A Review of Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis

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***Abstract*—The state-of-the-art advancement in wind turbine condition monitoring and fault diagnosis for the recent several years is reviewed. Since the existing surveys on wind turbine condition monitoring cover the literatures up to 2006, this review aims to report the most recent advances in the past three years, with primary focus on gearbox and bearing, rotor and blades, generator and power electronics, as well as system-wise turbine diagnosis. There are several major trends observed through the survey. Due to the variable-speed nature of wind turbine operation and the unsteady load involved, time-frequency analysis tools such as wavelets have been accepted as a key signal processing tool for such application. Acoustic emission has lately gained much more attention in order to detect incipient failures because of the low-speed operation for wind turbines. There has been an increasing trend of developing model based reasoning algorithms for fault detection and isolation as cost-effective approach for wind turbines as relatively complicated system. The impact of unsteady aerodynamic load on the robustness of diagnostic signatures has been notified. Decoupling the wind load from condition monitoring decision making will reduce the associated down-time cost.**

***Keywords*—Wind turbine, condition monitoring, fault diagnosis, gearbox; bearing, generator, power electronics, rotor, blade, pitch control**

I. BACKGROUND

Wind power has become the world's fastest growing renewable energy source. The world-wide wind power installed capacity has exceeded 120 GW [1], and the new installation in 2008 alone was more than 27 GW. The US targets 20% wind-based electricity generation, i.e. over 300 GW, by 2030 [2]. The TPWind envisions the coverage of European Union electricity generation up to 12-14% by 2020 and 25% of by 2030 [3]. China aims for 15% renewable power generation by 2020 [4]. As wind power is growing towards a major utility source, reducing the cost of energy (COE) becomes a critical issue in order to make wind power competitive to conventional sources. The United States Department of Energy (US DOE) Office of Energy Efficiency and Renewable Energy (EERE) expects to reduce the COE of large wind systems in Class 4 winds to 3.6 cents/kWh by 2012 from a baseline of 5.5 cents/kWh in 2002 [5].

A major issue with wind power system is the relatively high cost of operation and maintenance (OM). Wind turbines are hard-to-access structures, and they are often located in remote areas. These factors alone increase the OM cost for wind power systems. Also, poor reliability directly reduces availability of wind power due to the turbine downtime [6]. According to General Electric (GE) Energy, a $5,000 bearing replacement can easily turn into a $250,000 project involving cranes, service crew, gearbox replacements, and generator rewinds, not to mention the downtime loss of power generation [7]. For a turbine with over 20 years of operating life, the OM and part costs are estimated to be 10-15% of the total income for a wind farm [6]. Although larger turbines may reduce the OM cost per unit power, the cost per failure is increased. The OM cost for offshore wind turbine is estimated to be 20-25% of the total income [8] [9]. Condition monitoring and fault diagnosis of wind turbines has thus greater benefit for such situations.

In addition, wind turbine repair and maintenance that require extensive usage of cranes and lifting equipment create a highly capital-intensive operation as well as delayed services due to lack of crane availability and needs for optimal weather conditions. Also, the trend that has currently emerged to dampen prospects is lack of personnel available to perform the consistent OM required to keep turbines functioning and efficient.

There have been a few literature reviews on wind turbine condition monitoring in literatures [10-14]. However, as the renewable energies have gained dramatically increasing attention from industries and academia since 2006, many new research works have been reported in the condition monitoring and fault diagnosis areas. The focus of this paper is to review the most recent advances in these areas with a special focus in wind turbines and their subsystems, and then identify future research opportunities for fault diagnostics and prognostics in these areas.

II. FAILURE CAUSES OF WIND TURBINE SYSTEMS

At early times, maintenance practices of wind turbine were mostly reactive maintenance, i.e. operate the wind turbines until failure occurs [8-10]. As wind turbines grew in capacity, preventive maintenance (PM) was more adopted. Many

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operators employ periodic inspections for condition assessment based on empirical and subjective measures. Such inspections are generally expensive and often require intrusive and require undesired scheduled downtime to be performed. Another disadvantage is that the condition assessment is only made in a periodic manner and the equipment conditions between checks remain unknown. With the help of condition monitoring and fault diagnostic techniques, predictive maintenance (PdM) and condition-based maintenance (CBM) have become increasingly adopted. Most subsystems in wind turbines may fail during operation, including rotors and blades, pitch control systems, gearboxes and bearings, yaw systems, generators, power electronics, electric controls and brakes among others [8-10].

Tavner et al. conducted a survey study on wind turbine failures based on 11 years of wind turbine failure data reported by a quarterly published newsletter WindStats [13]. Failure data for up to 4,000 turbines in Germany and more than 1,000 turbines in Denmark were included in that study. The failure rates of fixed-speed, variable-speed-indirect-drive and variable-speed-direct-drive turbines were compared. The major findings from a smaller population size were:

i) Direct-drive turbines do not seem to have a lower failure rate than indirect-drive ones;

ii) The failure rates of gearboxes in indirect drive turbines are much greater than the failure rate of inverters in indirect drive turbines;

iii) The aggregate failure rates of inverters and electronics in direct-drive turbines are greater than those of gearboxes in indirect-drive ones;

iv) For larger direct-drive turbines, the failure rate for generators is at least double that of the indirect-drive ones.

The first three findings led to the claim that the price paid by direct-drive wind turbines for the reduction of failure rate by the elimination of the gearbox is a substantial increase of the failure rate of all electrical related subassemblies. Nevertheless, since the mean time to repair (MTTR) of electronic subassemblies is lower than that of gearboxes, the availability of direct-drive units should be higher than that of the indirect-drive.

Later, further analysis on the above data was conducted by Wilkinson et al. in [14], mainly focused on comparing variable-speed and fixed-speed wind turbines. These studies showed that a major source of failure has root causes in subsystems centered on the drive train, which includes the main-shaft and bearings, gearbox, rotor brake, blades and generator. Among all the subsystems of wind turbine drive train, gearbox is considered the most critical for maintenance purpose, and the most failures manifested in gearbox bearings. For fixed-speed turbines, the failure rates for drive train components, mainly gearbox and blade, are significantly high. For variable-speed units, the failure rates of drive train greatly reduced, while the failure rates of control and electrics components increased dramatically, with the pitch mechanism, sensors, electric and electronic components being the most remarkable. The failure rate of the generator stays about the same for the two cases. Reference [10] made similar statement.

III. Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis

There have been a few literature reviews on wind turbine condition monitoring in literatures [10-14]. However, as the renewable energies have gained dramatically increasing attention from industries and academia since 2006, many new research works have been reported in the condition monitoring and fault diagnosis areas. This paper aims to review the most recent advances of condition monitoring and fault diagnostic techniques with the focus on wind turbines and their subsystems. This section summarizes the monitoring and diagnostic methods for the major subsystems in wind turbines that are reported in recent work.

A. *Gearbox and Bearing*

Gearbox fault is widely received as the leading issue for wind turbine drive train condition monitoring among all subsystems [10-14]. Gear tooth damage and bearing faults are both common. According to McNiff [15], bearing failure is the leading factor of turbine gearbox. In particular, it was pointed out that the gearbox bearings tend to fail in different rates. Among all bearings in a planetary gearbox, the planet bearings, the intermediate shaft-locating bearings and high-speed locating bearings tend to fail at the fastest rate, while the planet carrier bearings, hollow shaft bearings and non-locating bearings are most unlikely to fail. This study indicates that more detailed stress analysis of gearbox is needed in order to achieve better understanding of the failure mechanism and load distribution which would lead to improvement of drive train design and sensor allocation.

Vibration measurement and spectrum analysis are typical choices for gearbox monitoring and diagnostics. For instance, Huang et al. presented a study on vibration spectrum analysis based gearbox fault classification using wavelet neural network [16]. For variable-speed wind turbine operation, wavelet analysis has been recently accepted for feature extraction, as compared to faster Fourier transform (FFT) and envelop analysis tools developed earlier [7], [11]. Based on the wavelet analysis of vibration signals, Yang et al. developed a neural network based diagnostic framework for gearbox in [17].

The relatively slow speed of the wind turbine sets a limitation in early fault diagnosis using vibration monitoring method. Therefore, acoustic emission (AE) sensing, which detects the surface stress waves generated by the rubbing action of failed components, has recently been considered a suitable enhancement to the classic vibration based methods for multi-sensor based monitoring scheme for gearbox diagnosis, especially for early detection of pitting, cracking or other potential faults. Lekou et al. presented their study using AE in parallel with vibration, temperature and rotating speed data for health monitoring [18]. 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. [19] set up a finite-element (FE) simulation study for the stress wave based diagnosis for the rolling-element bearing of wind turbine gearbox. Wavelet analysis was applied to the output signals and to identify the artificial faults introduced to both the inner and outer race of the ball bearings in the simulated case. It is noteworthy that FE analysis is a good complementary tool to the experimental based study, with which the physical insight of various levels of faults can be investigated. Notice that AE measurement features very high frequencies compared to other methods, so the cost of data acquisition systems with high sampling rates need to be considered.

Yang et al. [20] presented a more comprehensive study on diagnosis for the drive train of the wind turbines with synchronous generators. Wavelet transforms were applied to deal with the variable-speed operation. In particular, the discrete wavelet transform (DWT) was employed to deal with the noise-rich signals from wind turbine measurements. For mechanical faults of the drive train, the electrical analysis was investigated. Diagnosis of gear eccentricity was studied using current and power signals. It is noteworthy that the data were obtained from a wind turbine emulator, on which the properties of both natural wind and the turbine rotor aerodynamic behavior were incorporated. Although the level of turbulence simulated was not described, the demonstrated performance was still promising for practical applications. The significant computational efforts of wavelet analysis were notified as a potential limitation.

Torque measurement has also been utilized for drive train fault detection. The rotor faults may cause either a torsional oscillation or a shift in the torque-speed ratio. Such information can be used to detect rotor faults, e.g. mass imbalance [14]. Also, shaft torque has a potential to be used as indicator for decoupling the fault-like perturbations due to higher load. However, inline torque sensors are usually highly expensive and difficult to install. Therefore, using torque measurement for drive train fault diagnosis and condition monitoring is still not practically feasible.

Table I summarizes the typical techniques for gearbox condition monitoring, with the target components, advantages and disadvantages listed for each. Some information comes from reference [21].

B. *Generators*

The wind turbine generators may subject to failures in bearing, stator, and rotor among others. For induction machines, about 40% failures are related to bearings, 38% to the stator and 10% to the rotor [22]. The major faults in stator and rotor of induction machines include inter-turn faults in the opening or shorting of one or more circuits of a stator or rotor winding, abnormal connection of the stator winding, dynamic eccentricity, broken rotor bars of cracked end-rings (cage rotor), static and/or dynamic air-gap eccentricities, among others. Faults in induction machines may produce some of the following phenomena: unbalances and harmonics in the air-gap flux and phase currents, increased torque pulsation, decreased average torque, increased losses and reduction in efficiency, and excessive heating in the winding. Popa et al. conducted an experimental study on fault diagnosis of doubly-fed induction generators (DFIG) [22]. Machine current signature analysis (MCSA) was investigated for turn-to-turn faults based on generator current spectrum analysis. The stator and rotor currents as well as the power signals were used for diagnostics.

TABLE I. SUMMARY OF TYPICAL GEARBOX CONDITION MONITORING TECHNIQUES

Sensing Scheme	**Monitored Components**	**Advantages**	**Disadvantages**
Vibration	• Gearbox • Bearing • Shaft	• Reliable • Standardized (ISO10816)	• Expensive • Intrusive • Subject to sensor failures • Limited performance for low speed rotation
Torque	• Rotor • Gear	• Direct measurement of rotor load	• Expensive • Intrusive
Oil/Debris Analysis	• Bearing	• Direct characterization of bearing condition	• Limited to bearings with closed-loop oil supply system • Expensive for online operation
Temperature	• Bearing	• Standardized (IEEE 841)	• Embedded temperature detector required • Other factors may cause same temperature rise
Acoustic Emission	• Bearing • Gear	• Able to detect early-stage fault • Good for low-speed operation • High signal-to-noise ratio • Frequency range far from load perturbation	• Expensive • Very high sampling rate required
Stator Current/Power	• Bearing • Gear	• No additional sensor needed • Inexpensive • Non-intrusive • Easy to implement	• Displacement based rather than force based • Difficult to detect incipient faults • Sometimes low signal-to-noise ratio

Watson and Xiang [23] used power signal to detect generator rotor misalignment and bearing faults using both FFT and wavelet analysis. Wavelet analysis was used to produce time-frequency representation of non-stationary signals. FFT analysis was used to determine the amplitude of the harmonic components more accurately, and thus to help find the peak amplitude spectrum of the wavelet coefficients during the given time period, which can be used as the fault signature. The results showed success in identifying early stage of failures. The authors stated that a variable loading on one hand presents difficulty for condition monitoring; while on the other hand, can excite a range of modes within a wind turbine and potentially provide rich information about the turbine health condition.

Shorted winding coil is a critical electrical fault, for which, immediate protection or remedial action should be taken. Shorted coil reduces the generator synchronous reactance. Wilkinson et al. [14] used shaft speed to detect shorted coil. Later, through the wavelet analysis, Yang et al. [20] studied the diagnosis of shorted coil. Through derivation, it was explicitly shown that mechanical torque is proportional to the ratio of shaft speed to the reactance, and thus shorted coil results in a larger mechanical torque to achieve the same shaft rotational speed. The current, voltage, power and torque-speed signals were all demonstrated effective for detecting shorted-coil. It was shown that such detection was more sensitive to changes in machine condition when the generator is fully loaded. However, shorted winding coil fault typically develops at a much faster rate (e.g., in minutes) as opposed to other mechanical degradation and faults (e.g., in days or months). This poses additional challenges to the accuracy and response time requirement for fault diagnostic and protection of such faults.

Bennouna et al. [24-26] conducted a series of work using model-based approach. The advantage of such methods is the ability for identifying the abnormal physical parameters in the generator system, rather than the signal signatures that are more dependent on the load conditions. A DFIG was studied and residual analysis was applied. It was also pointed out in [26] that the conducted analysis was based on linear assumption, which cannot be applied to strong nonlinear systems, e.g. generators under variable-speed operation. A special case was demonstrated for removing the nonlinearity. Durovic et al. [26] conducted another model-based diagnosis study on DFIG wind turbine, with similar motivation of identifying faulty physical parameters. A time-stepped coupled-circuit model was developed, with winding unbalance and excitation unbalance on either the stator or rotor explicitly included in the model. The proposed model was extensively verified through experiments on a specially constructed test rig with a 4-pole and 30-kW wound-rotor machine, coupled to a converter-controlled dc machine. In order to tackle the nonlinear converter model of DFIG wind turbine, a neural network based model was proposed by Wang and Guo [28]. A radial basis function based neural network was developed for diagnosis of inter-turn short circuit.

C. Power Electronics and Electric Controls

Electronic controls account for only about 1% of the cost of a wind turbine, but cause 13% of failures. Therefore, it is very beneficial to enhance the effort for diagnostics of electronic controls. Power electronics are a much more significant portion of cost for variable-speed and direct-drive turbines compared to constant-speed turbines. Compared to the relevant mature development of diagnostic techniques, diagnosis of power electronics seems much harder as very little time elapses exist between the appearance of fault and the catastrophic failures. It was suggested in [10] that redundant controls and power electronics, as used in aerospace applications, may be useful for larger and offshore turbines. However, the additional cost of having system redundancy still prevent such approaches due to cost concerns.

It has been concluded that a large portion of power electronics system failures are caused by the defects and failures of the semiconductor devices in the power electronics circuits. A fairly detailed survey of fault diagnostic methods for such semiconductor device failures especially IGBT's was reported in [29] for three-phase power converters, with the focus on three major system faults: open-circuit faults, short-circuit faults and gate drive circuit faults. The survey suggested that because of the time criticality of these faults, the fault detection and diagnostic methods for these semiconductor devices should be implemented as protection functions instead of monitoring functions.

D. Rotors, Blades and Hydraulic Controls

Wind turbine rotors are subject to creep fatigue and corrosion fatigue, which are reflected as cracks and delaminations in the composite blades. Rotor imbalance and aerodynamic asymmetry may occur due to manufacturing defects, non-uniform accumulation of ice, dirt, moisture or accumulated damage to the rotor blades. Due to erosion, icing, insects etc, the blade surface roughness may increase, which results in loss in energy capture efficiency. Blade fault diagnostics has been studied based on strain measurement techniques such as fiber-optic Bragg grating (FBG) and AE [10] [30-33]. For the blades of small wind turbine, Yuji et al. used a piezoelectric impact sensor [34], while Bouno et al. used AE sensor for fault detection [35].

Blade pitch control system is critical for turbine operation, as pitching is an important action for enhancing energy capture, mitigating operational load, stalling and aerodynamic braking [36-37]. Under very strong wind in particular, it is used as aerodynamic brake to stop the turbine. Avoiding pitching failure is thus important for the overall system operation. Pitching motion is typically driven by hydraulic actuators or electric motors. Electric motor driven pitching systems have larger bandwidth, which is more desirable for faster actions such as individual pitching. Hydraulic pitching systems have slower response, but bearing much larger stiffness, little backlash and higher reliability. For large to extreme aerodynamic loading situations, hydraulic systems are considered more fail-safe. Hydraulic actuation system failure takes a remarkable portion among different factors of wind turbine failure. According to the statistical study on Swedish wind farm during 2000 to 2004 by Ribrant and Bertling, 13.3% of failure events during 2000 to 2004 were due to the hydraulic system [38]. For the fail-safe operation of wind turbines, failure of hydraulic pitching may lead to catastrophic failure of the whole turbine, which must be prevented from.

Some faults of hydraulic systems may lead to operation instability. For instance, the effective bulk modulus of hydraulic fluid can be greatly reduced due to even a very small amount of air contamination. Reduction of fluid bulk modulus leads to the reduction of plant bandwidth, and thus reducing the stability robustness of the corresponding closed-loop system. Similar issue occurs for significant leakage in the hydraulic system [39].

Asymmetry in pitch angle may lead to unit shutdown during operation. Therefore, detecting blade pitching fault such as excessive backlash through control signals is an important diagnostic measure. MLS Electrosystem reported their practice of predictive maintenance for blade pitch control systems [40]. GE reported their activities in diagnosing the blade angle asymmetry and cabinet over temperature faults [41]. One possible solution is to seek diagnostic signatures from the control signal of the hydraulic pitch system in order to detect possible faults in the valve and drive path based on the relevant dynamic models [42].

E. System-Level Fault Detection and Isolation

Wind turbine and even its subsystems include many components, and thus the system- or subsystem-level fault detection and isolation presents quite some complexity. Fault isolation also requires more systematic analysis. Relationship between component-level faults and system-level faults need to be established efficiently. The framework of Discrete Event System (DES) is considered a suitable choice. As the finite-state machines suffered from the so-called combinational explosion for complex system, Petri Nets has been studied for wind turbine system-level decision making for fault diagnosis. In [43], Rodriguez et al. used the colored Petri Nets to diagnose a lubrication and cooling system for wind turbine.

Echavarria et al. [44] [45] developed a qualitative physics based approach in order to develop an intelligent maintenance system for wind turbine. The fault diagnosis system was developed based on a model-based reasoner (MBR) and functional redundancy designer (FRD). Both design tools used a function-behavior-state (FBS) model. The advantages of using MBR and qualitative physics were claimed to be capability of reasoning with little information, no need to solve a complex system of equations, reusability of easy access of knowledge, and robustness in fault prediction. The disadvantage of reasoning system is the ambiguity in setting up the thresholds. Zaher and McArthur [46] presented a preliminary framework of multi-agent fault detection system developed for wind turbine fault detection and identification. The development of an Anomaly Detection Agent, Power Curve Agent and Downtime Classifier Agent was briefly described. Multi-agent deserves more study due to its reconfigurability and scalability for system development.

A sensor network was applied to wind plant conditioning monitoring in [47]. Vestas reported their work on remote condition monitoring of wind turbines [48]. It was pointed out that many vibration monitoring systems on the market today overwhelm the user with alarms, of which many are caused by transients, or numerous alarms all related to the same faults. It is critical to convert data into information in order to make the condition monitoring system more efficient and robust. Wiggelinkhuizen et al. [49] presented the assessment of several condition monitoring techniques in the EU-CONMOW project carried out from 2002 to 2007. Vibration data along with other SCADA measurements were used for fault detection. The usefulness and capabilities of condition monitoring systems were analyzed, including algorithms for identifying early failures. The economic consequences of applying condition monitoring systems have been quantified and assessed.

IV. CONCLUSIONS

Condition monitoring and fault diagnosis have been received an important measure for predictive maintenance and condition based maintenance of wind turbine operation. Although many techniques existing in other industries can be directly or indirectly applied, wind turbines present particular challenges for successful and reliable diagnostics and prognostics.

For drive train components, the main issues are variable-speed operation and the stochastic characteristics of aerodynamic load, which prevent the usage of traditional frequency domain techniques. Time-frequency analysis such as wavelet transforms has been widely received as a necessary tool for such situations. Acoustic emission is considered more robust for low-speed operation of wind turbine compared to the classic vibration based methods. This approach is also more ideal for identifying early faults in gearbox bearings. Electrical faults such as generator and power electronics failures may be too fast for successful prognosis to be possible, and are most likely to be mitigated through online protections or hardware redundancy. Diagnostic and prognostic techniques developed in aerospace industry provide references for wind turbine condition monitoring. Model-based fault diagnosis has received more attention, from sub-system level to whole system level. The linear system analysis is not sufficient for the whole turbine system. Grey-box modeling approaches appear more appropriate and thus deserve more study in the future. Multi-agent system approach also deserves more study. Compared to the DES approach, hybrid system framework could be a better solution. The impact of unsteady aerodynamic load on the robustness of diagnosis signatures has been notified. Decoupling the wind load from condition monitoring decision making will reduce the associated down-time cost.

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