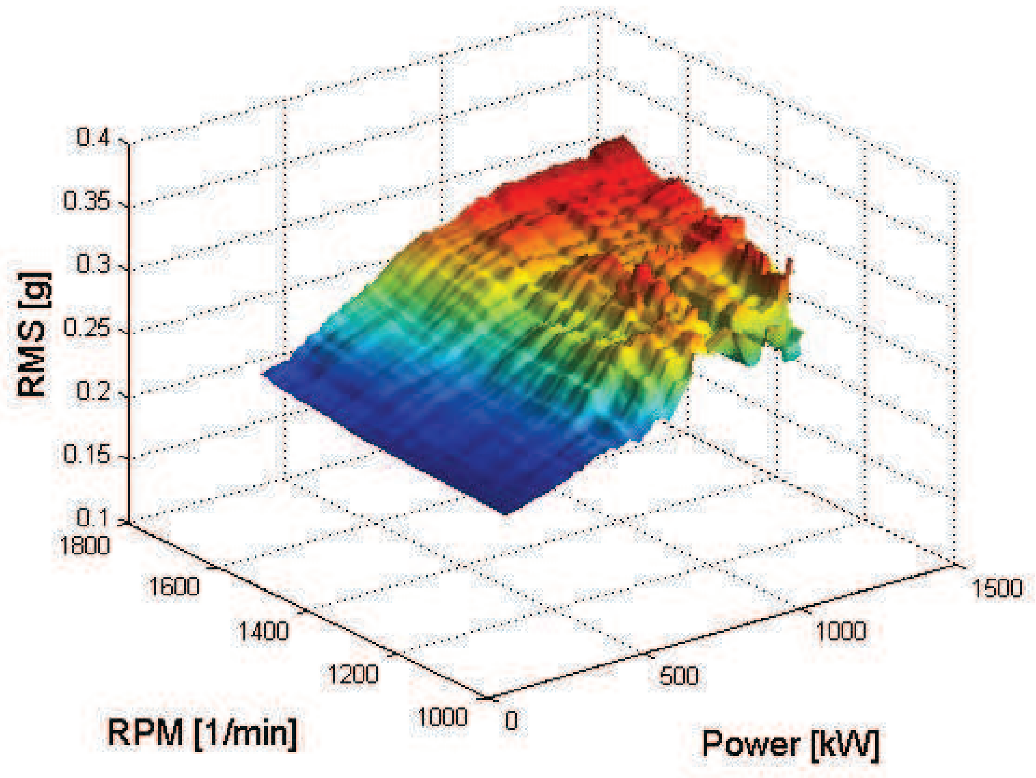


Fig. 5 RMS in relation to power and RPM presented for generator bearing in undamaged condition

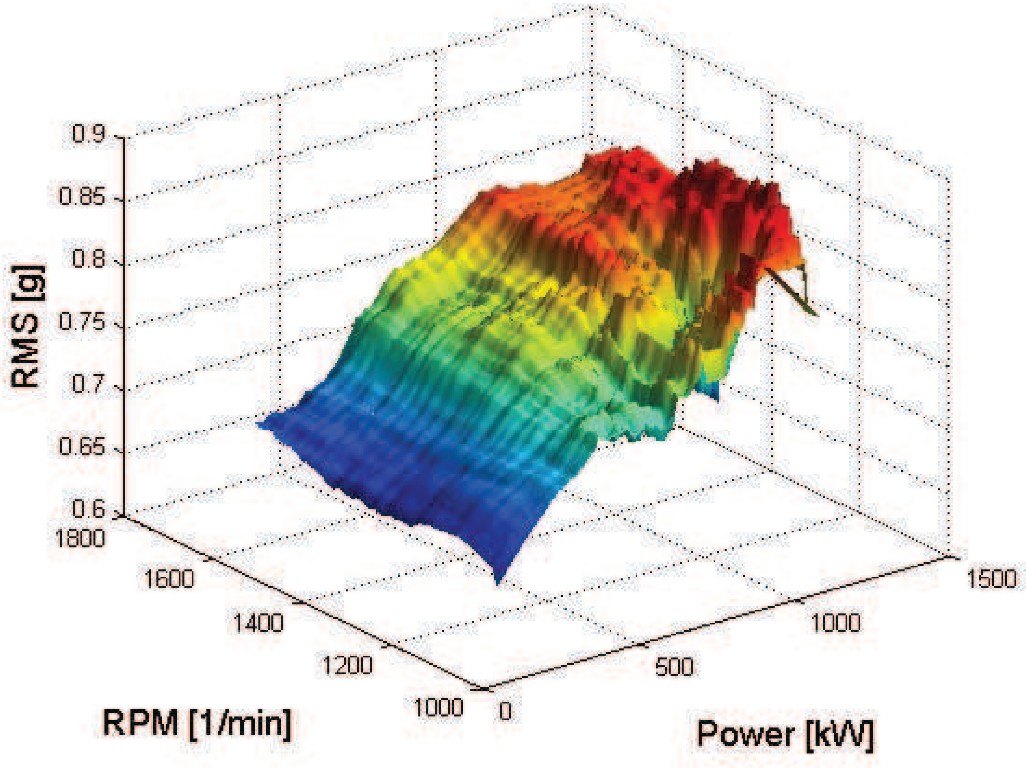


Fig. 6 RMS in relation to power and RPM presented for generator bearing in damaged condition

More interesting conclusions can be drawn from comparison of results obtained for bearing in undamaged and damaged condition. Beside clear increase of RMS value for damaged case (please notice different scaling of vertical axis in Fig 5 and 6), also dynamics of obtained results changed increase more rapidly with respect to the power. Additional increase can be noticed with respect to rotational speed, especially for power values up to sensitive mainly to the generator output power, but also in lesser extent to rotational speed.

In order to reveal the differences between RMS as a function of power and RPM, it was plotted with constant value of one of them.

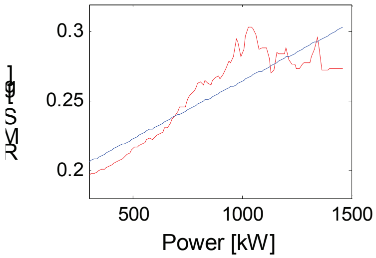
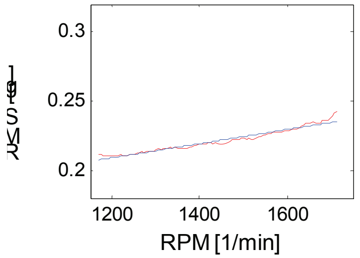
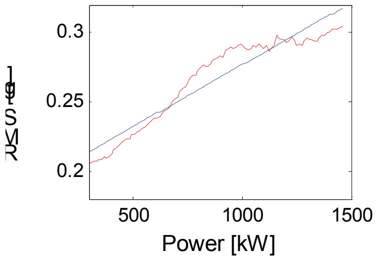
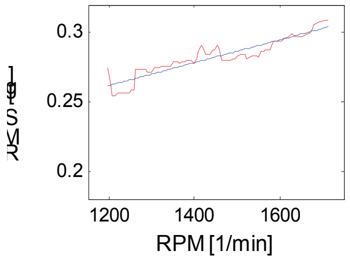
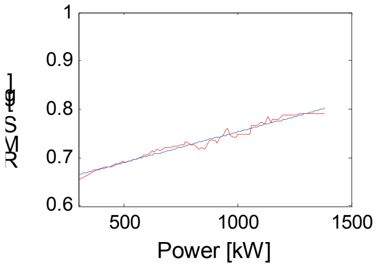
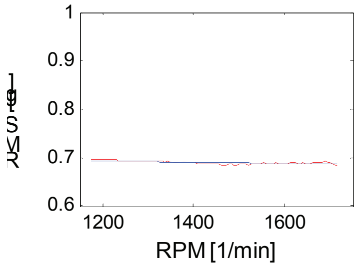
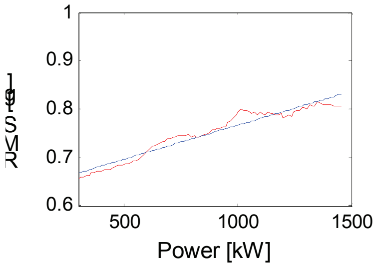
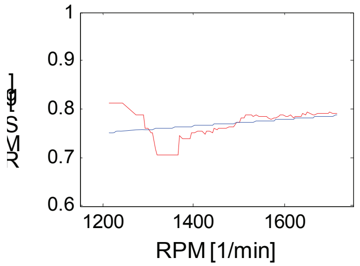
As stated, the values of the slopes in each of the analyzed cases are higher for variable power. It should be understood that the change of power more dynamically affects the value of the estimator RMS. This confirms the earlier observations. Interestingly that for a fixed, low-value output power of 300 kW, with an increase in RPM, the RMS is decreasing. This issue should be explored in the further investigation.

5. SUMMARY

The paper presents the dependence of RMS of vibrations measured on wind turbine generator bearing as a two-dimensional function of rotational and output power. Results are presented in the form of three-dimensional charts, which allow assessing the impact of parameters on the estimator. As observed, a greater impact on the RMS has the power which reveals as more dynamic changes of RMS to the fluctuation of power. The variation of RPM does not affect RPM so rapidly. Therefore, it might lead to the conclusion that operational state of wind turbines should be assessed due to generated power level not due to rotational speed. Unfortunately, majority of commercial industrial condition monitoring systems designed for wind turbines uses rotational speed as a reference value.

In general, it is the authors belief that representation of selected diagnostic feature as a function of two main operational parameters (rotational speed and power/load) can give comprehensive information about dynamic character of observed machinery. It can be a valuable source of knowledge not only about the influence of operational parameters on selected diagnostic feature but also about object resonances or the character of its operation.

Tab. 1 RMS graphs as a function of rotational speed and power for undamaged and damaged bearings, presented for different operating parameters. Linear regression lines with slope, and variation of the relation

	RMS in function of power; constant value of rotational speed	RMS in function of rotational speed; constant value of power
Undamaged bearing, small value of parameter		
	Slope: $8.3606\cdot10^{-5}$, variation: 0.0010	Slope: $5.1101\cdot10^{-5}$, variation: $6.9777\cdot10^{-5}$
Undamaged bearing, high value of parameter		
	Slope: $8.9452\cdot10^{-5}$, variation: 0.0010	Slope: $8.2114\cdot10^{-5}$, variation: $1.8089\cdot10^{-4}$
Damaged bearing, small value of parameter		
	Slope: $1.2634\cdot10^{-5}$, variation: 0.0017	Slope: $-1.5184\cdot10^{-5}$, variation: $1.1390\cdot10^{-5}$
Damaged bearing, high value of parameter		
	Slope: $1.4066\cdot10^{-4}$, variation: 0.0024	Slope: $6.9516\cdot10^{-5}$, variation: $8.3034\cdot10^{-5}$

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