APPLICATION OF DIAGNOSTIC ALGORITHMS FOR WIND TURBINES

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Summary

The paper presents the choice of diagnostic algorithms for condition monitoring of wind turbines. The device under monitoring is the power train, i.e. a main bearing, gears and a generator. The object also contains several roller bearings. The typical mechanical structure and characteristic frequencies are shown. The next chapter presents the sensor location and choice of sampling parameters. Additionally the monitoring should include a few key process parameters (output power, wind speed and rotational speed). Quick changes of the operational point are an important feature of wind turbines and should be addressed.

There are several diagnostic methods which could be used for the monitoring of a wind turbine. A few of them should be selected for the proper detection and identification of the most important faults. The main part of the paper presents malfunctions and diagnostic algorithms which should be used to detect those malfunctions. To avoid the influence of varying operational point, some additional preprocessing should take place. Apart from relatively simple methods mentioned above, there is a number of more advanced methods. The example of such an algorithm based on the spectral kurtosis is also presented.

Keywords: vibration, monitoring, diagnostics, wind turbines.

DOBÓR ALGORYTMÓW DIAGNOSTYCZNYCH DLA TURBIN WIATROWYCH

Streszczenie

Artykuł przedstawia dobór algorytmów diagnostycznych do nadzorowania stanu turbiny wiatrowej. Nadzorowanymi elementami są: główne łożysko wirnika, przekładnie i generator wraz z ich łożyskami. Przedstawiono typową strukturę i zaprezentowano częstotliwości charakterystyczne obiektu. Kolejny rozdział omawia lokalizację czujników drgań oraz parametry próbkowania sygnałów. Dodatkowo monitorowanie powinno obejmować najważniejsze parametry procesowe (tj. moc generatora, prędkość wiatru i prędkość obrotową). Charakterystyczną cechą turbin wiatrowych są szybkie zmiany punktu pracy, które należy brać pod uwagę.

Istnieją liczne algorytmy diagnostyczne, które mogą być wykorzystane do monitorowania turbin wiatrowych. Wybrane algorytmy zostały zastosowane do właściwego wykrywania i identyfikacji najważniejszych uszkodzeń. Kolejny rozdział przedstawia typowe uszkodzenia i algorytmy, które powinny być zastosowane do ich detekcji. Aby uniknąć wpływu zmian punktu pracy, konieczny jest dodatkowy preprocessing sygnałów. Oprócz stosunkowo prostych metod, stosowane są również metody bardziej zaawansowane. Przedstawiono przykład takiego algorytmu opartego na kurtozie widmowej.

Słowa kluczowe: drgania, monitorowanie, diagnostyka, turbina wiatrowa.

1. INTRODUCTION

The paper presents the selection of diagnostic algorithms for condition monitoring of wind turbines. In recent years wind energy has been the fastest growing branch of the power generation industry. Development of renewable energy sources is one of EU priorities. The goal for Poland is that in year 2020 15% of installed power generation capacity should come from green sources. It is estimated that every year new wind power turbines having total power output of 450 MW should be commissioned from now till 2020 [1]. The distribution of costs during the lifecycle of the unit for wind energy is significantly different from that of traditional fossil fired plants [2]. Initial investment costs are relatively higher but during operation the maintenance is the biggest cost. With proper maintenance policies wind turbines can achieve very high availability – even up to 98%. The basis of proper maintenance is continuous monitoring of transmission of a wind turbine.

Fig. 1 [3] presents typical layout of the wind turbine. The main rotor with three blades is supported by the main bearing and transmits the torque to the planetary gear [4]. The planetary gear input is the plate, to which the main rotor is connected. The planetary gear has three planets, with their shafts attached to the plate. The planets roll over the stationary ring and transmit the torque to the sun. The sun shaft is the output of the planetary gear. Further, the sun drives the two-stage parallel gear. The parallel gear has three shafts: the slow shaft connected to the sun shaft, the intermediate shaft and the fast shaft, which drives the generator. The generator produces AC current of slightly varying frequency. This current is converted first into DC power and then into AC power of frequency equal to the grid frequency. Electric transformations are performed by the controller at the base of the tower. There exist other configurations of wind turbines, where e.g. only parallel gear is used. It has typically three stages, to be able to change the rotational speed from ca. 25 rpm on the main rotor to ca. 1500 rpm at the generator.

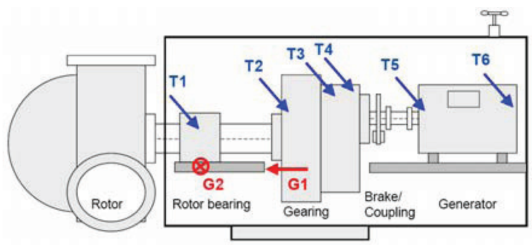

Fig. 1. Typical layout of the wind turbine. Gx and Tx present recommended locations of vibration sensors [3]

The device under monitoring is the power train, i.e. a main bearing, gears and a generator. Every of mentioned elements also contains several roller bearings. Gears and bearings are the most vulnerable parts of the structure and the monitoring should be first of all focused on them.

In order to enforce high standards of maintenance, since the year 2003 insurance companies in European markets introduced certification of condition monitoring systems for the wind power segment [3, 5]. The further part of the paper is based on such requirements, literature and experience of the author.

2. MEASUREMENTS

Since few years more and more wind turbines are equipped with condition monitoring systems. All such systems are based on measurement of vibration and key process variables. In general, number of sensors depends on the design of the wind turbine. There are several setups, but the most popular one includes
8 vibration sensors (see Fig. 1). Sensors G1 and G2 are used to monitor structural vibrations of the nacelle and the tower. Sensors T1 … T6 measure vibration of the drive train. On some installations it is possible to combine G1 with T1 and G2 with T2 and only 6 sensors are sufficient for the monitoring. One of those sensors (typically G2/T2) must monitor the transversal direction. T1/G1 measures axial vibration and all the others – vertical.

All used sensors are accelerometers, in most cases with ICP® output. Proper selection of frequency range and acquisition length are also very important. The combined gear ratio is in the range of approx. two decades, typically from 25 rpm on the main rotor to 1500 rpm on the generator. Thus, sensors close to the main bearing should have relatively low band (in the range of 100 Hz). Those ones close to the generator should monitor frequencies up to 10 kHz or even more. On the other hand even sensors on the main bearing should have high frequency band, because it is necessary for the detection of bearing faults. Another problem is the frequency resolution of the spectrum. The number of characteristic frequencies in a wind turbine is in the range of one hundred, and many of them and placed close to each other. If we want to be able to distinguish such frequencies, spectral resolution must be in the range of 0.1 Hz. For lower frequencies it is even 0.01 Hz or less. All those considerations lead to the measurement system having sampling frequency of 25 kHz and sampling signals for 10 or even 100 s. These are rather high requirements, especially when we consider storage of data in the database.

Additionally the monitoring should include a few key process parameters, like the output power, wind speed and the rotational speed of a generator. Rotational speed has special importance, as it is used for advanced processing of signals. In order to that, it must have a once-per-revolution form which is next transformed into the analogue value. The exact location of once-per-rev signal must be correlated with vibration signals. Additionally such signals like: ambient, bearing temperatures, oil and generator windings temperatures can be monitored. Also wind direction and activity of yaw drive should be taken into account. During operation of the yaw drive vibration should not be monitored due to excessive disturbances it has to the structure.

Quick changes of the operational point are an important feature of wind turbines. The example of such changes is presented on the Fig. 2. During 120 seconds the generator output power varies between 400 and 1400 kW. Such a changes have significant influence on vibration and can blur the changes caused by a malfunction.

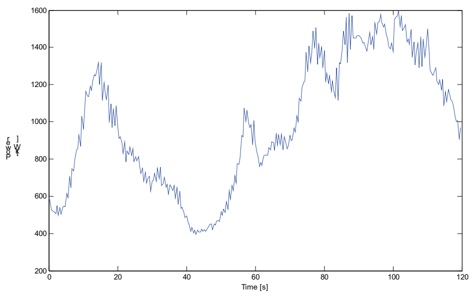

Fig. 2. Changes of generator output power during 120 seconds

Those problems can be overcome with proper signal preprocessing. In most cases, one can define states of the machine (e.g. depending on the power). Next, vibration signals are assigned the state they were acquired in and limits for this state are applied to the signal [6]. There are also other methods, like e.g. model based scaling, but due to complexity of this method it is not used in practice.

3. SELECTION OF DIAGNOSTIC ALGORITHMS

Condition monitoring based on analysis of vibration is a discipline developed for several decades. There are well established methods and a variety of new methods, alike. Broad survey of many methods can be found e.g. in [7] or in shorter form and very practice oriented form in [8]. The work [9] presented many basic and advanced methods with several application, but didn’t cover wind turbines. Some guidelines towards condition monitoring of wind turbines can be found in [5], where the insurance company attempted to standardize methods for monitoring of wind turbines.

Out of many developed algorithms, some should be selected for the monitoring of a wind turbine. The process of selection should be based on two key elements:

- key components;
- most common malfunctions.

As listed in the fist section, the supervised components are:

- generator (shaft, bearings);
- gearbox (shafts, teeth, bearings);
- main rotor (shaft, blade pass, main bearing);
- structure (tower, nacelle).

There are three types of vibrations which should be investigated. Most common ones are excitation frequencies, generated by rotors and gears. Another type of excitation frequencies are impulses generated by bearing faults. The last group are resonance frequencies generated by tower, main rotor blades and machinery casings. Methods depend on those types of vibrations, so in total a 3D matrix of components (generator, gear, …), parts (shaft, teeth, bearing, blade,…) and algorithms should be created. In other words, an algorithm should be selected for every part of a component.

Special group of algorithms are **general signal estimates** which show overall technical state of the machinery. Such estimates are so called broadband parameters: rms, pp, crest and kurtosis. They serve as a general warning and are important when develops a malfunction, which is not covered by any other algorithm or when such other algorithms are not configured properly. This algorithms should be used as a fault detection tool. Since a very important part in the wind turbine are roller bearings, it is necessary to analyze the vibration signal envelopes, which show malfunctions earlier than the original signal [10]. The group of general signal estimates should also include broadband parameters from the **envelope signal**. It is very important that envelopes are obtained after high-pass filtering. Choice of the filter cut off frequency is very important parameter of the algorithm and must be adjusted to the monitored machine. It should be higher than frequencies excited by shafts and meshings. For most types of wind turbines this is in the range of a few kHz.

Second group of algorithms are **frequency selective estimates** from the vibration signal spectra. All relevant characteristic frequencies should be monitored. Most important ones are:

- main rotor (1X, blade pass);
- shafts (1X, 2X);
- gears (1X, 2X, meshing with sidebands);
- roller bearings (inner and outer rings, rolling elements, overroll, cage);
- structural (resonances).

Presented characteristic frequencies should be extracted from appropriate spectra. In general rotor, shafts and gear frequencies should be extracted from amplitude spectra, whereas roller bearings – from envelope spectra. There are also situations, where envelope spectra should be also investigated for the first group of components. There are cases when monitoring of the envelope spectrum can lead to detection of a tooth fault. One has to remember that similarly to general signal estimates, algorithm to obtain envelope spectra should be configured to cut off unwanted frequencies and carry impulses induced by bearing faults.

Another important problem is variability of the rotational speed. Frequency selective components depend linearly on the rotational speed, since they are defined as multiplies of the reference shaft rotational speed (this reference shaft is typically the generator shaft). Large part of wind turbines have variable speed. In such cases spectra should be monitored in the order domain, not the frequency domain. To obtain the **order spectrum**, the acquired vibration signal should be resampled so that the output signal has a constant number of samples per revolution, not a constant number of samples per a unit of time. Choice of resampling parameters should be also done with care. Detailed discussion of resampling parameters can be found in [11].

General and frequency selective parameters form basic set of monitored vibration signal estimates. All those estimates are scalar values and can be easily checked against defined warning and alarm levels. After generation of such a warning, complete signal spectra should be investigated by a vibration expert.

4. CASE STUDY

Presented algorithms were implemented in an on-line vibration monitoring system on a 1.5 MW wind turbine.

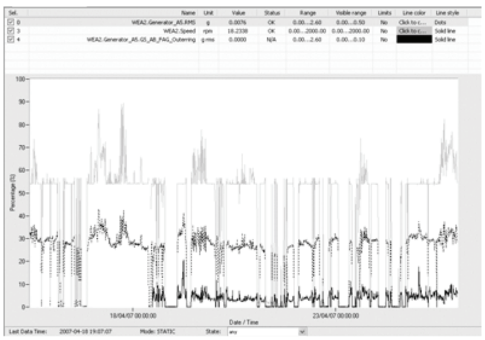

Fig. 3. Trend of BPFO on the wind turbine

Frequency selective parameter, monitoring the outer ring ball pass frequency (BPFO) on the generator bearing, showed increased value (see solid black line on the bottom of Fig. 3). The figure also presents rotational speed (grey, top) and rms (dotted black line, middle). The rms did not show any significant increase and seems to follow the rotational speed. The hypothesis of faulty outer ring was confirmed by investigation of the order spectrum of the signal envelope (see Fig. 4).

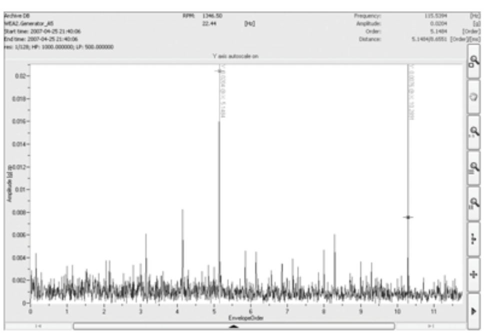

Fig. 4. Spectrum of the signal envelope

The characteristic frequency of the outerring is 5.14X. The cursors on the plot are set on 5.14X and its second harmonics (10.28X). Those components are dominating the spectrum of the envelope. Additionally, the original spectrum was also investigated (see Fig. 5).

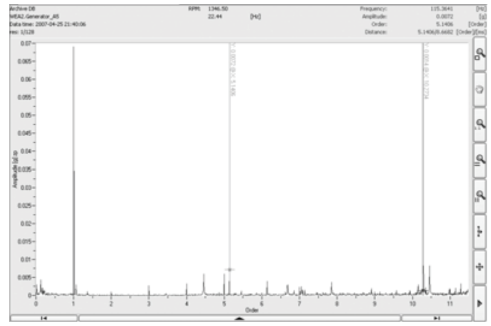

Fig. 5. Spectrum of the signal

The first vertical line is the fundamental frequency (1X). The first two harmonics of the ORBP (middle and right vertical lines) can be clearly seen, but are much smaller than on the envelope spectrum.

5. CONCLUSIONS

The paper presented set of diagnostic algorithms, which can be used for monitoring of the wind turbines. Presented case study shows that generator bearing fault could be detected. Care must be taken when data are analyzed, especially due to excessive changes of the operating point of the machine, which causes vibration changes much higher than those caused by a malfunction. Some more algorithms can be used (e.g. cepstrum), but were not discussed. They should be used when necessary at later stages of diagnostic investigations.

Apart from relatively simple methods discussed in the paper, there is a number of more advanced ones. They require more complex data acquisition and processing, but may deliver better results. One of such algorithms can be application of spectral kurtosis [12] to detect tooth fillet crack on the ring of the planetary gear. Such a crack can not be detected by standard methods and was successfully detected by application of SK for preprocessing of the vibration signal [13].

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