Applied Mechanics and Materials Vol. 197 (2012) pp 206-210
Online available since 2012/Sep/26 at www.scientific.net

doi:10.4028/www.scientific.net/AMM.197.206

Research of Condition Monitoring and Fault Diagnosis Techniques for Wind Turbine Gearbox

Xianyou Zhong[1, 2, a], Liangcai Zeng[1, b], Chunhua zhao[2, c], Jin zhang[2, d], Shiqing Wan[2, e]

[1] The Ministry of Education Key Laboratory of Metallurgical Equipment and Its Control; Wuhan University of Science and Technology; Wuhan 430081; China

[2] Hubei Key Laboratory of Hydroelectric Machinery Design & Maintenance, China Three Gorges University, Yichang, 443002, China

[a]zhxy@ctgu.edu.cn, [b]zengliangcai@wust.edu.cn, [c]zhaochunhua@ctgu.edu.cn

[d]zhangjin20062008@163.com, [e]wanshiqing2007@yahoo.cn

Keywords：Wind turbine, condition monitoring, fault diagnosis, gearbox; bearing, vibration analysis; oil analysis; acoustic emission

Abstact: Wind power industry enormously expanded during the last several years. However, wind turbines are subjected to different sorts of failures, which lead to the increasement of the cost. The wind turbine gearbox is the most critical component in terms of high failure rates and long time to repair. This paper described common failures and root causes of wind turbine gearboxes. Then it focused on fault diagnosis and monitoring techniques for the wind turbine gearbox. The challenges and future research directions were presented, and the simulator rig of wind turbine gearbox was designed to develop condition monitoring and fault diagnosis techniques for wind turbine gearbox.

1. Introduction

Wind energy is the fastest growing renewable energy source in the world. The use of wind power around the world has been strong researched and developed in recent years. But the wind turbine is easy to damage, especially for the key parts as gearbox failure. Among the various subsystems comprising a wind turbine, the gearbox has been shown to cause the longest downtime and is the most costly to maintain. As a result, it is necessary for the industry to improve wind turbine's reliability and reduce downtime. Detecting incipient failures of gearboxes could reduce the chances of catastrophic failures. For instance, gear coating can be used to repair the gear surface if pitting failure appears on the gear surface; when the bearings have some trouble, the gearbox can begin to run in a low speed to wait to be repaired, thus maintenance is arranged reasonably. The gearbox is placed between the hub and the generator and used to convert the slowly rotating high torque power from the wind turbine rotor to high speed low torque power used by the generator. A wind turbine gearbox consists of three major components: gears, bearings and shafts. This paper focused on condition monitoring and fault diagnosis techniques for gears and bearings of the wind turbine gearbox.

2. Failure Modes and Their Causes in Wind Turbine Gearbox

Wind turbines are often located in a mountainous area or at sea with traffic inconvenience, which leads to high maintenance cost. The wind turbines work under very harsh environment [1], with rapidly changed environment temperature, air pressure and alternating load operation conditions. Thus, the transmission system is under complex time-varying load. The common faults in wind turbine gearbox include gear damage, bearing damage, broken shaft, leaking oil and high oil temperature. And the most common faults are gear damage and bearing damage.

2.1 Gear Damage

Gear damages include wear of tooth surfaces, tooth surface's pitting and broken tooth.

- Wear of tooth surfaces: when the gearbox work at a low temperature, and the low temperature and lubricant solidification make the lubricant not reach lubrication part causing wear; When the gearbox work at a high temperature, the high temperature caused by motor heating make temperature of lubricating oil rise abnormally, which causes the failure of mechanical lubricant which lead to wear of the gear; Entry of foreign matter is other cause of wear of tooth surfaces

- Tooth surface's pitting: due to large alternating stress, fatigue cracks arise on the tooth surface or below the surface, and further expansion of the cracks lead to the tooth surface's pitting.
- Broken tooth: due to repeated bending stress, sudden severe overload, shock load or further expansion of the cracks.

2.2 Bearing Damage

Bearing damages include wear, pitting, fracture.

- Wear: due to insufficient lubrication or entry of foreign matter
- Pitting: due to alternating loads or insufficient lubrication
- Fracture: due to insufficient lubrication, alternating loads, heavy loads or fatigue rupture.

3. Condition Monitoring and Fault Diagnosis Techniques

At present techniques of condition monitoring and fault diagnosis for wind turbine gearbox mainly includes vibration method, oil analysis and acoustic emission. Among these different techniques, vibration analysis and oil monitoring are the most predominantly used for wind turbine gearbox.

3.1 Vibration Analysis

Vibration analysis is one of the proven and effective technologies being used in condition monitoring for wind turbine gearboxes. Equipment used for vibration analysis is relatively simple. Signal analysis technologies are more mature. The test and diagnosis process can be in the process of operation and it is easy to realize the equipment's condition monitoring. Vibration analysis can be applied online, offline, and periodic data acquisition. Limitations of vibration analysis include: expensive, intrusive, subjecting to sensor failures and limited performance for low speed rotation. Several reports on wind turbine gearbox condition monitoring have been already published. Yassine et al. detected bearing failure in DFIG-based wind turbines [2], the gear fault diagnosis method of $\alpha 0$ value was adopted into the condition monitoring and fault diagnosis system [3].Yanyong Li detected and diagnosed incipient fault of the wind turbine gearbox using empirical mode decomposition [4]. Tomasz et al. used spectral kurtosis for detection of a tooth crack in the planetary gear of a wind turbine[5].

3.2 Oil Analysis

Oil analysis on wind turbines [6, 7] is an effective tool to assess lubricant condition, contamination, and mechanical wear. In wind turbines, the lubricant is subjected to extreme temperatures, varying load weights and contamination. Lubricant performance deteriorates under these conditions and it becomes essential to monitor lubricant condition through oil analysis. Oil analysis is typically applied to the gearbox, as it is the only oil-lubricated component in the drivetrain. The oil analysis is done through a particle counter being fitted directly into the gearbox lubrication system measuring metallic debris generated by bearing and gear damage. The objective of oil analysis is to detect oil contamination and degradation. Oil monitoring is an important factor in achieving maximum service life for wind turbine gearboxes. Oil analysis is an effective way for detecting gear damage at an early stage, so that the level of deterioration can be estimated. By detecting the number of particles and their sizes, one can determine gear-pitting damage at an early stage, which is not possible through vibration analysis. Oil analysis, especially for particle's counts, is effective for monitoring gearbox components' damage, but it is not effective for damage's location. There is no access to the gearbox when a turbine is in operation. Oil analysis is mostly executed off line by taking samples. For safeguarding the oil quality, application of on-line sensors is increasing. However, on-line oil analysis is still very expensive.

3.3 Acoustic Emission

Acoustic emission (AE) sensors are extremely sensitive devices that listen for the sound of failure, which is taking place in materials and structures[7]. AE is unaffected by typical environmental noise. AE requires highly specialized sensors and signal processing; it is available for all machines irrespective of operational speed. Cracks expansion due to fatigues, stress corrosion and creep can be found and identified with AE technology. There have been numerous investigations reported on applying AE for bearing and gearbox defect diagnostics. Lekou et al. [8] presented their study using AE in parallel with vibration, temperature and rotating speed data for health monitoring. It was shown that monitored periodic statistics of AE data may be used as an indicator of damage presence and damage severity in a dynamic operation of wind turbine. Chen et al. [9] set up a finite-element (FE) simulation study for the stress wave based diagnosis for the rolling-element bearing of wind turbine gearbox.

4. Research Challenges and Future Research Directions

As mentioned above, various techniques including vibration analysis, acoustic emission and oil analysis have been successfully applied to wind turbine gearbox, and are increasingly deployed in the wind turbine gearbox. However, there are still challenges faced by these monitoring and diagnosis techniques, which must be addressed.

- Vibration analysis is the dominant technique, but the input shaft speed of wind turbine gearbox is about 20 rpm. It is difficult for vibration to diagnose damage or degradation of rotating machines working at less than 50 rpm because of the small amount of energy. In wind turbine gearbox, low speed and intermediate stage appear relative slow peripheral speeds, which are at the limits of the validity range of ISO6336. Some similar research works have been reported to solve this problem, Eric Y. Kim et al. [10] developed a low speed fault simulation test rig to simulate common machine faults with shaft speeds as low as 10rpm under loading conditions using AE signal for early detection of low speed bearing defects. Sako, Takashi et al. [11] diagnosed bearing in low speed rotating equipment of 100 rpm or less using AE envelope waveform of a 100k to 1MHz frequency region. Haiyang Jiang et al. analyzed AE signals and vibration signals for fault diagnosis of low-speed rotating machinery [12].
- Study the failure mechanism for gearboxes. Take care of not only symptoms, but also root causes. Planetary gearboxes are widely used in wind turbines.Bad operation conditions cause faults, such as severe pitting and fatigue crack etc., occurring in the planetary gearboxes frequently. In the planetary gearboxes, complicated vibration transmission paths make fault response quite weak and feature extraction extremely difficult[13], and composite transmission movement makes the failure characteristics modulate and couple reciprocally. Modeling and dynamic behavior of planetary gearbox need to be studied in depth [14]. Vibration monitoring and vibration-based diagnosis of planetary stages in gearboxes is at present still challenging. So an improvement of condition-monitoring technology for this purpose is subject to intensive development. Aiming at this problem, a method based on multi-sensor information fusion is proposed in [15], time- and frequency-domain statistical features are extracted from vibration signals. The method is applied to fault diagnosis of planets gearboxes having pitting damage with different damage levels. And the result demonstrates its effectiveness, but the result isn't ideal when running at a speed of 300r/min and 600r/min with load.
- Vibration analysis is the dominant technique, but it is not really possible to compare a wind turbine gearbox with gearboxes employed in other applications for the reason that a wind turbine gearbox is characterized by stochastic loads due to the large wind speed variability. The wind conditions are constantly changing, so each vibration measurement could potentially be at a different speed and load condition. The result is that the peaks in the spectrum will not line-up with peaks in previous spectra, and the amplitudes of peaks are no longer comparable. Due to the non-stationary operation, it appears to be difficult to develop effective algorithms for early fault detection, especially for variable speed operation. Order analysis is a suitable gear fault diagnosis method for variable- speed and load conditions. The basic idea is to convert the data based on time domain to the angle domain, and then analyze fault based Fourier transform. In order to solve the inaccurate character of vibration signals in gearbox and during nonstationary course with traditional computed order analysis, the computed order analysis is improved and the nonlinearity fitting order analysis method is explored. The nonstationary vibration signals in the gearbox are sampled at constant time increments in time-domain and then the data are resampled with nonlinearity fitting order analysis arithmetic[17].

- It is clear that each technique has its strengths and limitations. It is necessary to integrate various techniques when conducting wind turbine gearbox in order to cover a broader range of potential failures and to increase the credibility of the results. For example, vibration analysis can pinpoint the crack locations but oil monitoring cannot. On the other hand, vibration analysis cannot detect lubricant deterioration but oil monitoring can. In order to improve the accuracy of diagnosis, it is needed to combine oil analysis with vibration or acoustic emission-based techniques. Loutas at el. used vibration, acoustic emission and oil debris on-line monitoring to monitor rotating machinery, the integration of vibration, AE and oil debris monitoring data improved the diagnostic capacity and reliability of the condition monitoring [18].

5. Rig for Wind Turbine Gearbox

Wind field environment is often hostile, in order to research gearbox fault diagnosis techniques in laboratory, it is necessary to design a wind turbine simulator instead of the actual gearbox. In order to study effective monitoring and diagnosis techniques for wind turbine gearboxes with variable speed and load. A test rig has been constructed, with features similar to a wind turbine drive train. The test rig (see Fig. 1) mainly includes variable frequency motor, reducer, gearbox and magnetic brake. A frequency conversion motor is selected, and the motor speed is changed through the inverter to simulate the time-varying characteristics, the current planetary gear structure in gearbox is selected, and the magnetic brake is used to regulate the load.

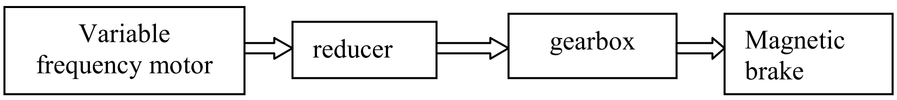

Fig1. Diagram of wind turbine gearbox test rig

6. Conclusion

This paper introduced various condition and diagnosis techniques for wind turbine gearbox. It is clear that each technique has its strengths and limitations. In order to improve the accuracy of diagnosis, it is needed to combine oil analysis with vibration or acoustic emission-based techniques. At last a test rig has been constructed to develop effective condition and diagnosis techniques for wind turbine gearbox.

7. Acknowledgements

I would like to express my gratitude to National Natural Science Foundation Project of China (No. 51075234) and Hubei Key Laboratory of Hydroelectric Machinery Design & Maintenance Open Fund (No. 2010KJX07), for their useful suggestions and funding support on our thesis.

References

[1] Z. Daneshi-Far, G. A. Capolino, H. Henao, Review of failures and condition monitoring in wind turbine generators, 19th International Conference on Electrical Machines, September 6, 2010

[2]Yassine Amirat, Vincent Choqueuse, Mohamed Benbouzid, Sylvie Turri, Hilbert transform-Based Bearing Failure Detection in DFIG-Based Wind Turbines, International Review of Electrical Engineering 6, 3 (2011) 1249-1256

[3]Hao Wangshen, Han Jiedong, Hao Xinmin, et al., Study on Development of Condition Monitoring and Fault Diagnosis System on MW-class Wind Turbines, Journal of Mechanical Transmission, 2011(06):56-62

[4]Yanyong Li, A discussion on using Empirical Mode Decomposition for incipient fault , World Non-Grid-Connected Wind Power and Energy Conference (WNWEC), 5-7 Nov. 2010 : 1 - 5

[5] Tomasz Barszcz, Robert B. Randall. Application of spectral kurtosis for detection of a tooth c rack in the planetary gear of a wind turbine. Mechanical Systems and Signal Processing, 2009, 23: 1352-1365

[6] S. Sheng, Investigation of Oil Conditioning, Real -time Monitoring and Oil Sample Analysis for Wind Turbine Gearboxes, 2011, AWEA Project Performance and Reliability Workshop, January 12–13, 2011, San Diego, CA.

[7]Sheng, S. "Investigation of Various Condition Monitoring Techniques Based on a Damaged Wind Turbine Gearbox," 8th International Workshop on Structural Health Monitoring 2011 Proceedings, Stanford, CA, September 13-15, 2011.

[8]D. J. Lekou, F. Mouzakis, A. Anastasopoulos, et al., Emerging techniques for health monitoring of wind turbine gearboxes and bearings, in Proc. EWEC 2009, Scientific Track Operation and Maintenance, Marseille, France, March 16-19, 2009.

[9]C. Chen, C. Sun, Y. Zhang, et al., "Fault diagnosis for large-scale wind turbine rolling bearing using stress wave and wavelet analysis," in Proc. 8th Int. Conf. on Electrical Machines and Systems, vol. 3, 2005, pp. 2239-2244.

[10]Eric Y. Kim , Andy C. C. Tan , Bo-Suk Yang, et al., Experimental Study on Condition Monitoring of Low Speed Bearings : Time Domain Analysis, 5th Australasian Congress on Applied Mechanics, 10-12 December 2007, Brisbane, Australia

[11]Sako, Takashi; Yoshie, Osamu, Diagnostic method of low speed rolling element bearing using AE envelope waveform, IEEE Region 10 Annual International Conference, Proceedings/TENCON, p 724-729, 2010, November 21- November 24.

[12]Jiang, Haiyang; Chen, Peng, Analysis and sensitivity evaluation of AE signals and vibration signals for fault diagnosis of low-speed rotating machinery, Applied Mechanics and Materials, 2012, v 128-129, p79-84.

[13]Yaguo Lei, Zhengjia He, Jing Lin etc, development of planetary gearbox fault diagnosis technology research, Journal of Mechanical Engineering, 2011, 47(19):59-67..

[14]Xuefeng Chen, Jimeng Li, Hang Cheng, et al., Research and application of condition monitoring and fault diagnosis technology in wind turbines, Journal of Mechanical Engineering, 2011, 47(9): 45-52

[15]Yaguo Lei, Lin Jing, Zhengjia He, Fault Diagnosis of Planetary Gearboxes Based on Multi-sensor Information Fusion, Journal of Vibration and Shock , 2010,29 (s):216-218

[16]Bin Lu, Yaoyu Li, Xin Wu and Zhongzhou Yang. A Review of Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis[J] .Power Electronics and Machines in Wind Applications, 2009. PEMWA 2009. IEEE 24-26 June 2009.

[17]Kang, Haiying; Qi, Yanjie; Yan, Wen; Zheng, Haiqi, Application of nonlinearity fitting order analysis arithmetic in nonstationary signals analysis, Proceedings of 9th International Conference on Electronic Measurement and Instruments, p 4890-4893, August 16, 2009

[18]Loutas,T.H.; Roulias, D.; Pauly, E.; Kostopoulos,The combined use of vibration, acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery,Mechanical Systems and Signal Processing, v 25, n4, p1339-1352, May 2011

Applied Sciences and Engineering

10.4028/www.scientific.net/AMM.197

Research of Condition Monitoring and Fault Diagnosis Techniques for Wind Turbine Gearbox

10.4028/www.scientific.net/AMM.197.206

DOI References

[1] Z. Daneshi-Far, G. A. Capolino, H. Henao, Review of failures and condition monitoring in wind turbine generators, 19th International Conference on Electrical Machines, September 6, (2010).
doi:10.1109/ICELMACH.2010.5608150
[4] Yanyong Li, A discussion on using Empirical Mode Decomposition for incipient fault , World Non-Grid-Connected Wind Power and Energy Conference (WNWEC), 5-7 Nov. 2010 : 1 - 5 reducer gearbox Magnetic brake Variable frequency motor.
doi:10.1109/WNWEC.2010.5673173
[5] Tomasz Barszcz, Robert B. Randall. Application of spectral kurtosis for detection of a tooth c rack in the planetary gear of a wind turbine. Mechanical Systems and Signal Processing, 2009, 23: 1352-1365.
doi:10.1016/j.ymssp.2008.07.019
[11] Sako, Takashi; Yoshie, Osamu, Diagnostic method of low speed rolling element bearing using AE envelope waveform, IEEE Region 10 Annual International Conference, Proceedings/TENCON, pp.724-729, 2010, November 21- November 24.
doi:10.1109/TENCON.2010.5686610
[13] Yaguo Lei, Zhengjia He, Jing Lin etc, development of planetary gearbox fault diagnosis technology research, Journal of Mechanical Engineering, 2011, 47(19): 59-67.
doi:10.3901/JME.2011.19.059
[14] Xuefeng Chen, Jimeng Li, Hang Cheng, et al., Research and application of condition monitoring and fault diagnosis technology in wind turbines, Journal of Mechanical Engineering, 2011, 47(9): 45-52.
doi:10.3901/JME.2011.09.045
[16] Bin Lu, Yaoyu Li, Xin Wu and Zhongzhou Yang. A Review of Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis[J] . Power Electronics and Machines in Wind Applications, 2009. PEMWA 2009. IEEE 24-26 June (2009).
doi:10.1109/PEMWA.2009.5208325
[17] Kang, Haiying; Qi, Yanjie; Yan, Wen; Zheng, Haiqi, Application of nonlinearity fitting order analysis arithmetic in nonstationary signals analysis, Proceedings of 9th International Conference on Electronic Measurement and Instruments, pp.4890-4893, August 16, (2009).
doi:10.1109/ICEMI.2009.5274732
[18] Loutas T.H.; Roulias, D.; Pauly, E.; Kostopoulos, The combined use of vibration, acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery, Mechanical Systems and Signal Processing, v 25, n4, pp.1339-1352, May (2011).
doi:10.1016/j.ymssp.2010.11.007