Wind Turbine Fault Diagnosis Techniques and Related Algorithms

Seyed Mohsen Miryousefi Aval *‡, Amir Ahadi*

* Young Researchers and Elite Club, Ardabil Branch, Islamic Azad University, Ardabil, Iran, 5615731567

(sm.miryousefi@gmail.com, amirahadi8@gmail.com)

‡ Corresponding Author; Seyed Mohsen Miryousefi Aval, Young Researchers and Elite Club 5615731567, Iran, sm.miryousefi@gmail.com

Received: 02.12.2015 Accepted: 01.16.2016

Abstract- The recent state-of-the-art developments in wind energy fault diagnosis and condition monitoring are surveyed. This paper reviewed different types of faults that might occur in wind turbine systems. Moreover, the symptoms of the common faults and related diagnosis techniques are discussed. Meanwhile, this paper mainly aims to survey the most recent condition and performance monitoring approaches of wind turbines with the primary focus on blade, gearbox, generator, braking system, and rotor. Different methodologies of wind turbine condition monitoring, performance monitoring, and fault diagnosis reported in the literature are discussed. The main objective of this paper is to supply invaluable information for future researchers in escalating the ability as well as accuracy of wind turbine condition monitoring techniques.

Keywords Condition monitoring, wind turbines, fault detection, diagnosis, review.

1. Introduction

The common types of wind turbine include horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) [1]-[4]. The components of wind turbines consist of shafts, generator, blades, and gearboxes [5]. Wind turbines might fail depending on the either momentary events or aging failures in their components and will lead to system interruptions as well as cause a huge amount of economic losses [6]. Repair actions for a few types of wind turbines cannot be accomplished due to their extremely high towers [7]. Hence, condition monitoring and fault diagnosis play a significant role in Wind Energy Conversion Systems (WECS) [8]-[15]. The main objective of this paper is to present a comprehensive review of the state of the art, different types of the fault that might occur in WECS, and the diagnosis strategies and related methods. The review will be mainly focused on the double-fed induction generators (DFIG) equipped with power electronic devices, since they are commonly used for the variable speed turbines. The rest of paper is organized as follows. Section 2 highlights the common faults that might occur in wind turbine systems. Sections 3 and 4 introduce condition monitoring and performance monitoring techniques of wind turbine systems, respectively. Eventually, Section 5 concludes this paper.

2. Wind turbine components degradation and consequences

As discussed earlier, the main objectives in wind turbine control systems are avoidance of excessive mechanical loads, maximisation of energy capture, and the provision of appropriate power quality [16]. Maximum power extraction in WECS can be achieved using bigger diameter of wind turbine blades [17]. Blades are made by either glass fiber with epoxy composites or high-density wood [18]. Blades are one of the weakest component in a WECS and some faults might happen directly on the blades such as hub and blade corrosion, crack, serious aero-elastic deflection, and rotor imbalance [19]-[23]. Furthermore, high force on the blades causes high vibration and fatigue in the main body of the turbine. It is important to note that failures in the pitch-controlled system will cause the blades breakdown. Tower of the wind turbine is basically designed to maintain vibrations within wind speed changes as well as to hold the nacelle. A tower might fail dues to a storm, fire, or earthquake [24]. A gearbox in the drive train increases the rotor speed to values more than the acceptable range of wind turbine speed (i.e., from 20-50 rpm to 1000-1500 rpm). The failure of the gearbox might be due to the shaft imbalance, shaft damage, shaft misalignment, gear damage, bearing damage, broken shaft, high oil temperature, and leaking oil [25]-[29]. Failures in the wind turbine generator will cause several issues such as abnormal noises and excessive vibration in the generator. Generator fault can be occurred due to the either internal or external failures [30]-[32]. External failures happen due to the short circuits in the AC grid which will lead to generator overheating. Internal failures are usually because of the poor insulation or mechanical failures such as slip ring and bearing. The yaw system failure can be occurred by failures in its components, typically control system and drive motor failure. Failure in the yaw system may cause some common failures such as losing the track of the wind direction, results the output power decline [33]. Regarding the failures in the brake system, the wind turbines must be stopped. Otherwise, it will cause serious damages to the mechanical units, main structure, and blades [34]. Fig. 1 illustrates the most frequent failures of components for both onshore and onshore wind turbines [35]-[37].

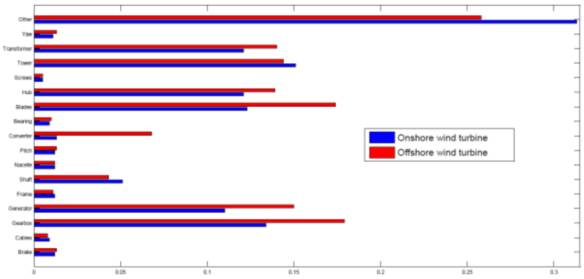

Fig.1. Failure distribution for components of onshore and offshore wind turbines.

The tower has the highest value, followed by the transformer and then the generator. Moreover, the most common failures associated with WECS components are shown in Table 1. Group A faults represent the most harsh failures which can lead to huge damages in WECS, thereby increasing maintenance costs. Failures in group B might cause derated operation of WECS. Group B failures occur because of the over speeding of wind turbines.

Table 1. Typical faults in WECS [38].

Group A	Group B	Group C
Catastrophic blade fault	Corrosion or cracks in blades	Controller fault
Catastrophic hub fault	Dirt/ice built up on blades	Hydraulic system fault
Main bearing fault	Hub spinng on shaft	Brake system fault
Main shaft fault	Pitch fault	Pitch system fault
Gearbox fault	Shaft misalignment	
Shaft-gearbox coupling fault	Yaw system fault	
Generator fault	Cable twist	
Tower fault	Wind speed/direction measurement error	
Foundation fault		
Metrological system fault		
Premature brake activation		
Electrical system fault		

3. Recent techniques in wind turbine condition monitoring

Due to the failures in WECS such as fractured gears, drive train, and bearings, condition monitoring plays a vital role in order to reduce the maintenance costs. Condition monitoring and fault diagnosis aim to decline maintenance costs by preventing failures in wind turbines. Fig. 2 illustrates the typical architecture of WECS condition monitoring and diagnosis. Note that in real-world installation, some signals can be either monitored or discarded. The following sub-sections review condition monitoring and fault diagnosis approaches associated with WECS.

page Due to the aero-elastic deflections and crack faults that might happen in the wind turbine blades, it is essential to monitor the blades in order to ensure better operation performance. For this aim, the efficient integration of structural dynamic and aerodynamic models should be available. In recent years, structural and aerodynamic modeling has been widely investigated, where the most focus was in the mode shape method. Since this approach is inappropriate for the detailed design of large wind turbine blades, a new aerodynamic model based on the modified strip theory and the fluid-structure interaction approach using multibody dynamics software is presented in [41]. The most popular methods for condition monitoring of rotating machinery are vibration based monitoring. In case of non-linear signals and non-stationary, a few methods based on the signal processing theory have been suggested such as wavelet transformation, empirical mode decomposition, and Wigner-Ville distribution. One of the preferred options for diagnosing the crack failure of the wind turbine blades is empirical mode decomposition. Currently, the most available and suitable methods for continuous monitoring of wind turbine blades are strain and acoustic emission monitoring.

Fig. 3 shows the structure of a gearbox, which consists of the low-speed stage (connected to the rotor), intermediate-speed stage, and high-speed stage (connected to the generator). Gearboxes are usually instrumented with around 125 sensors. Gearbox fault diagnosis has been a significant challenging issue because of their complex structures and harsh working conditions. Fault diagnosis of wind turbine planetary gearboxes re-lies on gear characteristic frequencies as well as monitoring their magnitude changes. Due to the background noise, complex kinetics, and unique structure, a gearbox vibration signal is a mixture of several complex components. At present, the most commonly used methods for non-stationary mechanical faults are time domain averaging method, vibration analysis, spectral kurtosis method, and time-frequency analysis. To some extent, it is complicated to diagnose gearboxes faults properly because of the spectral complexity of gearbox vibration signals and their frequency modulation nature. For fault diagnosis of planetary gearboxes, a frequency demodulation method using the ensemble empirical mode decomposition and energy separation algorithm is proposed in [42]. The proposed method can be used to detect both the wear and chipping faults. Since demodulation analysis methods and conventional spectral analysis cannot identify the constituent frequency components of gearbox faults from non-stationary signals, a time-frequency analysis based on the adaptive optimal kernel is proposed in [43, 44] in order to indicate the frequency characteristic of non-stationary signals as well as their time-varying features for wind turbine planetary gearbox monitoring.

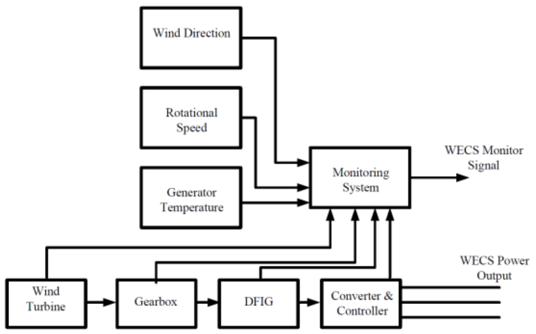

Fig. 2. Main configuration of WECS condition monitoring and diagnosis [39, 40].

Additionally, different levels of impulses induced due to the gearbox faults can be extracted and identified. The iterative atomic decomposition thresholding method has been applied to analyze the complex signals from wind turbine gearboxes in order to enhance extracting the feature frequencies and suppressing noise for diagnosing both the distributed and local gear faults [45]. Shannon wavelet support vector machine using manifold learning is employed for fault identification in the wind turbine gearboxes. This method can satisfy the accuracy of 92% in gearbox fault diagnosis in comparison with other methods [46]. A novel method for intelligent fault diagnosis of wind turbine systems based on the FMECA (Failure Mode, Effects and Criticality Analysis) and ontology is proposed in [47]. The vibration response model using the Fourier series analysis is explored to investigate the impacts of the local faults that might occur at the sun gear, any parts of planet gears, or annulus gear [48]. Meanwhile, a statistical diagnosis algorithm for the detection of different mechanical defects such as unbalance and misalignment faults under a wide range of working conditions of load and speed is presented in [49]. The fault tree method in accordance with the structural features of wind turbine gearbox is established and the related quantitative and qualitative analysis of the gearbox faults is carried out in [50]. With this diagnosis algorithm, the duration of fault diagnosis significantly declines and boosts the maintenance efficiency of the gearbox faults. Table 2 summarizes these techniques used for the fault detection and condition monitoring of wind turbine generators.

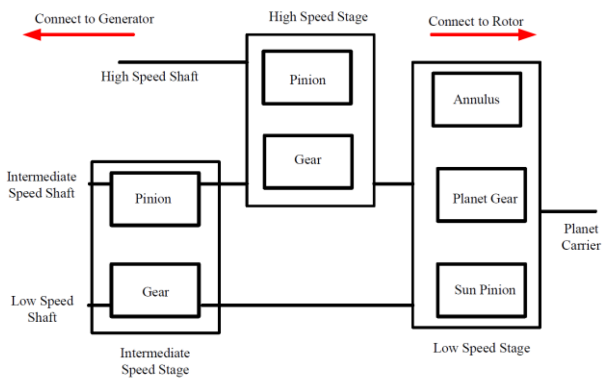

Fig. 3. Side view of the gearbox.

Table 2. Summary table with the aim of generator fault diagnosis and condition monitoring [51].

Monitoring schemes	Major advantages	Major disadvantages
Vibration	Reliable, standardized (ISO10816)	Expensive, intrusive, subject to sensor failures, limited performance for low speed rotation
Torque	Direct measurement of rotor load	Expensive, intrusive
Chemical analysis	Directing monitoring the bearing and its oil	Limited to bearings with closed-loop oil supply system, specialist knowledge required
Temperature measurement	Standardized (IEEE 841)	Embedded temperature detector required, other factors may cause same temperature rise
Ultrasonic frequency	Able to detect early-stage fault, good for low-speed operation, high signal-to-noise ratio, frequency range far from load perturbation	Sensor required, expensive, specialist knowledge required
Sound measurement	Easy to measure	Background noise must be shielded
Laser displacement measurement	Alternative way to measure bearings vibration	Sensor required, expensive, di cult to implement
	No additional sensor needed,	Displacement based rather than force based, di cult to detect

Stator current monitoring	inexpensive, non-intrusive, easy to implement	incipient faults, sometimes low signal-to-noise ratio

Condition monitoring of the induction generators in the wind turbine systems is being often accomplished based on several well-known approaches such as noise, partial discharge, temperature, vibration, and electrical signals collected from the generator. Transient stability and steady-state analysis has been carried out in order to compare dynamic characteristic of wind farm equipped with either DFIG or PMSG wind turbines [52]. DFIGs are imposed by the grid voltage and if the current is controlled at the rotor side, this might lead to high voltages, thereby destroying the converter. A method considering rotor short circuit current of DFIG wind turbines is suggested to obtain suitable expression of the rotor current [53]. This method is appropriate for analyzing several cases under different levels of both the voltage rise and voltage sag. In addition, it improves the available capacity of the uninterrupted operation of the wind turbine systems during the voltage failures. In order to protect the DFIG wind turbine systems during the low voltage faults, a dynamic characteristic analysis is established from the points of district grid voltage stability and generator operation constrains [54]. Modelling and control of a DFIG wind turbine system during the grid disturbances were investigated in [55]. The main contribution of this study is to establish a comprehensive control technique of the power from the dc-link through the grid side converter when the line to ground faults occur. Fault diagnosis based on the Fractional-Order Controller (FOC) for both the stator and rotor faults considering main flux, and cross flux saturation, and iron losses in a Self-Excited Induction Generator (SEIG) wind turbine system is investigated in [56]. An effective pre-processing analysis for diagnosing new classes of faults in the controlled DFIG sensors under missing data scenarios is proposed in [57].

Bearings and braking system are particularly the vital parts of wind turbine systems, since faults in these parts can results in catastrophic failure of the WECS. Bearing faults lead to the increased wind turbine maintenance costs as well as expensive breakdowns. In order to indicate bearing faults in wind turbine systems, one approach used data mining using historical wind tur-bine data by neural network algorithm [58]. The accuracy of the proposed method is estimated to be around 97% which faults can be predicted 1.5 hours before their occurrence. An online condition monitoring based on currents and voltages for fault diagnosis of wind turbine brake system is studied in [59]. A diagnostic algorithm for bearings under non-stationary operational conditions [60] is proposed. The ensemble super-wavelet transform taking signal decomposition and feature extraction as an interactive process into account is used to investigate vibration features of bearing faults [61].

Failures in rotor are of significant importance since they might cause secondary faults which can lead to severe motor malfunction. Technically, condition monitoring and fault diagnosis approaches for wind turbine rotors can be categorized as acoustic emission, air-gap torque, stator current, electromagnetic field monitoring, induced voltage, instantaneous angular speed, instantaneous power, motor circuit analysis, surge testing, vibration, and voltage. The interested readers are referred to a detailed review paper [62] for more information about the mentioned techniques.

4. Fault diagnosis based on performance monitoring techniques in WECS

Condition monitoring approaches require installations of specific equipment and sensors in or-der to identify faults at specific parts of a wind turbine. In addition, these techniques are usually based on either the constrained experiments or simulated dataset. Performance monitoring is an-other stream of research which focuses on utilizing historical operational turbine data in regular time-interval. The costs associated with these techniques are almost negligible since wind turbine performance data are recorded by the Supervisory Control and Data Acquisition (SCADA) system in real time. Performance monitoring approaches using statistical methods and data mining o er an alternative technique of wind turbine condition monitoring. Wind turbine faults are usually recognized with a delay by the SCADA data. Thus, data mining approaches are widely used to extract the hidden patterns in the data in order to perform an appropriate maintenance on the system.

Faults of blades are of particular concern because of their cost to repair. Two main faults associated with turbine blades which negatively affect the performance of wind turbines are the blade angle implausibility (i.e., the deviation between the actual and set pitch angle), and blade asymmetry (i.e., the deviation of the blade pitch angle). Data-mining approaches utilizing genetic programming algorithm were used to monitor and predict the performance of a blade pitch [63]. A data-mining algorithm was built to predict and identify status patterns of wind turbines using status and operational data collected [64]. A performance monitoring approach based on wind turbine SCADA alarms was investigated in [65]. The authors in [66] proposed the continuous wavelet transform-based approach to enhance the fault detection of wind turbine blades considering the Meyer wavelet as the basic wavelet. Non Destructive Testing (NDT), also called Non Destructive Evaluation (NDE), is used in [67] to monitor the behavior of a wind turbine blade during a quasi-static test-to-failure. Acoustic emission technique [68]-[70] is used for monitoring of a typical wind turbine blade during the fatigue test. In addition, a technique based on the infrared thermal image is carried out for non-destructive testing of wind turbine blades in [71]. The equivalent damage loading techniques for full-scale wind turbine blade which might result in the occurrence of fatigue were also investigated in [72, 73] The authors in [74] explored the piezoceramic based impedance and active sensing methods for the monitoring of wind turbine blades.

Performance monitoring regarding gearbox faults is mainly utilized based on the frequency-domain analysis. Fourier transformation and wavelet are the two widely used methods. Fault detection of a gearbox using discrete wavelet transformation is discussed in [75]. The Fourier transform method and the variable amplitude Fourier series are developed to study gearbox fault detection based on vibration signals [76, 77]. The Morlet continuous wavelet transform is used to gearbox fault diagnosis considering fluctuating loads [78]. High frequency vibration data collected from gearbox testing were used to gearbox fault detection in [79]. The authors included the Fourier transformation as well as k-means clustering algorithm. The frequency analysis assumes that the underlying process is stationary and linear. Additionally, the time factor is eliminated in the frequency-domain analysis and the change of a process is not taken into account. These factors are the main drawbacks of this technique. A model of variable-speed wind turbine considering thermodynamic process of gearbox lubrication system and using the SCADA data is developed to fault detect of wind turbine gearbox [80]. The authors in [81] developed a technique based on neural networks for fault forecasting of wind turbine gearbox. A novel methodology using the statistically robust Mahalanobis distance techniques for the prognosis of wind turbine gearbox failures is proposed in [82]. Wavelet techniques using high frequency data are used [83] for monitoring gearbox vibration signals. In addition, diagnosis techniques based on the acoustic emission data and high frequency vibration using wavelet transforms are used for monitoring wind turbine gearbox failures [84, 85]. Physics of failure techniques, for example as useful life (RUL) prediction, were used for the prognosis of the gearbox [86]. Statistical techniques were also developed for the prognosis and diagnosis of wind turbine gearbox such as linear regressive techniques [87] and auto-regressive models [88]. Diagnosis methods for wind turbine gearbox using low frequency data and based on the artificial neural networks have also been investigated [89].

Predicting generator faults helps timely maintenance as well as replacement of brushes. Performance monitoring of wind turbine generators have been widely performed using the Fourier transformation and wavelet. The literature regarding the gearbox failures is mainly focused on the frequency-domain analysis. For instance, fault diagnosis in terms of multistage gearbox by demodulation of motor current waveform is investigated in [90]. Application of wavelets to gear-box vibration signals for fault diagnosis is discussed in [91]. Variable amplitude Fourier series using vibration signals were developed for wind turbine gearbox diagnosis [92, 93]. The wavelet approach is used in another study [94] for fault diagnosis of gearbox considering varying load conditions. Data-mining algorithms based on the datasets collected from the SCADA systems were applied for early prediction of generator carbon brush faults in wind turbines [95]. A neural network is used to improve the accuracy of fault diagnosis of wind turbine generators [96]. The authors in [97] proposed the architecture of a novel predictive maintenance system, called Intelligent System for Predictive Maintenance (SIMAP), where its main objective is finding the most appropriate diagnosis and maintenance actions for wind turbine generator. Data mining algorithms and statistical quality control theory are applied to monitor the vibration excitement of the gearbox in its high-speed stage in [98].

5. Conclusion

In this paper, we have attempted to summarize the developments and research of practical condition monitoring and fault diagnosis approaches for WECS. The performance monitoring methods embedded with wind turbine systems are also summarized. First, the structure of wind turbine systems is discussed. Then, the typical faults of wind turbine systems with related diagnosis algorithms are presented. The privileges and drawbacks of each technique are compared well in detail in order to find the most appropriate approach. Fundamentally, the main purpose of this paper is to provide a widespread view over recent approaches in the area of condition monitoring and fault diagnosis of wind turbine systems in order to guide the future research activities. It is expected that the given information in this paper could lead to some major directions for future researches.

References

[1] Ackermann T, Soder L. Wind energy technology and current status: a review. Renewable and Sustainable Energy Reviews 2000;4(4):315-74.

[2] Joselin Herbert GM, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. Renewable and Sustainable Energy Reviews 2007;11(6):1117-45.

[3] Global Wind Energy Council. [Online]. Available from:http://www.gwec.net/global-figures/graphs/.

[4] Hepbasli A, Ozgener O. A review on the development of wind energy in Turkey. Renewable and Sustainable Energy Reviews 2004;8(3):257-76.

[5] W. Y. Liu, B. P. Tang, J. G. Han, X. N. Lu, N. N. Hu, Z. Z. He. The structure healthy condition monitoring and fault diagnosis methods in wind turbines: A review. Renewable and Sustainable Energy Reviews 2015; 44(2015)466-472.

[6] J. Perez, F. Marquez, A. Tobias, M. Papaelias. Wind turbine reliability analysis. Renewable and Sustainable Energy Reviews 2013; 23 (2013) 463-472.

[7] Kusiak A, Li W. The prediction and diagnosis of wind turbine faults. Renewable Energy 2011;36(1):1623.

[8] Islam MR, Mekhilef S, Saidur R. Progress and recent trends of wind energy technology. Renewable and Sustain-able Energy Reviews 2013;21:456-68.

[9] T. Ackermann, Wind Power in Power Systems. Hoboken, NJ, USA: Wiley, 2008.

[10] D. J.Burke andM. J. OMalley, Maximizing firm wind connection to security constrained transmission networks, IEEE Trans. Power Syst., vol. 25, no. 2, pp. 749759, May 2010.

[11] H. Li and Z. Chen, Overview of different wind generator systems and their comparisons, IET Renew. Power Generat., vol. 2, no. 2, pp. 123138, Jun. 2008.

[12] Perveen R, Kishor N, Mohanty SR. O -shore wind farm development: present status and challenges. Renew Sustain Energy Rev 2014;29:780-92.

[13] Tian Z, Jin T, Wu B, Ding F. Condition based maintenance optimization for wind power generation systems under continuous monitoring. Renewable Energy 2011;36:1502-9.

[14] Ding F, Tian Z. Opportunistic maintenance for wind farms considering multilevel imperfect maintenance thresh-olds. Renewable Energy 2012;45:175e82.

[15] Jin T, Tian Y, Zhang CW, Coit DW. Multicriteria planning for distributed wind generation under strategic main-tenance. IEEE Trans Power Deliv 2013;28(1): 357-67.

[16] A. M. Eltamaly, H. M. Farh. Maximum power extraction from wind energy system based on fuzzy logic control. Electric Power Systems Research 2013; 97 (2013) 144-150.

[17] B. Yang, D. Sun. Testing, inspecting and monitoring technologies for wind turbine blades: A survey. Renewable and Sustainable Energy Reviews 2013; 22(2013)515-526.

[18] J. W. Van Wingerden, A. W. Hulskamp, T. Barlas, B. Marrant, G. A. M. VanKuik, D. P. Molenaar, and M.Verhaegen, On the proof of concept of a smartwind turbine rotor blade for load alleviation,Wind Energy, vol. 11, no. 3, pp. 265280, May 2008.

[19] Xudong W, Shen WZ, Zhu WJ, Sorensen JN, Jin C. Shape optimization of wind turbine blades. Wind Energy 2009;12:781-803.

[20] Liao CC, Zhao XL, Xu JZ. Blade layers optimization of wind turbines using FAST and improved PSO algorithm. Renew Energy 2012;42:227-33.

[21] Kong C, Bang J, Sugiyama Y. Structural investigation of composite wind turbine blade considering various load cases and fatigue life. Energy 2005;30:2101-14.

[22] Sagol E, Reggio M, Ilinca A. Issues concerning roughness on wind turbine blades. Renewable and Sustainable Energy Review 2013;23:514-25.

[23] A. Chehouri, R. Younes, A. Ilinca, J. Perron. Review of performance optimization techniques applied to wind turbines. Applied Energy 2015; 142 (2015) 361-388.

[24] Yoshida S. Wind turbine tower optimization method using a genetic algorithm. Wind Eng 2006;30:45369.

[25] Sun H, Zi Y, He Z, Yuan J, Wang X, Chen L. Customized multiwavelets for planetary gearbox fault detection based on vibration sensor signals. Sensors 2013;13:1183-209.

[26] Bartelmus W, Zimroz R. A new feature for monitoring the condition of gearboxes in non-stationary operation conditions. Mech Syst Sig Process 2009;23: 1528-34.

[27] R. Errichello, J. Muller, Gearbox Reliability Collaborative Gearbox 1 Failure Analysis Report, NEREL/SR-5000-530262, February 2012.

[28] S. Sheng, Wind turbine gearbox condition monitoring round robin study vibration, analysis, NREL/TP-500054530, July 2012.

[29] Feng Z, Liang M, Zhang Y, Hou S. Fault diagnosis for wind turbine planetary gearboxes via demodulation analy-sis based on ensemble empirical mode decomposition and energy separation. Renew Energy 2012;Vol. 47:112e26.

[30] Yang W, Tavner P, Wilkinson M. Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train. IET Renew Power Gener 2009;3(1):1-11.

[31] Bennouna O, Heraud N, Camblong H, Rodriguez M. Diagnosis of the doublyfed induction generator of a wind turbine. Wind Engineering 2005;29: 431e48.

[32] K.Rothenhagean and F.W.Fuchs, Doubly fed induction generator model-based sensor fault detection and control loop configuration, IEEE Transactions on Industrial Electronics, vol 56, no. 10, pp.4229-4238, October 2009

[33] A. Ghaedi, A. Abbaspour, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie. Toward a Comprehensive Model of Large-Scale DFIG-Based Wind Farms in Adequacy Assessment of Power Systems. IEEE Transactions on Sustainable Energy 2014; 5(1): 55-63.

[34] K. Rajambal, B. Umamaheswari, C. Chellamuthu. Electrical braking of large wind turbines. Renewable Energy 2005; (30)15:2235-2245.

[35] Tavner PJ, Xiang J, Spinato F. Reliability analysis for wind turbines. Wind Energy 2007;10:1-18.

[36] Spinato F, Tavner PJ, Bussel GJW van, Koutoulakos E. Reliability of wind turbine subassemblies. Renewable Power Generation, IET 2009;3(4):387401.

[37] Koutoulakos E. Wind turbine reliability characteristics and o shore availability assessment. Master's thesis, TU Delft; 2008.

[38] A. Kusiak, Z. Zhang, A. Verma. Prediction, operations, and condition monitoring in wind energy. Energy 60 (2013) 1-12.

[39] Y. Amirat, M.E.H. Benbouzid, E. Al-Ahmar, B. Bensaker, S. Turri. A brief status on condition monitoring and fault diagnosis in wind energy conversion systems. Renewable and Sustainable Energy Reviews 2009; 13: 2629-2636.

[40] Caselitz P, Giebhardt J, Kru ger T, Mevenkamp M. Development of a fault detection system for wind energy converters. In: Proceedings of EUWEC; 1996. p. 1004-7.

[41] Lee Jong-Won, Lee Jun-Seong, Han Jae-Hung, Shin Hyung-Ki. Aeroelastic analysis of wind turbine blades based on modified strip theory. J. Wind Eng. Ind. Aerodyn. 2012;110:62-9.

[42] F. Zhipeng, L. Ming, Z. Yi, H. Shumin. Fault diagnosis for wind turbine planetary gearboxes via demodulation analysis based on ensemble empirical mode decomposition and energy separation. Renewable Energy 2012;47:112-26.

[43] F. Zhipeng, L. Ming. Fault diagnosis of wind turbine planetary gearbox under non stationary conditions via adaptive optimal kernel time-frequency analysis. Renewable Energy 2014;66:468-77.

[44] F. Zhipeng, C. Xiaowang, L. Ming. Iterative generalized synchros-queezing transform for fault diagnosis of wind turbine planetary gearbox under non stationary conditions. Mechanical Systems and Signal Processing 2015;52-53:360-75.

[45] F. Zhipeng, L. Ming. Complex signal analysis for wind turbine planetary gearbox fault diagnosis via iterative atomic decomposition thresholding. Journal of Sound and Vibration 2014;333:5196-211.

[46] T. Baoping, S. Tao, L. Feng, D. Lei. Fault diagnosis for a wind turbine transmission system based on manifold learning and Shannon wavelet support vector machine. Renewable Energy 2014;62:1-9.

[47] Z. Anmei, Y. Dejie, Z. Wenyi. A research on intelligent fault diagnosis of wind turbines based on ontology and FMECA. Advanced Engineering Informatics 2014;5(November)(InPress).

[48] H. Liu, S. Dhupia, Sh. Shuangwen. An explanation of frequency features enabling detection of faults in equally space planetary gearbox. Mechanism and Machine Theory 2014;73:169-83.

[49] V. Luisa, R. Anbal, P. Jose, J. Luis. Statistical fault diagnosis based on vibration analysis for geartest-benchundernon- stationary conditions of speed and load. Mechanical Systems and Signal Processing 2012;29:436-46.

[50] Z. Yang, B. Wang, X. Dong, H. Liu. Expert system of fault diagnosis for gearbox in wind turbine. Systems Engineering Procedia 2012;4:189-95.

[51] W. Zhou, T. G. Habetler, and R. G. Harley, Bearing condition monitoring methods for electric machines: a general review.

[52] M. Dicorato, G. Forte, M. Trovato. Wind farm stability analysis in the presence of variable-speed generators. Energy 2012;39:40-7.

[53] Y. Ling, X. Cai. Rotor current dynamics of doubly fed induction generators during grid voltage dip and rise. Electrical Power and Energy Systems 2013;44:17-24.

[54] L. Shi, N. Chen, Q. Lu. Dynamic characteristic analysis of doubly-fed induction generator low voltage ride-through. Energy Procedia 2012;16:1526-34.

[55] H. Fatma, K. Lotfi. Rotor power control in doubly fed induction generator wind turbine under grid faults. Energy 2012;44:853-62.

[56] A. Issam, O. Amar. Modeling, control and fault diagnosis of an isolated wind energy conversion system with a self-excited induction generator subject to electrical faults. Energy Conversion and Management 2014;82:11-26.

[57] R. Roozbeh, Z. Enrico, P. Vasile. E cient residuals pre-processing for diagnosing multi-class faults in a doubly fed induction generator, under missing data scenarios. Expert Systems with Applications 2014;41:6386-99.

[58] K. Andrew, V. Anoop. Analyzing bearing faults in wind turbines:A data-mining approach. Renewable Energy.2012;48:110-6.

[59] M. Entezami, S. Hillmansen, P. Weston, P. Papaelias. Fault detection and diagnosis within a wind turbine me-chanical braking system using condition monitoring. Renewable Energy 2012;47:175-82.

[60] Z. Radoslaw, B. Walter, B. Tomasz, U. Jacek. Diagnostics of bearings in presence of strong operating conditions non-stationarity- A procedure of load-dependent features processing with application to wind turbine bearings. Mechanical Systems and Signal Processing 2014;46:16-27.

[61] H. Wangpeng, Z. Yanyang, Ch. Binqiang, W. Feng, H. Zhengjia. Automatic fault feature extraction of mechani-cal anomaly on induction motor bearing using ensemble super-wavelet transform. Mechanical Systems

and Signal Processing 2014;8(October)(InPress, Available online).

[62] M. R. Mehrjou, N. Mariun, M. H. Marhaban, N. Misron. Rotor fault condition monitoring techniques for squirrel-cage induction machineA review. Mechanical Systems and Signal Processing 2011;25(8):28272848.

[63] Kusiak A, Verma A. A data-driven approach for monitoring blade pitch faults in wind turbines. IEEE Transac-tions on Sustainable Energy 2011;2(1): 87-96.

[64] Kusiak A, Verma A. Prediction of status patterns of wind turbines: a data mining approach. ASME Journal of Solar Energy Engineering 2011;133(1). 011008-1-011008-10.

[65] Qiu Y, Richardson P, Feng Y, Tavner P, Erdos G, Viharos ZS. SCADA alarm analysis for improving wind turbine reliability. In: European wind energy conference and exhibition, Brussels, Belgium 2011. p. 14-7.

[66] Tsai, C.S., Hsieh, C.T., Huang, S.J. Enhancement of damage-detection of wind turbine blades via CWT-based approaches. IEEE Transactions on Energy Conversion Vol. 21, pp. 77681, 2006.

[67] H. Sutherland, A. Beattie, B. Hansche, W. Musial, J. Allread, J. Johnson, and M. Summers, The application of non-destructive techniques to the testing of a wind turbine blade, Sandia Nat. Labs. Rep. SAND 93-1380, Jun. 1994.

[68] A. G. Beattie, Acoustic emission monitoring of a wind turbine blade during a fatigue test, presented at the 35th Aerospace Science Meeting, Reno, NV, Jan. 1997.

[69] P.A. Joosse,M. J.Blanch,A.G.Dultton,D.A.Kouroussis,T.P.Philppidis, and P. S. Vionis, Acoustic emission mon-itoring of small wind turbine blades, in Proc. ASME Wind Energy Symp., 2002, pp. 400406.

[70] J. Wei and J. McCarty, Acoustic emission evaluation of composite wind turbine blades during fatigue testing, Wind Eng., vol. 17, no. 6, pp. 266 274, 1993.

[71] T. P. Yan, G. M. Smith, B. R. Clayton, A. G. Dutton, and A. D. Irving, Infrared thermography for non-destructive testing of wind turbine blades, presented at the 3rdWorldWind EnergyConf.Renewable Energy,Beijing, China, Oct. 2004.

[72] G. Freebury and W. Musial, Determining equivalent damage loading for full-scale wind turbine blade fatigue tests, presented at the 19th ASME Wind Energy Symp., Reno, NV, Jan. 2000.

[73] G. Anindya, J. S. Mannur, J. S. Mark, and P. P. Frank, Structural health monitoring techniques for wind turbine blades, J. Wind Eng. Ind. Aerodyn., vol. 85, no. 3, pp. 309324, Apr. 2000.

[74] J. Ruan, S. Michael, D. Patil, G. Song. Structural health monitoring of wind turbine blade using piezoceremic based active sensing and impedance sensing. 11th International Conference on Networking, Sensing and Control (ICNSC), 2014 IEEE.

[75] A. R. Mohanty and C. Kar, Fault detection in a multistage gearbox by demodulation of motor current waveform, IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 12851297, Jun. 2006.

[76] X. Yuan and L. Cai, Variable amplitude Fourier series with its application in gearbox diagnosis-Part I: Principle and simulation, Mech. Syst. Signal Process., vol. 19, no. 5, pp. 10551066, 2005.

[77] X. Yuan and L. Cai, Variable amplitude Fourier series with its application in gearbox diagnosis-Part II: Experiment and application, Mech. Syst. Signal Process., vol. 19, no. 5, pp. 10671081, 2005.

[78] X. Wang, V. Makis, and M. Yang, A wavelet approach to fault diagnosis of a gearbox under varying load conditions, J. Sound Vibration, vol. 329, no. 9, pp. 15701585, 2010.

[79] Zhang Z, Verma A, Kusiak A. Fault analysis of the wind turbine gearbox. IEEE Transactions on Energy Con-version 2012;27(2):526-35.

[80] Q. Yingning, S. Juan, C. Mengnan, W. Hao, F. Yanhui, Y. Wenxian. Open Access Model based wind turbine gearbox fault detection on SCADA data. Renewable Power Generation Conference (RPG 2014), 3rd .

[81] R. F. Brand£o, J. A. Carvalho, F. P. Maciel Barbosa. Forecast of Faults in a Wind Turbine Gearbox. ELEKTRO, IEEE 2012.

[82] J. L. Godwin, P. Matthews, Prognosis of wind turbine gearbox failures by utilising robust multivariate statistical techniques. IEEE Conference on Prognostics and Health Management (PHM), 2013.

[83] W. Wang and P. McFadden, Application of wavelets to gearbox vibration signals for fault detection, Journal of sound and vibration, vol. 192, no. 5, pp. 927939, 1996.

[84] J. Lin and M. Zuo, Gearbox fault diagnosis using adaptive wavelet filter, Mechanical systems and signal pro-cessing, vol. 17, no. 6, pp. 12591269, 2003.

[85] J. Rafiee, M. Rafiee, and P. Tse, Application of mother wavelet functions for automatic gear and bearing fault diagnosis, Expert Systems with Applications, vol. 37, no. 6, pp. 45684579, 2010.

[86] M. Gasperin, D. Juricic, P. Boskoski, and J. Vizintin, Model-based prognostics of gear health using stochastic dynamical models, Mechanical Systems and Signal Processing, vol. 25, no. 2, pp. 537548, 2011

[87] W. Bartelmus and R. Zimroz, A new feature for monitoring the condition of gearboxes in non-stationary operat-ing conditions, Mechanical Systems and Signal Processing, vol. 23, no. 5, pp. 15281534, 2009.

[88] X. Wang and V. Makis, Autoregressive model-based gear shaft fault diagnosis using the kolmogorovsmirnov test, Journal of Sound and Vibration, vol. 327, no. 3, pp. 413423, 2009.

[89] M. Garcia, M. Sanz-Bobi, and J. del Pico, Simap: Intelligent system for predictive maintenance: Application to the health condition monitoring of a wind turbine gearbox, Computers in Industry, vol. 57, no. 6, pp. 552568, 2006.

[90] A. R. Mohanty and C. Kar, Fault detection in a multistage gearbox by demodulation of motor current waveform, IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 12851297, Jun. 2006.

[91] W. J. Wang and P. D. McFadden, Application of wavelets to gearbox vibration signals for fault detection, J. Sound Vibration, vol. 192, no. 5, pp. 927939, 1996.

[92] X. Yuan and L. Cai, Variable amplitude Fourier series with its application in gearbox diagnosis-Part I: Principle and simulation, Mech. Syst. Signal Process., vol. 19, no. 5, pp. 10551066, 2005.

[93] X. Yuan and L. Cai, Variable amplitude Fourier series with its application in gearbox diagnosis-Part II: Experiment and application, Mech. Syst. Signal Process., vol. 19, no. 5, pp. 10671081, 2005.

[94] X. Wang, V. Makis, and M. Yang, A wavelet approach to fault diagnosis of a gearbox under varying load conditions, J. Sound Vibration, vol. 329, no. 9, pp. 15701585, 2010.

[95] Verma A, Kusiak A. Fault monitoring wind turbine generator brushes: a data mining approach. ASME Journal of Solar Energy Engineering 2012;134(2): 021001-1-021001-9.

[96] Zaher A, McArthur SDJ, Infield DG, Patel Y. Online wind turbine fault detection through automated SCADA data analysis. Wind Energy 2009; 12(6):574-93.

[97] Garcia, M.C., Sanz-Bobi, M.A., Del Pico J. SIMAP: intelligent system for predictive maintenance application to the health condition monitoring of a wind turbine gearbox. Journal of Comput Ind, Vol. 57(6), pp.55268, 2006.

[98] Zhang, A., Verma, A., and Kusiak, A. Fault Analysis and Condition Monitoring of the Wind Turbine Gearbox. IEEE Transactions on Energy Conversion, Vol. 27, No. 2, 2012, pp. 526-535.