Condition monitoring of wind turbines: Challenges and opportunities

İbrahim Sina Kuseyri
Marmara University Faculty of Engineering, Mechanical Engineering Dept., Göztepe-İstanbul, Turkey

Abstract

Advances in wind turbine power generation technology and legislative decisions of governments that are favorable to renewable power have lead wind energy to be an increasingly viable alternative to conventional power generation. However, because of the broadly variable loads and the aggressive operating conditions, wind turbines are subject to relatively high failure rates and their measurement signals reflecting the condition monitoring parameters are eminently variable and subject to large dynamic range. In this respect, keeping away from costly breakdowns and pursuing an operation with acceptable performance requires implementation of advanced condition monitoring and diagnostic systems to be developed specifically for wind turbines. Condition-based maintenance is recognized as the best method in maintenance strategies as its diagnostic and prognostic features allow avoiding catastrophic failures and schedule timely maintenance according to the estimations made on the remaining useful life. In this respect, methods for condition monitoring of wind turbines are surveyed comparing their diagnostic features. We conclude with a discussion on conceivable future trends and pertinent challenges and opportunities on condition monitoring of wind turbines.

Key words: Wind turbines, condition monitoring, condition-based maintenance, fault diagnosis, wireless sensor network.

1. Introduction

Wind is currently the fastest growing renewable energy source for electrical power generation around the world [1]. As the number of wind turbines (WTs) continues to grow, it becomes more challenging for engineers to maintain them for reliable operation. As many WTs are situated on high towers, installed in remote rural areas, exposed to harsh environment, and subject to relatively high failure rates [2], inspection and maintenance for the WTs requires significant effort and cost. To make wind power competitive with traditional power generation technology, it is necessary to minimize the maintenance costs and improve the reliability and availability of WTs. Condition monitoring (CM) systems can be used to aid wind farm owners/Operators in achieving this goal. The objective is to acquire information regarding the health of the machines, which can aid to improve operational efficiency. Condition monitoring provides the tools for condition-based maintenance (CBM), instead of time-based periodic maintenance which is implemented at fixed time intervals regardless of actual state of the health of machines. Adapting a condition-based maintenance system, any degradation or incipient faults can be detected in advance, through the use of CM techniques, before they result in costly failures. In addition, healthy turbines can be left to operate, thereby reducing outages due to possible redundant time-based scheduled maintenance.

*Corresponding author: Address: Marmara University Faculty of Engineering, Mechanical Engineering Dept., Göztepe-İstanbul, Turkey. E-mail address: **sina.kuseyri@marmara.edu.tr**

Most modern turbines are manufactured with some form of integrated CM system. These systems typically monitor condition parameters such as temperatures of bearings, lubricating oil and windings. Some of the more recent systems monitor vibration levels of the drive-train as well. The data from all turbines in the wind farm is transmitted to supervisory control and data acquisition (SCADA) system for the purpose of monitoring and analysis [3]. However, this data quickly accumulates to create large and unmanageable volumes that can hide useful information on the health of specific components of individual turbines. The lack of expertise in how faults manifest themselves in the measured data is the main challenge that has to be overcome. Hence, it would prove beneficial to operators if the data could be analyzed and interpreted automatically to identify faults and potential failures. This highlights the main reason for the use of condition monitoring techniques, since it provides the means to detect and identify faults as early as possible. Condition monitoring is particularly beneficial for the sub-systems such as the gearbox, generator, and the rotors and blades, as the cost of these components constitutes the largest part of the total cost of the WT [4]. The challenge is to detect possible incipient faults in advance, and correctly isolate and identify the faulty component(s).

Originally condition monitoring was performed by the people who actually operated the machinery. Because they worked physically close to the machinery they were operating, they could assess its condition directly, based on experience. When the machinery became more complex, measurement systems were installed to make information about its condition available to the operators at a central operating console or an engine control room. To prevent information overload, the condition monitoring process must be automated to provide the information on a higher level and at the desired location. Automation also makes condition monitoring more accurate and provides faster response times. This allows a more critical design of machinery and smaller design margins, and will result in a reduction of the life-cycle costs. Modern condition monitoring systems may also be augmented by a system that advises the personnel on actions to be taken when certain faults occur. As a result, operating costs and reliability can be improved significantly. Modern wireless sensors provide the ability to monitor machinery at locations that are difficult to access [5]. Wireless communications has become an acceptable way of communicating various types of information today. When used as designed wireless technology can significantly reduce the installation cost of asset management systems, permit fast system installation, and provide a long-lasting and reliable communications link.

The paper is organized as follows: In Section 2 we summarize the essentials of monitoring applications in WTs, comprising SCADA, structural health monitoring, and condition monitoring/diagnostic techniques, along with the relevant academic literature. In Section 3 we discuss on the present state of the technology and future trends with respect to the challenges and opportunities. In Section 4 we present our final comments

2. Monitoring of wind turbines

2.1. SCADA and Performance Monitoring

The first class of system on CM of WTs is the SCADA system. It is an integral part of all modern

WTs to monitor energy generated and confirm the operation of the turbine. While measurements are often recorded using high frequency sampling, they are averaged over time and a single 5-10 minute averaged value is transmitted back to the operator. The SCADA system also triggers alarms as and when they occur. Moreover, SCADA systems have developed to also provide alarms for malfunctions of the WT. According to [5], 10 minute averaged signals often monitored in more recent SCADA systems include:

i) Active and reactive power generated and the power factor (and standard deviations over 10 min interval).
ii) Anemometer-measured wind speed (and standard deviation over 10 min interval).
iii) Nacelle temperature (1 hour average).
iv) Gearbox oil and bearing temperatures.
v) Generator winding and bearing temperatures.
vi) Phase currents.

These SCADA systems are able to transmit alarms to the operator but are not currently able to provide detailed information on the health of a turbine. However, more recent SCADA systems are increasingly able to provide alarm signals based on time domain amplitude of temperature transducers and on measurements from drive train vibration transducers. The alarms are generally based on the average or peak value for vibration during the 5-10 minute period.

The performance parameters of the wind turbine is monitored and stored in implicit form by the SCADA system. To ensure a safe and reliable operation, the correlation between power, wind velocity, rotor speed and blade angle can be used and in case of large deviations, an alarm is generated. The detection margins are large to avoid false alarms. More sophisticated methods such as estimation of parameters and trending, reflecting the performance, are not often used.

2.2. Structural health monitoring

The second class of system covers the area of structural health monitoring (SHM). These systems aim to determine the integrity of the WT tower, structure and foundations for faults driven by blade-passing frequencies, through low frequency sampling, below 5Hz, of accelerometers and similar low frequency transducers. Other monitoring technologies increasingly found for structural health monitoring of blades include fiber-optic strain measurement and acoustic emission sensing.

Acoustic emission sensing has not found great interest in the wind industry up to now because of its expense and equipment complexity, whereas fiber-optic measurement systems have gained interest [6]. It is clear that the monitoring of WT blades should be classed as CM, despite being carried out in a different fashion from rotating machinery CM.

2.3. Condition Monitoring and Diagnosis

The third class of monitoring system are the two areas of CM and diagnosis. CM itself may be considered as a broad method for determining the overall operational health of the WT. The key function of a successful CM system should be firstly to provide a reliable indication of the presence of a fault within the WT system and secondly to indicate the location and severity of the situation. This second point is important as the severity of the fault will be the trigger for further investigation in detail by monitoring engineers with the aim of diagnosing the fault. This point is the link between CM and diagnostic systems where CM leads to diagnosis. The main components for WT CM that need are shown in Figure 1 including blades, rotor and shaft, gearbox, yaw system, and the electric generator.

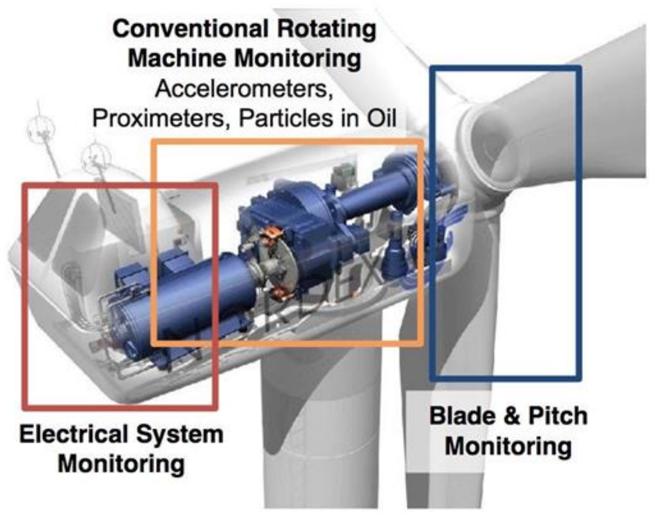

Figure 1. WT Condition monitoring [3]

All five of these components are inevitably subject to failure during operation of the WT. Blade imbalance and aerodynamic asymmetry are two major faults in WT blades. Blade imbalance can stem from manufacturing and construction errors and tolerances, icing, or plastic deformation due to fatigue [7]. Aerodynamic asymmetry can be caused by high wind shear and control system errors [8]. Errors in the mechanism to control the pitch angle may cause one blade pitch different from the other blades, imposing unbalanced torque generation on the rotating shaft, leading to aerodynamic asymmetry. Faults in the rotor and shaft of a WT include shaft imbalance, impending cracks, shaft bearing faults, etc.

The rotor and shaft of a WT transmit variable mechanical energy generated from kinetic energy of wind to the electric generator and is always considered an important component for condition monitoring and fault detection of WT. Faults of wind turbine gearboxes include tooth wear or breaks, eccentricity of tooth wheels, gearbox bearing faults, etc. [9]. The gearbox has compact structure, fixed transmission ratio, great drive torque, complicated load, and changeable state in the running process. It reports that gearboxes are considered highly critical for maintenance purpose. The yaw system of a WT controls how the tower turns, because as the wind direction turns the nacelle needs to adjust itself to face the wind properly. A yaw system may be subject to yaw angle offset and wear or break of yaw gear tooth and has a high failure rate in WTs [4]. Currently, most WTs are equipped with a doubly-fed induction generator (DFIG) or a direct-drive permanent-magnet synchronous generator (PMSG). Faults in generators include generator rotor damage, bearing faults, stator turn faults, overheating, etc. Many technologies have been developed for condition monitoring and fault detection of electric machines based on current measurements [10]. Bearing faults constitute a significant portion of all faults in WTs. As mentioned before, bearing faults may occur in rotors and shafts, gearboxes, or generators of WTs. The experience feedback from the wind energy industry corroborates that bearing failure is one of the typical failures in WTs [9].

The failure frequency and the associated downtime vary among main components of WTs. To find the most critical components of a WT, both the failure frequencies and the associated downtime of the WT components should be considered. The failure frequencies and associated downtime of wind turbine main components are summarized in [2] and [9]. Gear-box has the most high failure frequency for DFIG WTs. Bearing faults are a typical type of faults in gearboxes. In WTs, 40% of failures are related to bearings [11]. Therefore, bearing faults have significant contribution to the total faults and downtime of WTs.

According to the sensor measurements used, most methods for condition monitoring and fault diagnosis of WTs can be classified into following categories: vibration monitoring, torque monitoring, temperature monitoring, oil/debris analysis, acoustic emission monitoring, optical fiber monitoring, and current/power monitoring. Monitoring techniques and current challenges on their successful application are discussed briefly in the next paragraphs.

2.3.1. Vibration monitoring

Most faults generated in the main components of WTs cause vibrations. The blade or shaft imbalance of a WT generates vibrations of the nacelle in the horizontal direction, due to the smaller stiffness of the wind turbine tower in this direction [11]. It has been reported that bolt loosing at the root of a blade would increase the vibration of the wind turbine nacelle [12]. A fault, e.g., surface pitting or tooth wear or break, in a gearbox may lead to the vibration of the gearbox. A bearing defect can generate a radial rotor movement and a shaft torque variation in the WT, and consequently vibration of the wind turbine nacelle. Therefore, commercial WT condition monitoring and fault detection systems mostly employ vibration-based techniques, which are sophisticated due to unsteady operating conditions of the turbine. It is a problem to extract WT fault signatures from such non-stationary vibration signals by using traditional spectrum analysis methods [13]. The vibration monitoring has been extensively studied in the literature and widely used in industrial applications [14]. However, the main disadvantage of vibration monitoring is the requirement of expert personnel to evaluate the data on measurement and analysis of turbine vibrations. The interpretation of vibration readings requires training and specialized personnel even for the ordinary machinery operating at stationary conditions. Considering the fluctuating load and speed conditions in the WTs it is more appropriate for the wind farm owners/Operators to establish an on-line condition monitoring system web-connected to expert CM companies or OEMs to get consulting service on prediction of faults and failures. Present challenge in the vibration-based CM technology is the development of automatic diagnostic systems for the isolation of detected faults, incorporating prognostic features, such as warnings of failures in advance and recommended time for maintenance [14].

2.3.2. Temperature monitoring

Abrupt temperature increases while in the ordinary operating condition often means the failure of wind turbine bearings [15]. For example, the lack of lubrication will lead to abrupt increases in the bearing temperature. Similarly, the temperature of gearbox oil should be in a certain range during wind turbine rated operating conditions. Therefore, temperature monitoring is able to disclose the health condition of wind turbine bearings and gearboxes. The major disadvantage of temperature monitoring is that the measured temperature is determined by multiple factors. Research shows that bearing temperature depends on bearing fault, environment temperature, stator current heating, and generator rotating speed [16]. Since a WT normally works in rough conditions, the environment temperature changes frequently. It is not sufficient to use solely temperature monitoring for bearing and gearbox fault detection of WTs.

2.3.3. Torque monitoring

Torque oscillations can be detected in a blade or rotor imbalance condition of WTs [7]. Torque monitoring has been utilized to detect the faults of a wind turbine's blades and rotors by measuring the torque on the shaft of the WT [17]. Torque monitoring has also been applied to detect stator short-circuit faults in the generator of a WT [18]. However, the complexity and cost of using torque monitoring is high. For instance, a torque transducer needs to be installed in the shaft in order to measure the torque of the wind turbine shaft, which increases the structure complexity of the WT. Therefore, torque monitoring is rarely used in the wind industry.

2.3.4. Oil/debris monitoring

In the wind industry, the oil/debris analysis data is one of the typical data for condition-based maintenance of WTs [6]. By analyzing the composition, content, size, and classification of wear particles in the lubrication oil of the gearbox and the bearings, their health conditions can be evaluated. This method only works for high power rating WTs with oil-lubricated bearings and gearboxes. For WTs whose lubrication of bearings and gearboxes is sealed inside, oil/debris analysis methods are not practical.

2.3.5. Acoustic emission monitoring

Monitoring of acoustic emissions, ranging from 1 kHz to 100 MHz, is a typical method for condition-based maintenance of WTs [6]. For instance, when a low-speed rolling bearing is loaded and stress reaches the limit of the material strength, it will result in a slight gap of the failed bearing components to emit some stress to keep energy balance [19]. The stress wave generated by a broken bearing can be measured and applied to detect the bearing fault of WTs [20]. The disadvantage of acoustic emission monitoring is its high cost. Since the frequency of acoustic emission signal is so high, sensors and data acquisition equipment are much more expensive than those used in other fault detection methods.

2.3.6. Optical fiber monitoring

Optical fiber monitoring can detect multiple physical parameters, e.g., temperature and strain. Therefore, more and more attention is drawn to apply optical fiber monitoring in the wind industry. Optical fiber sensor system is used to detect the structural states of wind turbine blades for condition-based maintenance [21], and to detect damages due to lightening [22]. However, the optical fibers need to be mounted on the surface or embedded into the body of WT components being monitored. Therefore, optical fiber monitoring is more complicated in real-world applications compared to other condition monitoring and fault detection methods.

2.3.7. Current/power monitoring

Current/power monitoring uses WT current and/or voltage measurements that have been used by the control system of the WT. Therefore no additional sensors or data acquisition equipment is needed. Moreover, current and/or voltage signals are reliable and easily accessible from the ground without intruding the WTs. Some research has been done on bearing fault detection of WTs by using current measurements. For example, current measurements have been applied for bearing fault detection of DFIG and PMSG wind turbines [23]. It has been reported that wind turbine blade faults can be successfully detected by using current measurements or power measurements [23], [24]. Moreover, current and power measurements have been used together for wind turbine rotor imbalance fault detection and gearbox failure detection [18]. However, there are still challenges in using current and/or voltage signals for wind turbine condition monitoring and fault detection. First, the useful information in current and/or voltage signals has non-stationary statistics due to the variable-speed operating condition of WTs. It is a problem to extract WT fault signatures from non-stationary current and/or voltage signals by using traditional spectrum analysis methods. Moreover, the dominant components of current and voltage signals are the fundamental-frequency component. Therefore, the useful information in current and voltage signals for wind turbine condition monitoring and fault detection usually has a low signal-to-noise ratio (SNR), which makes the condition monitoring and fault detection difficult.

3. Future trends and opportunities

In the wind industry the availability of information could be one of the limiting factors to the development of CM systems. This stems from the structure of the wind industry in that turbine operators rarely have access to any turbine CM data during the initial WT warranty period. It is also common that wind farm owners/operators cannot retrofit their own preferred monitoring systems to turbines until the turbine is out of the manufacturer's warranty period. This means that valuable data may never be accessible to the operator and, less likely still, to those researching CM. Perhaps the most obvious direction for the development of CM systems is to take existing systems and incorporate refined monitoring algorithms and techniques into them to increase the clarity of results and simplify or increase confidence in alarm signals generated. This concept is already visible in the systems which have been developed from industrial vibration-based CM. The adaptation of analogue inputs to allow for oil debris particle counters, for example, demonstrates how new analysis methods can be incorporated into existing systems. The same may be true for many other transducers, for example current and voltage probes, which produce signals that are essentially composed of low frequency vibrations. In addition, the industry is already noting the importance of operational parameters, such as load, speed and wind speed, when monitoring WTs so techniques will begin to adapt further to include these signals within analysis techniques. The vibration monitoring system should seamlessly integrate primary data into the SCADA systems and provide detailed data including spectrum analysis for trending and longer term predictive maintenance purposes. The system must work properly with SQL database servers and be easily expanded to match an expanding installed base of wind turbines. Some systems are already able to do this to an extent, such as Rockwell Automation's integrated CM system, depicted in Figure 2.

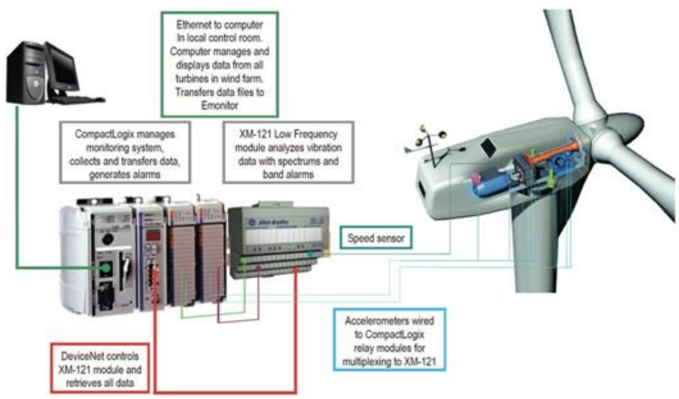

Figure 2. MachineDynamix Integrated condition monitoring [14]

In this configuration the controller will sequentially multiplex pairs of accelerometers into a single vibration monitoring and analysis module. Simultaneously, controller downloads the optimal monitor configuration parameters for the specific pair of accelerometers connected to the module. The monitor generates a complete vibration analysis including the spectrum analysis with frequency band alarms. This data is retrieved by the controller and the process repeats for the next set of sensors. Depending on the monitor's data analysis specifications a complete set of data from all accelerometers are collected every 2-5 minutes. As the data is collected, the controller applies a set of data analysis rules that corresponds to the actual application to identify specific mechanical problems in the drive train. Controller requires an Ethernet connection to the control room at the wind farm. Through this Ethernet connection, the HMI and process historian can access all of the measurement data generated by the MachineDynamix system, all of the mechanical problem analysis data, and all of the alarms from the monitoring module.

Condition monitoring was from the outset an early adopter of emerging sensor technology. Soon after wireless technologies started to mature in modular designs and implementations, advances in hardware integration of wireless circuits and embedded programming of wireless protocols lead to the concept of wireless sensor networks [5].

The availability of wireless devices and their applicability to industrial automation enabled remote measurement and transmission of information. Wireless sensor networks can scale up to large monitoring environments. The main advantages of using wireless sensors in wind turbine condition monitoring include ease of installation (sensor positioning is freed from the constraints of cables), and accessibility (every point of measurement becomes accessible provided that the sensor can be safely attached). Furthermore, it is also possible to retrofit wireless sensors on to the WT after the latter has been installed, with minimal intervention. Nonetheless, deployment and applicability of wireless sensor networks may be constrained by the battery life of sensor nodes, unless energy harvesting devices are also employed. Furthermore, high powered interference, electromagnetic scattering and noise may reduce the reliability and effective bandwidth of the network [25].

4. Conclusions

In this paper we have reviewed the available methods and techniques on condition monitoring of wind turbines. It is clear from the literature survey and from the commercial applications that the main tools for condition monitoring are the SCADA systems, and vibration-based systems. Condition monitoring through SCADA is the most practical approach, as they are already installed in most of the modern turbines. Some recent SCADA systems also incorporate overall vibration measurements for the rotating systems in the turbine. However the information provided to the operator, based on 5-10 minutes averages of overall values, are not sufficient for early diagnosis of faults and failures. To capture the features of the dynamic vibration signals, high sampling rates and fast signal processing are required. Hence the need for an exclusive vibration monitoring/analysis system. Moreover, main problem in the diagnosis through vibration analysis is the fact that the signals are non-stationary. Therefore sophisticated algorithms must be incorporated rather than basic FFT analysis. Condition monitoring by generator current or power signal analysis is also a promising method for wind turbine monitoring, not only for the generator but for the mechanical sub-systems as well. Having the same features as vibration signals, current/power monitoring should incorporate advanced algorithms for effective diagnosis. Although electric signature-based technique appeared less effective than the vibration for gearbox diagnosis in the literature, no additional sensors or cables are required for their implementation as the signals are already available in the SCADA system. Trend in the technology is through integration of SCADA and diagnostic data. Moreover, advances in wireless sensors will facilitate the application of vibration-based condition monitoring. Further research in the condition monitoring of wind turbines must be on advanced automated diagnostic and prognostic algorithms to allow extensive implementation of condition-based maintenance.

References

[1] Pure Power: Wind energy targets for 2020 and 2030. The European Wind Energy Association. 2011; Available online: http://www.ewea.org.

[2] Ribrant J, Bertling LM. Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005. IEEE Transactions on Energy Conversion 2007; 22: 167-173.

[3] Feng Y, Crabtree CJ, Long H, Tavner PJ. Use of SCADA and CMS Signals for Failure Detection and Diagnosis of a Wind Turbine Gearbox. Proceedings of the European Wind Energy Conference, Brussels, Belgium 2011.

[4] Spinato PJ, Tavner, van Bussel GJW, Koutoulakos E. Reliability of wind turbine sub-assemblies. IET Renewable Power Generation 2009; 3: 1-15. 2009..

[5] Frank J, Shannon D. Maximizing Uptime and Efficiency with Wireless Vibration Monitoring. 2013. Available online;
http://www.power- eng.com/content/pe/en/whitepapers/2013/maximizing-uptime-and-efficiency-with- wireless-vibration-monitor.whitepaperpdf.render.pdf.

[6] Amayri A, Tian Z, Jin T. Condition based maintenance of wind turbine systems considering different turbine types. Proc. International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering. 2011; 596-600.

[7] Ramlau R, Niebsch J. Imbalance estimation without test masses for wind turbines. Journal of Solar Energy Engineering. 2009; 131: 011010-1 - 011010-7.

[8] Kusiak A, Verma A. A data-driven approach for monitoring blade pitch faults in wind turbines. IEEE Trans. Sustainable Energy. 2011; 2:87-96.

[9] Lu B, Li Y, Wu X, Yang Z. A review of recent advances in wind turbine condition monitoring and fault diagnosis. Proc. 2009 IEEE Symposium on Power Electronics and Machines in Wind Applications. 2009; 1-7.

[10] Benbouzid MEH. A review of induction motors signature analysis as a medium for faults detection. IEEE Trans. Industrial Electronics. 2000; 47: 984-993.

[11] Popa LM, Jensen BB, Ritchie E, Boldea I. Condition monitoring of wind generators. Proc. IEEE IAS Annual Meeting. 2003; 3: 1839-1846.

[12] Yan J, Xu Y. Operational fault feature extraction of blade based on vibration of wind turbine. Proc. International Conference on Control, Automation and Systems Engineering. 2011; 1-3.

[13] Sheng S. Investigation of Various Condition Monitoring Techniques Based on a Damaged Wind Turbine Gearbox. Proc. of 8th International Workshop on Structural Health Monitoring. 2011.

[14] Rockwell Automation Condition monitoring application note ”A Flexible and Cost Saving Condition Monitoring System for Wind Turbine Manufacturers”.

[15] Zhang X, He S, Zho P, Wang W. Summarization and study of fault diagnosis technology of the main components of wind turbine generator system. Proc. IEEE International Conference on Sustainable Energy Technologies. 2008; 1223-1226.

[16] Maru B, Zotos PA. Anti-friction bearing temperature rise for NEMA frame motors. IEEE Trans. Industry Applications. 1989; 25: 883-888.

[17] Wilkinson M, Tavner P. Extracting condition monitoring information from a wind turbine drive train. Proc. 39th International Universities Power Engineering Conference. 2004; 591- 594.

[18] Yang W, Tavner P, Wilkinson M. Wind turbine condition monitoring and fault diagnosis using both mechanical and electrical signatures. Proc. IEEE International Conference on Advanced Intelligent Mechatronics. 2008; 1296-1301.

[19] Chen C, Sun C, Zhang Y, Wang N. Fault diagnosis for large-scale wind turbine rolling bearing using stress wave and wavelet analysis. Proc. 8th Int. Conf. on Electrical Machines and Systems. 2005; 3: 2239-2244.

[20] Chen L, Zhang Y, Xia X. Contact stress and deformation of blade bearing in wind turbine. Proc. International Conference on Measuring Technology and Mechatronics Automation. 2010; 833-836.

[21] Zhang F, Li Y, Yang Z, Zhang L. Investigation of wind turbine blade monitoring based on optical fiber Brillouin sensor. Proc. International Conference on Sustainable Power Generation and Supply. 2009; 1-4.

[22] Kramer SGM, Leon FP, Hernandez YNM, Lewke B. Integration of a distributed fiber optic current sensor setup for lightning detection in wind turbines. Proc. Instrumentation and Measurement Technology Conference Proceedings. 2007; 1-5.

[23] Jeffries WQ, Chambers JA, Infield DG. Experience with bicoherence of electrical power for condition monitoring of wind turbine blades. IEE Proceedings: Vision, Image and Signal Processing. 1998; 145: 141-148.

[24] Gong X, Qiao W. Imbalance fault detection of direct-drive wind turbines using generator current signals. IEEE Trans. Energy Conversion. 2012; 27: 468-476.

[25] Conant R. Wireless sensor networks: Driving the new industrial revolution. Proc. Int.Conf. on Industrial Embedded Systems. 2006; 8-11.